Movement and socioemotional development – a multilevel approach examining sub-second motor patterns and behaviour in infancy and childhood

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Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Yu Wei Chua
Date: 28 February 2022

Chapter 4 contains the submitted version of the manuscript which is now published in *Developmental Science* (see Page vii). I designed the research questions, data analysis, carried out all the analyses with feedback from co-authors, and wrote the manuscript with contribution from my co-authors. I acknowledge the work of Dr Anna Anzulewicz in collecting the smart-tablet gameplay data, and Krzysiek Sobota and Dr Szu-Ching Lu in contributing to processing the data. I acknowledge the work of Dr Szu-Ching Lu in creating Figure 4-1.

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Dedication

This thesis is dedicated to my late grandfather, Low Song Koon.

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Contributions to the Theirworld Edinburgh Birth Cohort Study

The data in Chapters 5, 6, 7 and 8 (Study 2) and Chapter 9 (Study 3) used in this thesis were from the Theirworld Edinburgh Birth Cohort Study (TEBC) Phase 2. The TEBC is a prospective longitudinal birth cohort study of the effects of premature birth on development. In this section I state my contribution to the Theirworld Edinburgh Birth Cohort Study.

I assisted with in-person data collection at the 9-month follow-up appointment of the study between June 2019 and March 2021. This involved administering the experimental protocols required at the 9-month appointment (eye-tracking battery, parent-child interaction, still-face paradigm, testing for visual acuity) and administering the parent interview of the Vineland Adaptive Behaviour Scales. I also contributed to questionnaire scoring and data entry of the developmental questionnaires and survey data collected at the 9-month and 2-year appointments, including data on anthropometry, adaptive behaviour, infant temperament, and autistic traits.

I contributed to study design of motor data using wearable sensors in the subsample of infants in Study 3, including the synchronisation of video and sensor data. I created the sensor pockets and attached them to infant clothing. I collected approximately 70% of the motor data.

I designed the observational video coding scheme used for Study 2 and coded all the videos of the still-faced paradigm to create the behavioural data used in Study 2.

I wrote the scripts in R to analyse behavioural data collected in TEBC using Chromatic Auto-Recurrence Quantification Analysis, and the scripts in Python to conduct Improved Multiscale Permutation Entropy, with reference from publicly available resources.

Abstract

Social-emotional capacities are key to social interactions and forming successful relationships with others. Bodily interactions with the world provide the experiences for developing these capacities. This thesis aims to understand the ways that movement in infancy and childhood are associated with differences in socioemotional development, through examining movement at two levels – sub-second motor patterns, and behaviours.

First, I examined differences in motor kinematics between autistic and neurotypical preschool children (Chapter 4), and provided further evidence supporting the notion that movement differences contribute to the social-cognitive features of autism.

To understand how movement is linked to the development of social-emotional competencies more generally, I investigated movement patterns related to emotional self-regulation in prematurely-born infants who are at risk of socioemotional difficulties - in studies set within the Theirworld Edinburgh Birth Cohort Study. A behavioural coding scheme was developed to capture the range of behaviours shown by infants in an experimental paradigm eliciting emotional distress.

9-months-old term-born (N=61) and preterm-born infants (N=50) differed in behaviours during emotional self-regulation and in the temporal characteristics of these behaviours - specifically, use of objects for attentional distraction, repetitive movements, and behavioural complexity (Chapter 5). Traits characterising emotional reactivity and regulation (Chapter 6), and motor development (Chapter 7) influenced emotional self-regulation. Further, certain behavioural patterns of emotional self-regulation at 9-months-old were prospectively associated with autistic traits at 2-years-old, suggesting that social cognition and emotional self-regulation depend on processes developing in concert (Chapter 8).

Finally, I examined in a proof-of-concept study whether sub-second motor patterns are able to distinguish infants by preterm birth status, or between different social-emotional contexts (Chapter 9).

This thesis demonstrates the use of new technology and cross-disciplinary approaches in studying infant and children's movement. Movement can reveal differences in the constraints shaping socioemotional development and has potential applications in identifying risks early.

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List of Abbreviations

%Dec	Percentage of time in the deceleration phase
ApEn	Approximate Entropy
DLS	Vineland Adaptive Behaviour Scales daily living skills domain
ENTb	Entropy of block structures
ER	Emotional self-regulatory / Emotional self-regulation
GA	Gestational age
IBQ-R	Infant Behaviour Questionnaire Revised
IMU	Inertial Magnetic Unit
LAM	Laminarity
LBW	Low birthweight
MOT	Vineland Adaptive Behaviour Scales motor domain
MSE	Multiscale Entropy
MU	Movement unit
MU-APV	Movement units after peak velocity
OBJ	Object exploration/distraction
PV	Peak velocity
PV1	Peak velocity of the first movement unit
Q-CHAT	Quantitative Checklist for Autism in Toddlers
R1	First reunion phase in the extended still-face paradigm
R2	Second reunion phase in the extended still-face paradigm
RME	Repetitive movement
RQA	Recurrence quantification analysis
RR	Recurrence rate
RRB	Repetitive and restricted behaviours
SC	Self-comforting
SF	Still-face paradigm
SF1	First still-face phase in the extended still-face paradigm
SF2	Second still-face phase in the extended still-face paradigm
SIMD	Scottish index of multiple deprivation
SOC	Social interactive/monitor
TEBC	Theirworld Edinburgh Birth Cohort Study
TT	Trapping time
TTPV	Time to peak velocity
VABS	Vineland Adaptive Behaviour Scales
VLBW	Very low birthweight

1. Socioemotional and motor development

"Development is about creating something from something less"
– L.B. Smith and Thelen (2003, p.2)

Section 1: Why are motor differences important for understanding socioemotional development?

Movement enables interactions with the world and it is through these experiences that infants develop increasingly complex abilities. This thesis is concerned with understanding socioemotional development and the importance of early motor and behavioural differences. In the first part of this chapter, I introduce the definitions of socioemotional development and highlight why it is important to understand. Second, I outline the reasons for considering how early motor difficulties might impact socioemotional development. Third, I introduce theoretical background that supports the idea that movement influences socioemotional development, and show how this has been applied to understand socioemotional differences in autism.

1.1. Definitions and measurement of socioemotional and motor development

1.1.1. Socioemotional development

Early in life, infants develop capacities that enable meaningful interactions with others and learn to cope with emotions including those arising from social interactions (Easterbrooks et al., 2013). Social and emotional development refer to the emergence of these capacities. Infant mental health depends on adequate development of social and emotional skills (Fitzgerald et al., 2011) and these early developing skills form the foundation for adjusting well in new social situations and emotional challenges. As such, social and emotional development can also be seen through the lens of behavioural difficulties.

In infancy, social development and emotional development are intertwined and often considered together (Easterbrooks et al., 2013; Thompson et al., 2003). For example, infants initially rely on caregivers to regulate emotions (Kopp, 1982, 1989); and their early social interactions with caregivers are shaped by their behavioural styles related to the reactivity and regulation of emotions. Attachment relationships with caregivers (Ainsworth, 1979) are social bonds, and also provide emotional security. Early attachment have social consequences as well, affecting the development of relationships with peers (Groh et al., 2017).

1.1.2. Social-emotional competence

The development and importance of socioemotional capacities can be considered within a hierarchical framework of social-emotional competence (Cavell, 1990; Taylor, 2020; Yeates et al., 2007). Social-emotional competence is the ability to form successful relationships with others (J. S. Calkins & Mackler, 2011; Ritchie et al., 2015), and depends on one's experience of social interactions. This in turn relies on a range of social cognitive functions and the processes to cope with emotional stressors (Happé & Frith, 2014).

Social cognition

At the lowest level, social cognition refers to the processing of social and emotional information. These mental capacities are recruited during social interactions to interpret social cues and depends on past experiences to interpret the present perceptual information about the social context. This includes perceiving affect in facial expressions, perceiving social intentions in gestures, and using knowledge about social cues and contexts to infer about others' mental states (i.e., having a "theory of mind"). Social cognition also encompasses emotional regulation and executive functioning to regulate one's behaviour to social and emotional contexts, such as decision making, impulse and inhibitory control in the presence of competing motivations or the need to suppress emotional reactions.

The neurobiology of social cognition demonstrates the inter-relation between the different socioemotional capacities. Social cognition is thought to involve not just processing of social signals, but connecting perception to motivational and emotional systems, in the service of adaptive behaviour in social contexts (Adolphs, 2001). Therefore, neural mechanisms implicated in social cognition include those processing social stimuli, understanding social stimuli through more complex knowledge systems, and modulating social behaviour.

At the next level, social cognitive processes determine patterns of social interactions, as these skills are evoked in daily social situations. This can lead to patterns of prosocial behaviour such as cooperation, turn-taking and expression of concern for others, withdrawn or impulsive behaviours. Over a longer timescale and at a higher level, these social interactions determine an individual's social relationships and functioning in particular social contexts, such as the classroom. Social-emotional development can also be described in terms of the difficulties faced in social interactions and the overall social adjustment, which I will now turn to.

Difficulties with social interaction

Difficulties with social interaction has been captured in terms of internalising and externalising behavioural difficulties. These difficulties may present with a consistent profile, and alongside specific patterns of difficulties of social cognitive difficulties, these socioemotional difficulties may be indicative of a neurodevelopmental disorder, or comorbid conditions.

Internalising and externalising behavioural difficulties

Internalising and externalising behavioural problems are broad groupings of behavioural emotional and social problems (Achenbach et al., 2016). In development, these behavioural problems can be seen as the result of difficulty in adjusting well to different interactional contexts, such as in the classroom, with peers, or when facing intense emotions or stimulation in day-to-day activities. Internalising problems include problems related to social withdrawal, fear, sadness, and inhibited behavioural profile – difficulties that are related to an inward psychological environment and associated with anxiety and depressive mood disorders later on (Liu, 2004). On the other hand, externalising problems are related to outward behaviours reflecting a child's behaviours on the environment, including problems with aggression, hyperactivity and difficulty with impulse control, difficulties that are later on related to conduct problems and ADHD (Liu, 2004). Behavioural difficulties have been linked to disrupted self-regulation - externalising behaviours are thought to result from insufficient regulation such that behaviour, attention and emotion are not adequately inhibited or adapted to the context, and internalising behaviours from overly controlled or constrained behaviour, usually as a result of high levels of negative emotions that need to be regulated (Cole et al., 1996; Nancy Eisenberg et al., 2001).

Neurodevelopmental disorders

Neurodevelopmental disorders refer to conditions associated with characteristic patterns of deficits that affect day-to-day functioning, and which develop early in life (American Psychiatric Association, 2013), when motor, cognitive and socioemotional capacities emerge.

While neurodevelopmental disorders are set out as distinct categories in the Diagnostic and Statistical Manual of Mental Disorders Fifth Edition (DSM-V), (e.g. intellectual disabilities, communication disorders; autism spectrum disorder (hereby autism), Attention deficit hyperactivity disorder (ADHD), Developmental Coordination Disorder and Specific Learning Disorders, co-occurrences of difficulties that span more than one category are the norm rather than the exception).

In particular, difficulties related to autism and ADHD appear to be related to altered socioemotional development. Autism is typically characterised by core differences in social cognition, encompassing difficulties such as understanding others intentions. However, autism is also accompanied by regulatory difficulties. Repetitive and stereotyped behaviours, another diagnostic criterion for autism, are associated with the need to cope with anxiety and sensory stimulation (Glod et al., 2019; Joyce et al., 2017; Rodgers et al., 2012; Wigham et al., 2014). In ADHD, difficulties with regulating impulsiveness, coping with sensory overstimulation can disrupt classroom behaviour (Daley & Birchwood, 2010) and peer relations (Nigg et al., 2020).

Social adjustment

Social adjustment refers to the extent that children behave in a socially desirable manner and the ability to participate in social interactions and achieve one's social goals. This encompasses self- and others' perception of social interactions, such as peer acceptance and rejection, quality of relationships and friendships, perceptions of social support and social self-esteem (Yeates et al., 2007). Difficulties may be directly observable such as bullying and victimisation. In addition, behaving appropriately in the classroom and at home, may affect a child's functioning and learning capabilities. Social adjustment difficulties impact children's and families' wellbeing and quality of life (Gómez-López et al., 2022; Hayes & Sharif, 2009), such as psychological distress resulting from related to bullying and victimisation (Sourander et al., 2000).

1.1.3. Measuring socioemotional development

Socioemotional development can be measured using questionnaires, assessing if a child demonstrates adaptive behaviour appropriate to their age of development, in social and emotional contexts. Different approaches can be used to assess adaptive behaviour, including through parent or teacher self-report, or parent-report through an examiner interview using the Vineland Adaptive Behaviour Scale (VABS) (Sparrow et al., 1984), or clinician assessed using the Bayley Scales of Infant Development (Bayley Scales) (Bayley, 1993).

From toddlerhood, social-emotional development is often seen through the lens of behaviour difficulties and adjustment, the second and third level in the framework of social competence described. These typically rely on parent or teacher report. The Strengths and Difficulties Questionnaire (SDQ) (Goodman, 2001) measures emotional and behavioural abilities and problems in five scales – hyperactivity, emotional symptoms, conduct problems, prosocial behaviour and peer problems. The Infant Toddler Social and Emotional Assessment (ITSEA) (Carter et al., 2003) also measures social-emotional problems and competencies in similar dimensions, and the Child Behavioural Checklist (Achenbach & Rescorla, 2001) measures parent-report of behaviour, focusing on social and emotional problems. Social-emotional development may be assessed using clinician-provided psychiatric diagnoses, which are based on clinical diagnoses (e.g. using the DSM V or the International statistical classification of diseases and related health problems (ICD 10)(World Health Organisation, 2004)). Trained researchers may also assess for a psychiatric diagnosis using diagnostic or screening tools, such as the Autism Diagnostic Observation Schedule (ADOS) (Lord et al., 2000). The SDQ is commonly used as a screening tool for ADHD.

Some questionnaires focus on behaviour that demonstrate social cognitive skills. This includes parent-report of skills related to autism, such as joint attention, use of gestures, in the Checklist for Autism in Toddlers (CHAT) (Baron-Cohen et al., 1992), and the Infant-

Toddler Checklist (Wetherby & Prizant, 2002); emotional regulation abilities, such as through parent-report on the Emotional Regulation Checklist (ERC) (Shields & Cicchetti, 1997), or examiner-rated on the emotional regulation scale of the Bayley Scales of Infant Development; or executive functioning such as using the Behaviour Rating Inventory of Executive Function (BRIEF) (Gioia et al., 2010). Social cognitive skills may also be assessed through experimenter observation of social interactions, assessing theory of mind using the false-belief tasks (Baillargeon et al., 2010), and tasks requiring attentional, cognitive and behavioural regulation (Archibald & Kerns, 1999; Henry & Bettenay, 2010).

1.1.4. Motor development

Difficulties with motor coordination, including severe impairments that meet criteria for Developmental Coordination Disorder, are another important type of difficulty that commonly co-occur with other neurodevelopmental difficulties.

Motor development can be measured using age-standardised questionnaires of gross and fine motor development, such as on the VABS and the Bayley Scales. In addition, motor skills may be assessed using a battery of tasks, such as the Movement Assessment Battery for Children (M-ABC) (Henderson et al., 2007; Henderson & Sugden, 1992) which assesses motor performance in tasks eliciting gross and fine motor skills, such as in balance and manual dexterity. More recently, motor functioning has been assessed at a kinematic level, looking at fine-grained differences in the way motor skills are achieved.

Motor delays are one of the first "red flags" of neurodevelopmental disorders (Gillberg, 2010; Micai et al., 2020). Delays in gross and fine motor skills - the coordination of body posture to achieve skilled movement such as sitting, crawling and walking, and of hands and fingers to manipulate small objects skilfully – are associated with later diagnoses of autism and ADHD (M. H. Johnson et al., 2015). The importance of motor skill delays as an early risk marker has been identified due to their prevalence in infants known to be at greater risk for neurodevelopmental disorders, such as in preterm infants (Fuentefria et al., 2017) and infant-siblings of individuals with autism (Canu et al., 2021).

While motor difficulties are recognised to implicate functioning and warrant intervention, these difficulties have traditionally been considered distinct from other "higher-level" psychological capacities. Motor difficulties are understood from the perspective of skilful-coordination – the coordination of the body to enable interactions with the physical world. Yet, there is ample evidence that movement goes beyond motor skills. In the following section I will introduce the philosophical position of *embodiment* and show the importance of characterising motor differences beyond difficulties with motor skills.

1.2. Theoretical background

Historically, mental processes were conceptualised as the processing of abstract symbols using internal mental representations of the world. This cognitivist conceptualisation of how the brain works was contemporaneous with the rise of artificial intelligence, contributing to the metaphor of the "brain as a computer" (Varela et al., 2016). Motor development, seen as the development of capacities to control the physical body, were as a result considered distinct from socioemotional development, seen as the development of capacities involving mental processing. However, a relatively recent philosophical position has emerged that counters this view. In this section, I will describe this philosophical position and similar theoretical perspectives emphasising the body's involvement in shaping mental capacities, and show how it has been applied to bridge motor and socioemotional development.

1.2.1. The embodied mind

The philosophical position that the mind is embodied holds that mental processes cannot be extricated from direct bodily interactions with the environment, a position that is the antithesis of the cognitivist view supposing that the brain is able to process information in a manner detached from the body's physical interactions (Varela et al., 2016). This philosophical position has also been termed *embodied cognition* (L. A. Shapiro, 2012). Cognition has also been described as enactive, meaning that cognition is constituted by ongoing action and interaction with the environment; embedded, that is grounded in and can be enhanced by physical interactions; and extended, such that cognition is not just constituted by internal processes, but can involve tools in the environment or other social agents.

Nevertheless, such a position does not just encompass processes regarded as "cognitive", such as memory, language and decision making, but other mental processes that the brain is involved in, such as emotion, attention and perception. In general, the position that the mind is embodied means that higher-level mental functions are shaped by bodily experiences which is, in turn, directly influenced by sensory and motor capacities. From the corollaries of the embodied mind position, I draw some implications for why motor experiences might be key to socioemotional development.

Socioemotional skills develop in the context of interactions with the world

Firstly, the embodied mind is one of multiple perspectives converging on the role of mental processes in, ultimately, enabling the successful interactions within the environment through the body (M. Wilson, 2002). From an evolutionary perspective, the mind affords increasingly complex sensorimotor interactions to match the complexities of the physical and social world, such as to be able to cache and remember food locations when food is scarce (Grodzinski & Clayton, 2010). The ecological psychology approach, pioneered by James Gibson (1979), considers the organism-environment system as a unit of analysis, placing on centre-stage this relationship in considering the organism's abilities and its development. In this view, the most basic interaction between an organism and the environment is perception and action. Perception is for action - rather than for creating disembodied mental simulations of the world based on transduction of chemical into electrical signals by sensory organs, perception has a key role in enabling action via capturing specific properties of the environment linked to how one can interact with it. In other words, perception captures information on affordances (Gibson, 1979). In Piaget's influential theory of cognitive development (Piaget, 1952), infants' earliest mental capacities are acquired as they act on the physical world. For example, Piaget showed that infants acquire knowledge of object permanence - learning that objects still exist even when they cannot be directly perceived – and they demonstrate this by searching in the location where they see a toy hidden from view. Piaget referred to the period where infants' mental capacities are closely linked to their actions as the "sensorimotor stage". These perspectives emphasise that first and foremost, the development of socioemotional skills should be considered in the context of infants' interactions with the world.

Socioemotional capacities engage sensorimotor processes

Secondly, high-level socioemotional capacities in part involve lower-level motor and sensory (exteroceptive and interoceptive) processes (Goldman & de Vignemont, 2009; Niedenthal, 2007). For example, understanding the meaning of others' actions is not encoded in an abstract, symbolic manner, but potentially linked to one's own experience of that action. Evidence for this comes from research on the parietal region of the brain which has been widely termed the "mirror neuron system" due to its activity during both action execution, and observation of the same action. Emotion is not an abstract mental state, but the combination of physiological changes, and facial and behavioural expressions. Emotional skills, such as perceiving emotions in others, involves re-activation of the same neural structures involved in the individual's prior experience of the emotion (Adolphs, 2002; Niedenthal, 2007). Differences in socioemotional capacities in neurodevelopmental disorders suggest that there are differences in infants' early experiences, linked to their emerging sensory and motor capacities.

Lower-level processes are involved in higher-level processing

Thirdly, mental processes are enactive, that is, it can be seen as a product of lower-level processes, including sensorimotor interactions. The dynamic systems theory of development, an approach compatible with the embodied mind position, shows how this is possible by drawing attention to the emergent characteristics of movement, that is interactions at multiple timescales and levels of components leading to richer, more complex functions that cannot be explained by individual components. This approach was first applied to motor development to understand how infants achieve motor skills (Thelen, 1995), given a high-dimensional musculoskeletal system which can be coordinated in infinitely many ways (Bernstein, 1967). Esther Thelen conceptualised motor skills as the result of cooperation of underlying structures, and that this is achieved through the intrinsic activity of the system, in other words through continuous trial-and-error. Thelen recognised the complexity of the motor system, that is involving a large number of interacting components, where cooperation between a group of components (for example to purposefully move the arm), can lead to higher-levels of cooperation within existing functional groups (for example in locomotion) (Thelen, 1995). Linda Smith further extended this approach to understand infants' mental skills, highlighting that these skills need to be understood as the result of interactions throughout all levels of the system (Thelen & Smith, 1994). She crucially showed that bodily interactions with the environment influence infants' cognition. Rather than being a modular entity that comes into existence with development, infants' concept of object permanence was sensitive to contextual changes during their interactions with the object. For example, in the A-not-B experiment, infants around 12 months old search correctly at location B when seeing an experimenter hide an object at that location, even after searching repeatedly at A. Infants who normally make an error to search at A on B trials, are able to search correctly when attention is enhanced to the hidden location – such as by increasing postural height; or when the motor memory of the repeated reach to location A was reduced by adding wrist weights (L. B. Smith & Thelen, 2003). In this way infants' cognitive skills are situated in the body's interactions with the environment, and depend on lower level skills that shape these interactions., Motor skills therefore provide opportunities to develop higher-level socioemotional skills through enabling new ways of interactions with the environment.

Similarly, emotional processing may also be seen as the product of interactions between different psychological domains, such as attention, cognition with physiology. Applying systems thinking to emotion, Panksepp and colleagues (1998) highlighted that emotion cannot be seen as solely involving cognitive or behavioural systems. They justified this through outlining the neurobiology of emotion. Emotional subcortical structures form a network between the brain and body such as through interoceptive signals; motor output via the periventricular gray; as well as through cortical structures involved in cognitive processes to respond and regulate these signals. As emotion is the biobehavioural response to perceived stimuli, it is the product of interactions across components, and not the activity of single components (Mascolo & Harkins, 1998).

Summary of the embodied mind position

To summarise, there are strong theoretical justifications for considering movement in socioemotional development. Crucially, motor differences might indicate differences in how the world is experienced; socioemotional capacities depend on lower-level processes; *vice versa*, lower-level processes influence higher-level mental processes. A modular view of the brain might conceptualise socioemotional capacities the maturation of disembodied abilities and neural networks. In contrast the embodied mind position posits that it is the result of processes across different domains working in concert, such as existing attentional, behavioural, cognitive skills and physiological tendencies. The involvement of early motor experiences in shaping socioemotional development needs to be understood better.

1.2.2. The movement perspective in autism

Advances in understanding autism through a "movement perspective" have underscored the importance of movement in socioemotional development. This perspective represents a paradigm shift (Kuhn, 2012) and sets the precedence for understanding the role of movement in socioemotional development. In this section I first define the core, and related, characteristics of autism and highlight how attempts to understand the disorder have not been able to isolate a single cause that might explain all the features of autism. Then, I introduce how the embodied mind perspective contrasts with top-down approaches to explain the various social features of autism, and how the movement perspective of autism fits within a bottom-up embodied view of autistic differences.

History of conceptualising autism as a result of "top-down" mental deficits

Autism is characterised by difficulties with social interaction, communication and repetitive and circumscribed interests (American Psychiatric Association, 2013). The social features of autism have historically been under the spotlight, thought to result from impaired social cognition. Repetitive and stereotyped behaviours – encompassing over or under-reactivity to sensory input – have only recently been recognised as diagnostic features of the condition (American Psychiatric Association, 2013). Autism is a heterogeneous condition with different extent of deficits and impairments in social interaction and communication. It is also often comorbid with other neurodevelopmental difficulties and psychopathologies (Masi et al., 2017). Furthermore, beyond diagnostic features of socio-communicative and behavioural differences, difficulties with executive functioning (Demetriou et al., 2018) and motor coordination (Fournier et al., 2010; Green et al., 2009) are also widely observed.

Theories have been put forth to attempt to explain some of the cognitive features of autism. Two highly influential accounts of autistic cognitive features are the theory of mind hypothesis and the Weak Central Coherence account of autism. The theory of mind hypothesis proposes that autistic individuals may lack the ability attribute mental states, such as such as beliefs, intentions and emotions, to self or others. Challenges with social interaction including difficulties with understanding intentions from actions or engaging in joint attention may be attributed to an impaired ability to infer another's mental state. Uta Frith's theory of Weak Central Coherence (Frith, 2003; Frith & Happé, 1994) posits that autistic individuals perceive details, rather than the global, coherent whole made up of those smaller parts. To further explain the broader cognitive phenotype in autism including difficulties with executive functions particularly inhibition, behavioural flexibility and self-monitoring is recognised, it has been suggested that dysfunction in higher-level cognitive control mechanisms may contribute to characteristic autistic behaviours such as insistence for sameness and perseveration (Hill, 2004).

While these theories are compelling, they fail to provide a complete picture (Rajendran & Mitchell, 2007) and tend to overlook the non-social aspects. To reconcile these perspectives, a "multiple-deficits" view has been proposed, suggesting that autism reflex a complex cognitive dysfunction, spanning more than one cognitive dysfunction (Happé et al., 2006). Some research have also linked executive dysfunction to impaired development of a theory of mind (Ozonoff et al., 1991).

A "bottom-up" explanation for autism

"Bottom-up" approaches may complement these "top-down" approaches to link features of autism to impaired mechanisms. Instead of purporting disruptions to modular cognitive functions, taking the position that the mind is embodied draws attention to how infants' early experiences reflect different perceptuomotor processing underlying the development of social cognition and other features of autism. Research on early identification focuses on signs in infancy and toddlerhood that are associated with a later diagnosis of autism (Yirmiya & Ozonoff, 2007). These may be detected within the first year of life (Zwaigenbaum et al., 2013). While early impairments in social communication (e.g. eye contact, gestures, attention to social situations) and language delays have been identified as one of the earliest markers of autism risk, a range of other risk factors such as repetitive behaviours and atypical object-use, patterns of emotional regulation, and motor delays are also present (Zwaigenbaum et al., 2013). Rather than focusing on cognitive deficits or specific differences in the attentional domain, motor behaviours – which reflect infants' emerging sensory, motor and mental capacities and which influence the development of more complex mental processes – may reveal the complex nature of autism risk.

Another recent view is that autism may be related to a general difficulty with predictive abilities due to a disruption in the neurobiological processing of "prediction error" (Sinha et al., 2014; van de Cruys et al., 2014). Such an impairment might account for a number of autistic characteristics. For example, when a perceived stimulus becomes predictable, the sensory system exhibits habituation such that the stimuli is no longer perceived at its original intensity. This may be linked to sensory hypersensitivities. Theory of mind difficulties may also relate to impairment in using past and present observations to make predictions about another individual's beliefs or intentions.

The "movement perspective" *embodies* another bottom-up approach (Donnellan et al., 2012; Torres & Donnellan, 2015). Central to an embodied and enactive view of the development of social cognition, is the idea that interactions with others – intersubjective experiences – is what enables this. This view has been termed the "Interaction theory" (Gallagher & Varga, 2015). Interaction theory suggest that early forms of one-to-one social interactions or primary intersubjectivity, are based first in perceptual experiences – these early interactions need not involve mentalising or inferring beyond the perceptions. For example, in early social interactions infants can imitate the facial expressions of others, and respond differently to human faces than to objects (Gallagher, 2004). Early in life, they are able to recognise the effects of their own bodily movements through proprioception, and their movements already differentiate between interactions with objects and with other agents in fetal life (Delafield-Butt & Gangopadhyay, 2013). When infants experience secondary intersubjectivity, i.e., interacting in shared context with reference to other objects, they then start to pick up contextual cues about these objects and develop more complex capabilities such as detecting others' intentions, and inferring from eye gaze direction. Some researchers purport that a disruption to sensorimotor processes – such as organising movements to achieve goals – directly affects infants' experience of one-to-one interactions. This, alongside a constellation of neurological and psychological differences, may cascade into differences in how infants experience the world with others (Gallagher & Varga, 2015; Colwyn Trevarthen & Delafield-Butt, 2013).

On one hand, proponents of such a view identify evidence of concerns with motor coordination in autism as support, emphasising that these have been overlooked when focusing on the social communicative aspects of autism (Whyatt, 2017). They also highlight that motor differences should be considered beyond physical movement, to look at behaviour, meaningful aspects of movement that enables different types of engagement with the external environment – for example, to reach for an object, or to communicate using gestures. Furthermore, movement can reveal something about its causes – because it is the product of multiple layers of processing within the central and peripheral nervous system, responding continuously to changes in the external environment, and emphasise new directions in using technology and statistical analyses methods to further characterise motor differences (Brincker & Torres, 2017). Additionally, this perspective acknowledges and brings to the forefront the first-hand views of autism self-advocates on how processing movement changes their experiences of the world.

Altogether, the movement perspective captures three main aims, to increase understanding of the social experiences of individuals with autism, to understand mechanisms how socio-communicative difficulties may derive from early differences in motor coordination, and to improve assessment and interventions for difficulties in autism (Torres & Donnellan, 2015).

1.2.3. Advances in understanding autism from a movement perspective

Research into the movement perspective on autism is already underway and has made significant advances in understanding differences in the processes underlying autistic individuals' interactions with the world. Several reviews have confirmed that motor differences – across motor skills assessed by experimental tasks and standardised batteries – are present in autism (Bhat et al., 2011; Coll et al., 2020; Green et al., 2009; Zampella et al., 2021) but research on motor differences in autism have since delved beyond mere characterisation of motor delays and difficulties with standardised assessments (R. B. Wilson et al., 2018), to quantitatively analyse and understand the processes operating behind motor coordination. For example, looking at how movement unfolds, such the spatial characteristics of movement during a tracing task, show that autistic individuals may have difficulties with coupling perceptual information to action output (Whyatt & Craig, 2013).

Motor coordination and kinematic differences

A large body of research reviewed by Gowen and Hamilton (2013) has considered the temporal course of movement to understand which processes are affected, guided by computational theories on processes involved in the real-time coordination of action. These computational theories address how movements are planned and executed in the presence of biological constraints and task demands. For example, the motor system is not able to access sensory feedback immediately after a movement due to delays in communicating sensory afference through the sensorimotor loop, yet, to reach the goal effectively, discrepancies such as due to environmental disturbances or noise within the system need to be corrected (Desmurget & Grafton, 2000; Miall & Wolpert, 1996). A speed-accuracy trade-off has also famously been described where fast movements tend to be less accurate and tasks demanding higher levels of accuracy lead to slower movements (Fitts, 1954; Harris & Wolpert, 1998). Woodworth (1899) first described a “two-component” process of motor control, including an early feedforward phase which translates sensory aspects of the goal into an initial motor command; followed by a later feedback phase using sensory information to correct discrepancies. This model has been elaborated on to include on how the motor system uses internal models. An inverse model represents desired goals as muscle activations in inverse models, while a forward model represents the expected sensory feedback from motor commands, to monitor the new motor state achieved from the motor command and enable correction of discrepancies before the true sensory feedback becomes available. The kinematics of movement show phases of accelerations and decelerations, respectively, representing the initial execution of the motor command and later online control (Elliott et al., 2010, 2017). These landmarks in the kinematic profile, relating to the acceleration and deceleration phase, have been shown to be sensitive to specific task demands (Bootsma et al., 2004; MacKenzie et al., 1987).

Gowen and Hamilton’s review identified differences in reaction time before a movement is executed, indicating that autistic individuals require more time to form a motor plan tailored to the perceptual aspects of the task. Work on the sub-second kinematics of action as they unfold also tell us about how autistic individuals use perceptual information to plan action, and existing evidence suggests this is not impaired. However, online control when ongoing action becomes altered by noise or environmental disturbances, appears to be different.

Finally, visuomotor adaptation paradigms have been used to test for differences in motor learning. In these paradigms, individuals control a cursor on the screen through a robotic arm, and the experimenter is able to add visual or motor perturbations to the cursor or robotic arm. Following practice in the novel environment, individuals learn to combine specific kinds of sensory feedback (e.g. haptic or visual information) to guide movement to counter the perturbations successfully. Looking at the generalisation of learning to achieve another goal reveals the learnt movement patterns. Autistic individuals performed better relative to neurotypical individuals when the new movement was more similar to the learnt joint rotations, than the learnt visual direction of movement (Haswell et al., 2009; Izawa et al., 2012). Focusing on how sensory differences may influence motor difficulties, Hannant and colleagues (2016) reviewed studies suggesting that sensorimotor integration may implicate motor performance where online control is needed, or in visuomotor tasks where visual information is crucial for task completion. They further highlighted that practice improves motor performance, although the resulting movement kinematics may reflect motor compensation. This body of evidence suggests that autistic individuals may show early differences in motor coordination, potentially due to sensory differences and difficulties with sensorimotor integration, leading to different ways of achieving successful movement.

Prospective actions

An emerging issue in motor control and a crucial part of developing motor capacities is how individuals prospectively control their actions (von Hofsten, 1993), in other words how future plans are incorporated in current actions. Although the computational theories do not explicitly state this, sensitivity of actions to future information has been demonstrated in research on action chaining, by examining how planning of the first step of an action is affected when the second step is manipulated. Some studies found differences in how autistic individuals planned their movement in relation to the immediate next step, for example how much slower a movement is when the next step requires greater accuracy (Fabbri-Destro et al., 2009), and the extent they showed muscular activations anticipating the next movement step (Cattaneo et al., 2007). However, work on action chaining remains inconclusive (Gowen & Hamilton, 2013).

Linking motor differences to social-cognitive patterns

The implications of movement differences in autism remains debatable. Some research has identified links between sensorimotor difficulties with autism (Fournier et al., 2010; Green et al., 2009), however a recent meta-analysis did not support a relationship between motor difficulties and social cognitive difficulties (Coll et al., 2020). Researchers have speculated that differences in action kinematics are directly involved in social-cognitive processes (Cook, 2016; Gowen, 2012; Colwyn Trevarthen & Delafield-Butt, 2013), drawing on evidence that social cognition taps on the sensorimotor system, where executing an action and observing someone else perform the same action evokes “mirror neuron” activity in the parietal cortex. As movement kinematics may contain information about the goal and allow prediction of the motor goal, differences between autistic and neurotypical individuals may impede intentional understanding (Gowen, 2012). Cook (2016) identified examples where individuals recognised degraded movements created by point-light displays better when they were more similar to their own. Observing others’ movement is an important process in motor learning, and difficulties with integrating visual information with movement may impede this (Gowen, 2012). Others have suggested that motor impairments impede social development by affecting the opportunities for social learning and engaging with caregivers and peers (Adolph & Franchak, 2017; Bhat et al., 2011; Campos et al., 2000) or the resources attributed to social cues encountered during movement (Bhat et al., 2011).

Early identification

Another branch of research on movement in autism has focused on early identification. While psychologists have designed standardised tasks to measure behavioural performance, as discussed movement is accessible to scientists through technology (Torres & Donnellan, 2015). Coupled with machine learning, movement biomarkers identified using technology show promise in diagnosis (Hocking & Caeyenberghs, 2017), and appear capable of differentiating between groups with a high sensitivity and specificity in children (Anzulewicz et al., 2016; Simeoli et al., 2021), though with lower specificity in young adults (Ardalan et al., 2019). However, machine learning is limited in that “movement feature engineering” focuses on successfully categorising groups and may not be externally valid. This is because there many algorithmic solutions that are able to categorise groups, and motor differences that successfully differentiate between groups may be different from sample to sample. This divide between research using movement for early identification and movement to increase mechanistic understanding of socioemotional difficulties in autism may limit advances in early identification. Drawing on the wealth of knowledge on autistic movement differences, and developing motor control has the potential to close this gap. Recently, a movement feature related to postural control was found to robustly distinguish autistic and neurotypical toddlers (Dawson et al., 2018). This feature was detected from computer vision analysis of head movements from camera data acquired in an ecological setting – when toddlers watched videos on an iPad at home. This demonstrates the potential of combining understanding of motor development and coordination with improving early identification through technology.

Challenges to the movement perspective

The movement perspective faces a number of challenges to further advance the field. Most importantly, although differences in motor skills are widely reported in autism, they are considered separate from the motor-related features of autism (i.e., stereotyped and repetitive movements) (Zampella et al., 2021). Motor skills differences are already widely recognised, and in recent years this has been elaborated further beyond standardised assessments, to look at subtle differences (Zampella et al., 2021). Instead of establishing a niche in the motor domain, researchers advancing movement perspective can start to understand how movement enables interactions beyond the physical world where motor skills take precedence, but also how movement enables interactions with the social world and reacts to internal motivations and cues. Doing so can also help to address a second challenge in understanding how motor skill difficulties cascade into other domains of development, when presently this claim draws mainly on theoretical accounts. Third, motor skill differences are not unique to autism (Bhat et al., 2011; Piek & Dyck, 2004), and the movement perspective therefore should not be limited to understanding autistic social communication and interaction. Understanding how movement relates to shared early risk factors with other disorders may help clarify the pathways through which movement affects autism. Finally, mechanistic understanding and early identification go hand-in-hand. While technological solutions show promise in differentiating autism and neurotypical children, it is unclear as yet what motor differences mean at different stages of development. We need to know how early, and how, such motor differences can indicate risk.

1.3. Summary of section

To summarise, in this section, I defined socioemotional development and introduced the importance of considering movement in socioemotional development. I explained that motor difficulties and delays are highly common in conditions related to socioemotional difficulties, such as autism and ADHD, and that they may be an early indicator for socioemotional difficulties. I outlined the embodied mind perspective which further supports the importance of movement in the development of mental functions. I provided an overview of an emerging field where research is underway to understand how motor differences shape the social experiences of autistic individuals.

Section 2. Socioemotional and motor outcomes in preterm birth

The literature I reviewed in the previous section highlight the potential of considering movement in early socioemotional development, because higher-order socioemotional capacities develop in the context of the body's interactions with the world. While research on movement have come into the spotlight in characterising differences in autism, motor differences are also related to other neurodevelopmental difficulties (Bhat et al., 2011; Piek & Dyck, 2004). It has been proposed that early pathways that lead to the overlap between autism and ADHD are related to shared developmental pathways (M. H. Johnson et al., 2015), and the importance of studying developmental processes prior to symptom development (M. H. Johnson et al., 2015). Furthermore, autism is only diagnosed reliably in toddlerhood, yet motor skills rapidly develop in infancy across the first year of life and most research on motor differences in autism are in young children who have already received a diagnosis. I also showed that researchers have started to establish the link between motor skills and other psychological domains. This nascent field of research using movement to understand developing mental capacities is only just scratching the surface – in mechanistic understanding and in early identification.

In this section, I introduce another population – individuals born preterm. I review literature to show why this population will benefit significantly from increased understanding on how motor differences might indicate socioemotional risk, and from early identification through movement.

1.4. Epidemiology and impact of preterm birth

Preterm birth is birth before 37 weeks of gestation (Vogel et al., 2018). Each year, more than 1 in 10 babies are born too early (Blencowe et al., 2012), affecting 15 million births (Blencowe et al., 2013). Births before 32 weeks of gestation are classified as "very preterm" births and births before 28 weeks of gestation are classified as "extremely preterm" (Blencowe et al., 2013). Preterm birth can result spontaneously, including from the early rupture of the amniotic membrane surrounding the foetus in the womb, but can also be induced to protect the mother or foetus, such as due to infections and maternal complications related to medical disorders (Blencowe et al., 2013; Goldenberg et al., 2008). Spontaneous preterm labour is strongly linked to black ethnicity, multiple gestations, and a previous history of preterm birth, and also stress, tobacco use and intrauterine infections (Goldenberg et al., 2008).

Preterm birth is a concern because the major organs are not yet fully developed before 37 weeks of gestation. It is a major cause of neonatal mortality (Blencowe et al., 2013), but improvements and innovation in medical care have increased the survival rate of infants born preterm, especially in those born extremely preterm, or with extremely low birth weight (Glass et al., 2015; Tucker & McGuire, 2004). Surviving preterm infants are at risk of many medical complications leading to morbidity and physical and neurological disabilities, including bronchopulmonary dysplasia, retinopathy, visual and hearing impairment and cerebral palsy. The risk of morbidity is as high as 20-50% in extremely premature infants (Glass et al., 2015). In addition, preterm born infants are at risk of developmental delays and poor neurodevelopmental outcomes across motor, cognitive, and socio-emotional domains (Allotey et al., 2018; Pascal et al., 2018; Pierrat et al., 2017; Serenius et al., 2016). At 2-years, 36.2% of preterm infants scored below threshold in at least one of five developmental domains (communication, problem solving, personal and social skills, gross motor skills and fine motor skills), rising to approximately 40% and 50% in very preterm and extremely preterm infants respectively (Pierrat et al., 2017). Delays or impairments are still apparent later at school age (Arpi & Ferrari, 2013; Pascal et al., 2018), and even beyond primary school age (Allotey et al., 2018).

Socioemotional development has been highlighted as one of the most important issues in the preterm population. Risk for psychiatric disorders are also 3 to 4-fold greater in preterm compared to term populations (S. Johnson & Marlow, 2011), with greater rates in those born at lower gestational age (Marret et al., 2013). Of particular note, there is a high prevalence of inattention, anxiety and social difficulties, the most severe of which meet criteria for ADHD, anxiety and autism. This constellation of co-occurring difficulties has been termed a “preterm behavioural phenotype” (S. Johnson & Marlow, 2011). Internalising and dysregulation behavioural problems can also be observed at 2 years (Arpi & Ferrari, 2013). Early socioemotional difficulties before 2 years are predictive of later behavioural problems: including emotional symptoms, hyperactivity/inattention problems at 5 years (Arpi & Ferrari, 2013), and psychiatric diagnosis at 11 years (S. Johnson et al., 2010b). Disrupted socioemotional development has been highlighted as an important pathway to mental health difficulties in this population (Montagna & Nosarti, 2016).

The long-term neurodevelopmental consequence of premature birth is becoming an important ethical issue in particular for infants born at the lowest gestational ages who at the greatest risk of morbidities - although neonatal intensive care can increase the chance of survival, there has been limited progress with improving neurodevelopmental outcomes (Albersheim, 2020; Arpino et al., 2010). Furthermore, the high prevalence of low severity impairments across multiple domains (Sansavini et al., 2011) is also a major concern as this can impact lifelong health and wellbeing of this group, such as affecting relationships, employment and quality of life (Wolke et al., 2019). Preterm birth is also related to a high public economic burden related to hospitalisation and resource use, as well as costs borne by family to support the child (Petrou et al., 2019). There is therefore a pressing need for research focused on understanding and improving the neurodevelopmental outcomes of preterm infants, to effectively addressing these important public health concerns at a societal level (McCormick et al., 2011), and ultimately increasing the wellbeing and quality of life of individuals and families.

1.5. Preterm brain development and neurodevelopmental outcomes

Brain injury in preterm infants is an important cause of neurodevelopmental impairments (Volpe, 2019). Diffuse, rather than focal, white matter injury is the most prevalent type of brain injury (Agut et al., 2020), thought to due to the vulnerability of the preterm brain during a crucial period of rapid brain maturation in the third trimester (Volpe, 1998, 2009), occurring alongside clinical complications such as intraventricular haemorrhage, asphyxia, hypotension, postnatal infections (e.g. neonatal sepsis, urinary tract infection, and meningitis) (Agut et al., 2020; Perlman, 1998)). White matter injury has been linked to poorer socioemotional competence (Spittle, Treyvaud, et al., 2009).

In addition, brain development can be affected by more distal causes (Duerden et al., 2013). Notably, development within the postnatal environment, especially early exposure to stress and sensory environment in the Neonatal Intensive Care Unit may alter neural structure and function (R. G. Pineda et al., 2014; G. C. Smith et al., 2011). Maternal care is also disrupted by Neonatal Intensive Care Unit (NICU) admission as the newborn infant lacks physical and emotional closeness with the mother, known to be important for developing an attachment relationship. Maternal wellbeing may also be impacted by the hospitalisation episode, and parent-child interactions may also be altered due to a less responsive behavioural profile linked to preterm birth (Lammertink et al., 2021). Social economic status (SES) has also been highlighted as a crucial factor shaping infants' neurodevelopment (Duerden et al., 2013), with lower maternal education having similar effects as brain injury on cognitive development at 4-years old (Benavente-Fernandez et al., 2019). SES has the potential to attenuate the effects of brain injury, though the influence of SES goes both ways and can worsen the effects of preterm birth (Benavente-Fernandez et al., 2019; Boardman & Counsell, 2020; Potijk et al., 2013).

Socioemotional behavioural problems tend to co-occur with poorer cognitive, motor, neurological and language outcomes (Arpi & Ferrari, 2013). Infants' developing capabilities across perceptual, communicative, attentional and cognitive domains, have also been proposed to affect infants' neurodevelopmental trajectory (Sansavini et al., 2011). Researchers have also highlighted the role of development in itself as a process that can alter how infants interact with the environment around them and learn from these interactions (Karmiloff-Smith, 1998). In particular, the motor domain is the most vulnerable to brain injury and neural alterations (Sansavini et al., 2011), and may lead to cascading effects on other domains of development. While brain abnormalities but showed associations with motor, cognitive and behavioural outcomes at 2-years old, they only continued to predict long-term motor outcomes at 10-years old (Jansen et al., 2021). Early neurological examination of movement abnormalities at 6-months, has been shown to aid MRI at term-equivalent age, in improving predictive accuracy for both motor and cognitive delays at 2-years (George et al., 2021). In the large French EPIPAGE cohort of preterm birth, severe white matter injury was associated with both motor and cognitive deficiencies, and motor deficiencies rarely occurred without cognitive problems, leading to the suggestion that altered motor and cognitive development have common origins in brain injury, and also highlight the influence of motor development on developing cognitive skills (Marret et al., 2013).

Therefore, biological factors are not the sole determinant of preterm neurodevelopmental outcomes, but interact with early environmental factors. Development is not a static process and infants' developing abilities could change the way infants interact with the environment, and affect the ongoing development of higher-order abilities. In this vein, infants' motor abilities, which develop rapidly prior to the emergence of more complex cognitive skills, may contribute to the complex interplay of biological and environmental factors in shaping infants' neurodevelopmental trajectory.

1.6. Motor development in preterm birth

Cerebral palsy is the most severe form of motor impairment related to preterm birth, but developmental delays and impairments in gross and fine motor skills are also very common in preterm-born infants and warrant attention (Bulbul et al., 2020; Pierrat et al., 2017; J. Williams et al., 2010). 1 in 5 very preterm or very low birth weight infants experience motor delays (Pascal et al., 2018), with a lower birth weight or gestational age leading to worse motor outcomes (Boonzaaijer et al., 2021; Bulbul et al., 2020; J. Williams et al., 2010). Risk for fine motor delays was high across all preterm phenotypes (i.e., complications related to preterm birth), and overall, 4 times more likely than controls to score lower than the 10^{th} centile of a measure fine motor development (Villar et al., 2021). Preterm infants are also 6 times more likely than term controls to receive a diagnosis of Developmental Coordination Disorder (Edwards et al., 2011). DCD is usually diagnosed when motor performance is not just poor relative to their chronological age standard ($<15^{th}$ centile of the Movement Assessment Battery for Children scale), but significantly interferes with academic achievement and daily living (American Psychiatric Association, 2013). Movement abnormalities can also be described qualitatively, such as monotonous, jerky character. These can be observed in preterm infants from 3 months (Örtqvist et al., 2021).

In particular, there is evidence that motor delays can lead to poor neurodevelopmental outcomes. Motor developmental delays not just co-occur with cognitive difficulties (Spittle et al., 2021) but can predict cognitive outcomes (Marlow et al., 2007; Uusitalo et al., 2020). Abnormal movement quality from birth also has the potential to predict delayed achievement of motor and cognitive milestones (Caesar et al., 2021; Einspieler, Bos, et al., 2016) and later neurodevelopmental disorder (Rizzi et al., 2021). This supports the idea that motor difficulties and delays are one of the earliest observable signs of neurodevelopmental disorder (Gillberg, 2010), preceding the emergence of other difficulties in preterm birth.

1.7. Socioemotional development in preterm birth

Socioemotional behavioural difficulties in preterm born infants are characterised by a phenotype of inattention, anxious traits alongside social difficulties (S. Johnson & Marlow, 2011). The risk and prevalence of psychiatric disorders associated with this triad of difficulties are also much higher in preterm populations than the general population. Prevalence estimates in preterm populations are from around 11-17% for ADHD (Treyvaud et al., 2013), 4-8% for autism (S. Johnson & Marlow, 2011) and 9-14% for anxiety (S. Johnson & Marlow, 2011; Treyvaud et al., 2013; Yates et al., 2020). Across any psychiatric diagnoses, there is a 2 to 3-fold greater risk for preterm populations, and risk increases with reducing gestational age and birthweight (Bhutta et al., 2002; S. Johnson & Marlow, 2011)). The risk for internalising disorders in preterm populations has been found to be specific to anxiety disorders, and not depressive disorders (Fitzallen et al., 2021) – however risk for subclinical symptomatology may need to be considered.

Two findings in particular highlight the need to consider the effect of prematurity on socioemotional development in general, and not just psychiatric outcomes: first that the pattern of highly prevalent but less severe, subclinical, behavioural difficulties (S. Johnson & Marlow, 2011; Kroll et al., 2018); and second, the presentation of difficulties may not be fixed over time and lead to different diagnoses over childhood and adolescence (Yates et al., 2020). Here, I consider evidence of that preterm born individuals are at risk of poorer socioemotional functioning and how it relates to later psychiatric outcomes. I use the definition socio-emotional functioning as the "ability to learn and successfully interact and communicate within a social context and to efficiently deal with emotions" (Montagna & Nosarti, 2016, p. 2). As reviewed in the previous section, the functions that are implicated to enable successful social interactions, and coping with day-to-day emotional stressors (Happé & Frith, 2014) can be captured by a hierarchical framework of social-emotional competence. As such, I consider evidence in terms of behavioural difficulties and social cognitive abilities in toddlerhood and childhood. The nature of socioemotional functioning in early life involves the successful regulation of neurophysiological states, to maintain alert, responsive and adaptive states to engage in social-emotional interactions; therefore, I will consider briefly differences in how infants regulate neurophysiological states, even when socioemotional problems may not manifest yet (Montagna & Nosarti, 2016). I will not consider general aspects of development (motor, attention, memory, language), even though they contribute to socioemotional functioning (Happé & Frith, 2014), but recognise that behavioural difficulties (such as those attributed to attentional regulation) manifest in social and emotional contexts.

Few studies have evaluated behaviour prior to 1-year of age in preterm infants (Litt et al., 2019; Wolf et al., 2007). Differences in behavioural responses are reported based on observer assessments of behavioural quality. Preterm differences in behavioural responses to the regulation of neurophysiological states (such as in the presence of aversive or intense stimulation and social interaction) have been observed (Wolf et al., 2007). Observer ratings using the Infant Behavioural Assessment show that infants born preterm show behaviours indicating greater stress and lower approach at term age and at 3-months, and by 6-months, infants born preterm use more coping behaviours in physiologically stressful or arousing situations (during assessment, caregiver routines and social interactions). However, ratings on the Behavioural Rating Scale of the Bayley Scales in infants born preterm show poorer quality of emotion regulation and orientation/engagement relative to term peers, with close to 50% falling in the non-optimal or questionable range, compared to just 10% of term infants. Some behavioural differences in early infancy also relate to state regulation such as abilities to maintain an alert, attentive state to objects and social interactions (Wolf et al., 2002) and irritability, inflexibility and difficult behaviours during routines (Litt et al., 2019). These state regulatory differences can be observed as early as the first 6 months after NICU discharge (Litt et al., 2019).

From toddlerhood, evidence shows that deficits in socioemotional skills and socioemotional difficulties are very prevalent in children born preterm and more common relative to term born controls. One large study of 2505 extremely preterm children around 1.5-2 years corrected age found behavioural problems in 35% of children and socioemotional competence (such as in imitation/pretend play, empathy) deficits in 26% (Peralta-Carcelen et al., 2017). Around 2-years of life, preterm infants show delayed socioemotional development (Gray et al., 2018), and more difficulties compared to term peers, including emotion dysregulation (including negative emotionality, internalising and externalising difficulties) and socioemotional competence (Arpi & Ferrari, 2013; Gray et al., 2018; Spittle, Treyvaud, et al., 2009). In studies conducted in childhood (age 3-5), the prevalence of total behavioural problems across domains measured in the CBCL and SDQ is two times greater in preterm than term groups (Arpi & Ferrari, 2013; Delobel-Ayoub et al., 2009). Differences in externalising behaviours were not found at 2-years (Spittle et al 2009), but may manifest later at school age. Meta-analyses show that studies consistently report greater total internalising and externalising behaviours (Aarnoudse-Moens et al., 2009; Allotey et al., 2018; Bhutta et al., 2002) though effect-sizes are small (Aarnoudse-Moens et al., 2009) and findings on parent-rated internalising problems were the most robust (Bhutta et al., 2002).

Notably, the effect of prematurity on socioemotional behavioural difficulties becomes stronger with age (Allotey et al., 2018; Arpi & Ferrari, 2013). Total behavioural problems were estimated to be prevalent at 20% in preterm-born children at age 3 and appears to double by age 5. Further, the presence of early behavioural difficulties appears stable in childhood, and presentations as early as age 2 longitudinally predicts later difficulties (Arpi & Ferrari, 2013; Linsell et al., 2019; Treyvaud et al., 2012) and are associated with psychiatric outcomes (Arpi & Ferrari, 2013; Treyvaud et al., 2013). Furthermore, difficulties within particular domains may be predicted by specific early functioning or earlier problems. At 5 years, emotional symptoms were predicted by 2-year internalising problems, conduct problems and hyperactivity/inattention were predicted only by externalising difficulties, peer relationships and prosocial behavioural problems by social-emotional competence (Treyvaud et al., 2012). This suggests that behavioural difficulties in preterm infants, which may meet clinical diagnoses later, are already related to patterns of early development.

1.8. Associations between motor and socioemotional development

In this section I will consider evidence from observational studies on whether motor development affects socioemotional development in preterm birth. I will consider evidence related to emotional and behavioural difficulties – anxious, attentional and social difficulties that characterise the preterm behavioural phenotype, as well as other internalising and externalising difficulties such as withdrawn behaviour, aggression, conduct problems and depressive symptomatology. In addition, I will consider socioemotional functioning at the level of social cognitive functions, such as emotional regulation, emotional competence, language, and communication skills, recognising that these functions affect social interactions and behavioural expression.

Despite the importance of motor development in infancy and childhood, few studies of preterm birth have investigated how it relates to socioemotional difficulties presenting early, before school age. Motor development assessed using the Bayley Scales is correlated with other domains of development including lower socioemotional development (Arpi & Ferrari, 2013; Gray et al., 2018; Peralta-Carcelen et al., 2013), and was identified to be the strongest predictor of socioemotional development at 2-years (Gray et al., 2018).These studies rely on cross-sectional evidence.

In childhood, children born very preterm, at 5 years corrected age presenting with or without motor impairments, showed the same rates of behavioural problems measured on the SDQ (Van Hus et al., 2014). Impaired manual dexterity was associated with greater scores on the hyperactivity/inattention scale. This study suggests that children who are at risk of behavioural difficulties may catch up on motor development and no longer show motor impairments by school age, but show different early trajectories of development. However, in preterm children born with extremely low birthweight, who are most at-risk of developmental delays, motor difficulties continue to persist in childhood, and contributed to poorer attentional and social outcomes (Danks et al., 2017).

Preterm infants showing persistent motor difficulties beyond early childhood may be more at risk for socioemotional difficulties in adulthood. In young adults, those born with very low birthweight showed greater internalising, total mental health problems and health-related quality of life (which includes individual's perceived mental, social and emotional functioning) which was related to poorer performance on motor tests. However, in this study, the association suggests that emotional difficulties led to lower motor performance later (Husby et al., 2016). Asking young adults to retrospectively report motor coordination difficulties in childhood, Poole and colleagues (2017) found that this was associated with poorer health-related quality of life only in those born with normal birthweight, but not in those born with extremely low birth weight.

Longitudinal studies may provide stronger evidence for the impact of motor difficulties in childhood. One study (n=217) followed infants born with very low birth weight or small for gestational age, and controls from birth to adulthood (Lærum et al., 2019). They found that poorer visuomotor coordination assessed at 5-years was associated with higher autistic traits in adulthood, and poor motor function assessed using standardised motor tasks at 14-years was associated with greater self-report of psychiatric symptoms and autistic traits. However, more research is needed to confirm these associations as only evidence of an association between motor function and overall psychiatric symptoms remained after adjusting for multiple comparisons and the strength of this association reduced after excluding very low birth weight infants with Cerebral Palsy. In another longitudinal study (n=174), motor coordination assessed in late childhood was associated with meeting diagnostic criteria in adulthood for Major Depressive Disorder (MDD) and Generalised Anxiety Disorder (GAD), but only in normal birth weight controls (Poole et al., 2016)

Surprisingly, in Poole and colleagues (2016) study, there was evidence approaching significance of an inverse relationship in extremely low birth weight infants, showing that poorer motor coordination led to reduced odds of MDD and GAD. The authors suggest that motor difficulties are more likely to be identified in childhood for infants born with extremely low birthweight and may be protective as it can increase access to interventions and support, as well as buffer against effects of motor difficulties on low self-worth and internalising problems. In a sample of preterm, very preterm and full-term children, Piek and colleagues' (2010) investigated motor development using the Ages and Stages Questionnaire from infancy to 4 years and compared this to later difficulties related to anxiety and depression. They found that when achievement of motor milestones varied greatly over time relative to age norms, children showed greater anxiety and depression symptomatology between 6-12 years, highlighting the role of atypical motor developmental trajectories rather than motor skill deficits. This suggests that there are multiple ways in which motor development may affect socioemotional outcomes.

I have reviewed evidence largely from observational studies showing that motor function is related to socioemotional difficulties in preterm-born infants. Most evidence are cross-sectional, and those conducted in infancy and preschool age tend to focus on correlations between motor and other developmental domains, assessed using age-standardised developmental questionnaires or standardised tasks. It is important to assess the association between motor and socioemotional development early, as children can catch up on motor development, making it difficult to establish associations. Longitudinal studies have highlighted the impact of motor development on longer-term psychiatric outcomes. Overall, there is evidence that motor and early socioemotional development are related in preterm birth, and motor development can impact later socioemotional outcomes, and the next step is to understand better how motor development can influence socioemotional development.

1.9. Section summary

In this section, I reviewed literature showing the impact of preterm birth on socioemotional development. Motor skill delays and difficulties are very common in preterm birth and have been found to be associated with behavioural difficulties and neurodevelopmental disorders. Motor skills have also been linked to differences in socioemotional processing. However, *how* early motor skills can affect socioemotional development remains an important question. In the next chapter, I outline why studying movement at the level of behaviours may provide novel insights to bridge the divide between motor and socioemotional skills.

2. Self-regulation and movement

Section 1. The role of self-regulation in socioemotional development

In Chapter 1, I introduced the importance of studying how motor difficulties influence socioemotional development, especially in preterm-born infants who experience poorer outcomes in both domains. I also reviewed literature focusing on how mental functions can be considered embodied – grounded in bodily functions and its development dependent on bodily interactions with the world.

Looking at the high rates of behavioural difficulties, and psychiatric diagnoses draw our attention to the problem, but understanding the mechanisms behind it will increase knowledge on possible solutions such as to identify early signs of disrupted socioemotional functioning, factors that promote successful socioemotional functioning and to develop interventions to do so. Researchers have also increasingly argued for a Research Domain Criteria (RDoC) framework to provide an integratory understanding of psychiatric disorders, given the heterogeneous presentations within individual diagnoses, as well as difficulties that cut across different diagnoses (Insel et al., 2010). Similarly, to understand the co-occurring difficulties seen in preterm birth, Johnson et al (S. Johnson & Wolke, 2013) highlighted that it is important to focus on the constellation of individual behaviours and traits, in contrast to focusing on diagnostic criteria. They highlight the early presentation of motor skills, attentional and temperamental difficulties in preterm birth, and consider how these interact to result in socioemotional difficulties. These reasons make it important to consider what underlies socioemotional functioning.

In the first section of this chapter, I introduce an early developing mental function, self-regulation, defined as the regulation of internal states including emotions, behaviours and cognitions (Nigg, 2017). It involves, and affects, movement (Campos et al., 1989; Kopp, 1982), and is required to respond appropriately to everyday social and emotional situations. The self-regulation of emotions, in particular is thought to be disrupted in socioemotional difficulties, and as such is important to understand how it develops. Eisenberg and colleagues (2010) provided strong conceptual arguments and empirical evidence for the association between self-regulation of emotions and internalising and externalising problems.

Socioemotional behavioural difficulties are thought to be inherently linked to patterns of regulatory responses to stressors or social situations that lead to arousal, overexcitation or emotions of various intensities, and are labelled as difficulties because they are generally considered unhelpful or inappropriate in the social context (Nancy Eisenberg et al., 2010; Montagna & Nosarti, 2016). These arguments are supported by meta-analytic evidence of a longitudinal relationship between self-regulation in various domains (Robson et al., 2020) in childhood with poor behavioural and social outcomes at school and adulthood, including depression and anxiety, and cross-sectional evidence of the association between self-regulation of emotions and internalising mental health difficulties (Compas et al., 2017).

2.1. Definitions of self-regulation

Self-regulation involves self-initiated internal processes to modulate internal states in an adaptive manner – in other words, processes resulting from activity in the central and peripheral nervous system are used to modulate neurophysiological and awareness states, such as behaviours, emotions and cognitions (Nigg, 2017). Self-regulation encompasses both top-down and bottom-up processes. Bottom-up processes are automatically initiated in response to external stimuli or fluctuations in internal states. In contrast, top-down processes are deliberate, voluntarily driven processes which tend to occur on a slower time scale. Top-down processes usually act on bottom-up processes to modify internal states. However, bottom-up processes are not simply the targets of self-regulation as it can activate, alter, or initiate feedback loops that modulate top-down processes. Self-regulation can therefore be seen as an interaction between deliberate and automatic processes that are in continuous fluctuation with internal states.

2.2. Concepts related to self-regulation

Executive functioning

Self-regulation has been defined in several other ways. In the study of infant development, self-regulation is often assessed by virtue of behaviours demonstrated in clearly defined contexts, such as compliance with caregiver's requests (Kochanska et al., 2001), the ability to demonstrate socially-appropriate behaviour even without explicit instructions, and delaying gratification in the face of competing internal and external drives (Kopp, 1982). Nigg (2017) argued that definitions tied to specific behaviours capture only a subset of self-regulation, as self-regulation is a domain-general term referring to the regulation of any internal state. Other definitions focus on the mechanisms involved in self-regulation, such as the recruitment of executive functions to act on dominant responses (Cole et al., 2019), and some researchers have taken this a step further to equate the mechanisms involved in state regulation (Nancy Eisenberg & Sulik, 2012; Nigg, 2017). Such mechanistic definitions, appropriately, highlight the interplay of top-down and bottom-up processes involved in state regulation. However, mechanistic definitions only partially characterise self-regulation, as self-regulation does not simply refer to the mechanisms involved, but their involvement in purposeful and adaptive modifications of internal states (Nigg, 2017).

Mechanistic definitions may not be adequate for capturing early self-regulatory abilities if these mechanisms have yet to develop. For example, executive processes develop from around 9-months, but this does not mean that infants are incapable of self-regulation before that age. Nevertheless, a crucial phase in the development of self-regulation is the increased engagement of top-down executive processes on prepotent behavioural, emotional or cognitive responses, and the dynamic process of self-regulation involving the relationship between multiple systems and processes has been emphasised (Cole et al., 2004, 2019; Rueda et al., 2004).

Temperament, reactivity and effortful control

Self-regulation within a temperamental model captures the multiple components involved - mainly cognitive, behavioural, emotional. In this model, temperament is the biologically-based individual differences in reactivity and self-regulation (Mary K. Rothbart & Derryberry, 1981). Reactivity refers to the threshold and temporal characteristics of a triggered response (could be in any domain such as emotion or motor activity), including the intensity and recovery time. Self-regulation refers to the processes that modulate the triggered changes in internal states, in accordance with the other definitions of self-regulation. Factor analysis of temperament confirmed this conceptualisation of temperament, where two factors were identified related to reactivity related to reactions to pleasant or distressing stimuli, as well as a third factor comprising measures of attentional deployment, inhibitory control, perceptual sensitivity and a low threshold for pleasure.

This third factor capturing self-regulatory processes has also been termed effortful control - involving attentional deployment (voluntary focusing or shifting attention), inhibitory control (effortfully inhibit behaviour triggered by a stimulus) as well as activation of behaviour (such as with objects) to produce an adaptive response in the face of a competing, more automatic, but less adaptive response (Rothbart & Bates, 2006; Rothbart et al., 2003). Due to the history of its conceptualisation, effortful control is more commonly used to describe processes involved in attentional and behavioural regulation of an emotional response, however effortful control can also be used to describe regulation of action and cognition in non-emotional contexts (Nigg, 2017; Michael I. Posner & Rothbart, 2000). For example, in the A-not-B task. In this task, children have to inhibit prepotent response towards a previous location where they have been repeatedly trained to reach for a hidden object, deploy attention and reach towards the new location in order to acquire the hidden object successfully (Rothbart & Rueda, 2006). Effortful control is closely related to executive functions which was first described in neuropsychology, in that both describe top-down executive processes. However, derived from the developmental literature, and focusing on early development of executive processes in regulation, effortful control captures only the lower-level behavioural and attentional aspects of executive functions (such as task maintenance and shifting, suppressing interfering stimuli), and not higher-level cognitive control aspects such as working memory, reasoning, problem solving and planning (Nigg, 2017).

Emotional self-regulation

The regulation of emotions refers to the control of emotional experience and expression, and can involve both internally, self-initiated processes and externally-mediated processes (Campos et al., 1989). Emotionality or emotional reactions, has been defined neuro-scientifically as coupled neurophysiological and behavioural responses linked to evocative stimuli (Damasio, 1999), and this can be accompanied by a phenomenal, subjective component. Based on the definitions of self-regulation outlined above, I refer to emotional self-regulation, or emotion-related self-regulation (Eisenberg & Spinrad, 2004) as self-regulation applied to emotional physiology and behaviour. As discussed above, emotional self-regulation is a domain-specific process, relying on domain-general self-regulatory processes to respond to emotional situations.

2.3. Development of self-regulation

The capacity to self-regulate develops progressively. Kopp's (1982) framework has been influential in outlining infants' self-regulatory capacities. From birth to around 2 to 3-months, infants show the capacity to modulate their arousal and behaviour in response to internal homeostatic cues as well as to their environment (including to external stimulation that may be too intense). For example, infants self-soothe through non-nutritive sucking and hand-to-mouth behaviours. Based in neurophysiological and motor reflexive processes, these early forms of self-regulation are activated automatically, driven bottom-up by external stimuli. However, Infants' fussing may also trigger other modes of regulation (not by initiated by self), such as for caregivers to assist in soothing. Early indicators of self-regulation lie in affective responses including both positive (e.g. laughing and smiling) and negative (crying), attention and orientation to environmental stimulus, as well as sleeping patterns, and eating. Atypical patterns in these responses, such as excessive crying, diminished ability to orient to stimuli, and sleep problems are signs of difficulties with self-regulation (Samdan et al., 2020). Parental interactions in this stage is crucial to infants' successful regulation (Samdan et al., 2020) and maternal mood (Mohr et al., 2019), parenting strategies such as soothing infants through body contact (Mohr et al., 2019; Planalp et al., 2021) and parenting stress (Planalp et al., 2021) are linked to early regulatory difficulties.

Between 3 to 9-months, infants' sensorimotor behaviour become sensitive to internal motivational states and they make voluntary motor acts to seek perceptual stimulation or seek social responses. The voluntary nature of their behaviour can also be perceived from their responses to events as they show the ability to select behaviours appropriate to the situation, and suppress automatic ones. Within the first year of life, infants regulate movement, attention, communication and emotional expression in accordance to changes in social situations or contextual task demands. Examples are infants' ability to smile to seek a similar social response from caregivers, and reach for people and toys. However, infants may not demonstrate awareness of the meaning of the situation, and these behaviours are almost always in response to immediately preceding events. These early sensorimotor abilities become more complex with the emergence of cognitive skills.

An important milestone in the development of self-regulation is when top-down control of cognition and behaviour emerges to enable more autonomous and flexible forms of self-regulation. The earliest observation of such top-down control is from around 6-months, in the executive control of attention. Infants show the ability to use orienting strategies to regulate distress, such as averting their gaze away from the distressing stimulus. From 1-year of age, they are capable of engaging with objects purposefully to provide attentional self-distraction in distressing situations (Nancy Eisenberg et al., 2007). Executive attention also features in non-emotional contexts, such as anticipatory looking eye movements to repeated stimulus presentations in the same location, and in error detection - sustaining attention to locations when perceptual expectations are disrupted (Michael I. Posner et al., 2007). As outlined in the definitions, executive attentional control has also been termed effortful control. This milestone coincides with the maturation of attentional networks in more anterior regions of the brain. Effortful control emerges in the second half of the first year, improves substantially across the first 2 years of life and becomes relatively stable afterwards (Nancy Eisenberg et al., 2007; Kochanska et al., 2000, 2001).

Cognitive strategies appear to develop later, from 9-12 months. When faced with competing goals, infants show the ability to deploy cognitive control processes to modulate behaviour, such as inhibition and behavioural activation. They are able to do so flexibly and show awareness of different situational demands and social expectations; and are capable of modulating their own behaviour in line with this, without explicit instruction (Kopp, 1982). For example, on approach to a desired object, infants are able to recognise the adverse consequences from a previous interaction with the object, and are able to inhibit reach towards the object via self-instruction. They are also able to delay an act upon caregivers' request, demonstrating cognitive processes of memory and inhibitory control and not simply a response to the immediate interaction. Overall early involvement of cognitive process in self-regulation show infants' awareness of goals, as their actions are adapted to achieve them (Kopp, 1982). Later, from 18-months, infants increasing demonstrate self-initiated control over behaviours, rather than restricted to the modulation of responses triggered by external environment. Infants' demonstrate representational capacities and recall memory, such as in engaging in pretend play and understanding of object permanence. They show self-monitoring capacities and are able to initiate behaviour that shows awareness of the social situations – such as eating and dressing routines.

This framework captures the initial reliance on automatic and external sources of regulation. It also captures the shift from external to internal sources of regulation as infants achieve the pre-requisite foundations to do so with increasing complexity -foundations in motor development, emerging attentional control, as well as language, memory and other cognitive processes (Cole et al., 2019; Nancy Eisenberg et al., 2007; Kochanska et al., 2001; Kopp & Neufeld, 2003). Attentional abilities, tied to motor responses, are one of the earliest demonstrations of control over internal states, before cognitive processes such as inhibition, memory and language develop.

2.4. Measuring self-regulation in infancy and childhood

Self-regulation at birth and early infancy are usually measured by neurobehavioural observation. The Neonatal Behavioural Assessment Scale (NBAS) (Brazelton, 1978) is administered around birth and measures 4 dimensions of functioning (autonomic stability, motor organisation, state organisation and attention/interactive capacities) as well as supplementary items to assess behavioural quality. Based on factor analysis, researchers have also scored all items in 7 clusters (habituation, orientation, motor processes, range of state, regulation of state, autonomic stability, signs of physiological stress and reflex items) (Wolf et al., 2007). The Infant Behavioural Assessment is observer rated tool of infant's behavioural expression across 4 subsystems, autonomic, motor, alertness, and attention/interaction. Behaviours are measured in terms of approach, coping and self-regulatory behaviours, and stress responses. The Bayley Scales (Bayley, 1993) measures delays in mental and psychomotor scale in infants age 1-42 months, and also includes a behavioural rating scale across 4 factors, attention/arousal, motor quality, orientation/engagement and emotional regulation. Behavioural ratings for each factor and across factors are rated as non-optimal if scores fall below 10th percentile, and questionable if falling between 11-25th percentile.

Self-regulatory difficulties may manifest as internalising and externalising behaviours in toddlers and school-age children. The Child Behaviour Checklist (Achenbach & Rescorla,

2001) and Strengths and Difficulties Questionnaire (Goodman, 2001) measures these problems , but does not directly quantify regulatory abilities. Both can be reported by parent, teacher or by self-report. The Child Behaviour Checklist is suitable for children and adolescents aged 6-18 years and is valid across cultures (Rescorla et al., 2007). It measures emotional, behavioural and social problem behaviours in the internalising and externalising domains, as well as adaptive functioning such as social and school competence. The strengths and difficulties questionnaire suitable for children age 3-16 and similarly measures prosocial behaviour and internalising and externalising difficulties, with a five-factor structure (emotional, conduct, hyperactivity, inattention, peer and prosocial) (Goodman, 2001). Both questionnaires show good reliability, validity and internal consistency (Achenbach & Edelbrock, 1991; Goodman, 2001).

Direct experimental observation of behaviours during stress-inducing situations are the predominant way to quantify self-regulation. Using this method, predefined behaviours thought to be related to self-regulation are coded by the researcher. Researchers also use measures of affective states to indicate regulation. However, Eisenberg highlights that it is difficult to distinguish emotional reactivity from its regulation, and therefore high amounts of emotion expressed may be due to unsuccessful regulation, high reactivity or both.

Self-regulation has been measured by performance on neuropsychological tasks designed to elicit effortful control, in other words a combination of attentional deployment, inhibitory control and behavioural activation in relation to a goal. Kochanska et al (2000) defined a battery of tasks involving regulation of distinct domains (motoric, vocal, attention) and found that performance across tasks of different domains was consistent. Self-regulation is dimensionally related to both effortful control and executive function (Dilworth-Bart et al., 2018) and measures of both effortful control and executive function in regulatory tasks may also provide a better indicator of self-regulatory abilities.

Physiological indicators such as heart rate, motor activity indicate levels of arousal and its temporal profile relative to the presentation of a stressor may provide an indicator of successful regulation. Heart rate increases when infants are subjected to stress, and decreases when the stressful stimulus is removed (Conradt & Ablow, 2010; Ginger A. Moore & Calkins, 2004). Another physiological indicator appears directly related to regulation. Respiratory Sinus Arrhythmia (RSA) can be measured using a chest ECG and provides a measure of the cardiac vagal tone, i.e., the rhythmic increase and decrease in heart rate related to frequencies produced during respiration (L. P. Dale et al., 2011). The amount of cycle-to-cycle variation in RSA can indicate the extent of regulation during stress. Increase of RSA or RSA augmentation reflects maintenance of internal equilibrium while RSA suppression indicates parasympathetic withdrawal to support greater metabolic demands and hence a readiness to support behaviour during stress (Brooker & Buss, 2010). RSA suppression was observed during stress (Ginger A. Moore & Calkins, 2004).

Self-regulation has also been measured within the framework of temperament. The Infant Behaviour Questionnaire (Revised) (Gartstein & Rothbart, 2003) assesses negative reactivity, positive reactivity and regulation through parent-report of the reactivity of infants' attentional, motor and emotional responses such as to positive and negative stimuli, including how these are modulated (e.g. how they change with time). Psychometric properties have been demonstrated as young as 2 weeks of age, though is recommended for use between 3 and 12-months of age. Questionnaires suitable for toddlers and older children tapping on similar domains of temperament are available - the Early Childhood Behaviour Questionnaire for age 1-3 years (Putnam et al., 2006) and the Children's Behaviour Questionnaire (Mary K. Rothbart et al., 2001). These questionnaires for older children includes age-appropriate scales, such as tapping on more complex attentional, behavioural and cognitive control abilities involved in later regulation (Putnam et al., 2006). Temperament has also been assessed through infants attentional and distress behaviours during distressing tasks or tasks requiring attentional switching or sustaining (Goldsmith & Rothbart, 1991; Poehlmann et al., 2011). The attentional component of temperament assessed through questionnaires has been found to be related to effortful control measured in neuropsychological tasks, highlighting the close link between regulatory behaviours observed by parents and regulation elicited through experimental tasks (Archibald & Kerns, 1999; Henry & Bettenay, 2010).

2.5. Implications of self-regulatory difficulties

Successful self-regulation is associated with fewer externalising and internalising behavioural difficulties. Eisenberg and colleagues' (2010) review identified extensive evidence of concurrent and prospective associations. Improvements in self-regulatory skills also appear to be linked to lower problems (Nancy Eisenberg et al., 2010). Recent evidence also supports this. Poorer emotional and attentional regulation alongside escalating sleep problems, from infancy to five years was related to emotional and behavioural problems in the classroom, as well as lower prosocial skills at 5-years (K. E. Williams et al., 2016). Greater improvements of self-regulation in childhood led to fewer problem behaviours at home and school (Sawyer et al., 2015). There is evidence that early state regulatory difficulties affect the later development of inhibitory behavioural control, and this leads to greater attentional problems (Baumann et al., 2019). Early self-regulation can have long-term effects - better inhibitory control and regulation of emotions in toddlerhood and childhood predicts decreasing trajectories of externalising behaviours in adolescence (Perry et al., 2018) and more regulatory problems in infancy was related to chronic dysregulated behaviour in childhood (Winsper & Wolke, 2014).

2.6. Self-regulation and social-emotional competence

Self-regulation may be an important transdiagnostic factor in particular in its involvement in developing social skills and successful peer relationships. Bachevalier & Loveland (2006) highlighted that self-regulation of socially-oriented behaviour may depend on the same mechanisms and may be implicated in autism. This is because self-regulation is needed to modify one's own behaviour in relation to the perceived intentions, emotions, and other mental states of others as well as awareness of the social context. Therefore, social behaviours do not just depend on social cognitive processes, but how these are integrated in the initiation and inhibition of appropriate behaviours during social interactions.

There is evidence that self-regulation, social skills and behavioural adjustments are interrelated. Positive screen for autism in premature infants correlated with both internalising difficulties and social-communication deficits (Limperopoulos et al., 2008). Better emotion regulation is also linked to lower internalising behavioural concerns (DeLucia et al., 2021) and anxiety (Sáez-Suanes et al., 2020) in autism. High-functioning autistic children with better emotion regulation showed better prosocial skills, and better executive function led to better school engagement and behavioural adjustment at school (Jahromi et al., 2013). Preschool self-regulation – conceptualised as attention and emotion regulation together with language abilities which contributes to complexity of self-regulatory abilities – was associated with social emotional competence, including in successful peer-relationships, prosocial behaviour, better social skills and adjustment to classroom settings; further, parenting influence social emotional competence via improving self-regulation (Russell et al., 2016). The relationship can also be bidirectional, with early communicative abilities (expressive, receptive language, as well as communicative gestures) linked to later development of socioemotional competence (including in the occurrence of internalising, externalising and regulatory difficulties) (Rautakoski et al., 2021).

In the general population, early regulatory difficulties and executive function difficulties were precursors to or associated with increased risk of ADHD, elevated ADHD symptoms or an ADHD diagnosis in childhood. Furthermore, intervening on these and other precursors led to improved ADHD symptoms (Shephard et al., 2022). Emotion regulation deficits are common in autism which may indicate it is core to the development of autism, or alternatively represent psychiatric comorbidity, i.e., co-occurrence of, but independent development of social and emotional difficulties (Mazefsky et al., 2013).

2.7. Self-regulation in a wider context

More recently, research has drawn attention to other factors that interact with self-regulatory abilities to influence behavioural difficulties. This includes both intrinsic, infant characteristics such as temperament and extrinsic, environmental and caregiving factors (Frick et al., 2018). Self-regulation was found to mediate the effect of family functioning in low-income households on externalising behaviours at 5-years; further behavioural interventions improved externalising behaviours via improving inhibitory control, an aspect of self-regulation (Hardaway et al., 2012). High sustained attention, reflecting executive attentional capacities, led to better emotion regulation, and acted as protective factors on the effect of insensitive parenting. The reverse was also true, where greater maternal sensitivity led to better regulation of emotions in infants with low levels of sustained attention (Frick et al., 2018). This has led to the push for models that capture the multiple processes involved in self-regulation (S. D. Calkins & Howse, 2004) and has highlighted the importance of considering that self-regulation does not develop in an isolated manner, but in the context of the individuals' interactions with the environment.

2.8. Self-regulation in preterm infants

I have evaluated socioemotional developmental functioning in the previous section, including differences in behavioural difficulties that reflect difficulties with self-regulation, typically assessed using observer ratings on questionnaires. In this section, I will additionally consider other evidence such as from direct experimental observation or neuropsychological assessments of self-regulation.

Early self-regulatory abilities have been examined as early as infancy, and the still-face paradigm and similar variations of the paradigm are commonly used. In toddlerhood, Woodward and colleagues (2016) found that very preterm infants showed poorer emotional and behavioural regulation during direct observation of interactions with parents, involving problem-solving play with toys. This included lower positive affect, less persistence in problem-solving and greater difficulty in shifting from one activity to the other. No difference in negative affect was found. Effortful control (EC) has been assessed using a battery of tasks in toddlers born preterm either with low birthweight or higher birthweight. Although no differences in EC was found when infants were categorised according to birthweight with a cutoff of 1500g or low, EC varied as a function of birthweight and was related to neonatal risks and medical complications including ventilation during NICU stay, gestational age, as well as sociodemographic risk factors (Poehlmann et al., 2010). Preterm children performed poorer across a range of executive function tasks including inhibitory control, which is a component of effortful control (Aarnoudse-Moens et al., 2009). Gestational age was related to a perceptual sorting task but not to other executive functions. At 4 years, very preterm children were rated by parents (ITSEA), as well as through observer ratings during developmental tests as having greater self-regulatory difficulties at home and greater emotional dysregulation, such as mood swings, fussiness and regulating excitement (Jones et al., 2013).

Self-regulation and later difficulties

Self-regulation measured using effortful control and executive functioning task batteries at 3 years predicted school competence and externalising behaviours at 6 years, but not internalising disorders (Dilworth-Bart et al., 2018). Similarly, self-regulation mediated the

effect of sociodemographic risk on these outcomes. While the study did not report a mediation effect of self-regulation on neonatal risk, this remains to be explored as the study included infants with high neonatal risks (a factor combining birthweight, gestational age and medical risks) and may not represent the whole range of neonatal risks (Dilworth-Bart et al., 2018). Effortful control at 2 years predicted cognitive ability later, but not behaviour problems measured on the Child Behaviour Checklist a year later, but effortful control was concurrently associated with attention problems, as well as ADHD symptoms (Poehlmann et al., 2010). The attentional component of temperament, sustained attention, as rated by observers was negatively associated with behavioural problems, but only in the presence of hostile parenting. In the presence of high maternal affect, sustained attention was related to better social skills such as turn taking and positive play (Poehlmann et al., 2011).
Children showing gross and fine motor scores in childhood presented with difficulties with self-regulation as neonates (Meether et al., 2021).

Self-regulation and neurodevelopmental disorders

In preterm infants, poorer self-regulation in preschool was also associated with any mental health disorder at age 9, as well as specifically increased risk of ADHD, conduct disorder and anxiety disorders even after adjusting for preschool behavioural problems and other demographic and environmental confounders (Woodward et al., 2016). Behavioural self-regulation was poorer in preterm infants at age 6 and correlated with teacher rated social functioning as well as inattentive dimensions related to DSM diagnoses (Scott et al., 2012). For preterm infants showing social difficulties indicative of not meeting criteria for ASD, difficulties correlated with executive function deficits, and overlapped with attentional and emotional problems (Korzeniewski et al., 2017).

2.9. Section summary

In this section I introduced self-regulation due to its key role in socioemotional functioning, and because it is a process implicated in the socioemotional difficulties seen in several psychiatric disorders. I describe its progressive development and highlight how disruptions to developing self-regulatory abilities are linked to behavioural problems later and can affect the development of social skills. I reviewed literature on differences in preterm infants' self-regulatory abilities, focusing at a micro-level the processes involved in self-regulation rather than the behavioural patterns linked to self-regulation difficulties at the macro-level. Further, I highlighted a recent push towards considering self-regulation as the interaction of multiple processes, and as a process that develops under the influence of environmental factors and different individual characteristics. In the next section, I identify perspectives that highlight the importance of movement need to be considered beyond motor skills and introduce the aims of my thesis.

Section 2. Movement as a multilevel and multiscale construct

"What is order? Order was usually considered as a wonderful building, a loss of uncertainty. Typically, it means that if a system is so constructed that if you know the location or the property of one element, you can make conclusions about the other elements. So order is essentially the arrival of redundancy in a system, a reduction of possibilities."
- von Foerster (2003, pp. vii-viii)

In the first chapter I highlighted that motor development is usually studied separately from socioemotional abilities, but introduce how movement, not just motor skills, are intrinsically linked to higher-order functions. In this chapter I highlight what dynamic systems theory can add to the embodiment perspective to further our understanding of the higher-order implications of motor differences. Then, I introduce the focus of my thesis.

2.10. Movement is the product of a complex, dynamic system

The embodiment perspective crucially reminds cognitive scientists of the relationship between the mind and the body. The mind depends on the physical workings of the brain (Bassett & Gazzaniga, 2011), and movement is the physical output of the body which the mind and brain influences (A. Clark, 1999; M. Wilson, 2002).

Mental functions are assessed through behavioural tasks that elicit those functions, and mental experience are assessed through subjective report. Advances has been made in linking mental functions to the activity of the brain. Through imaging the human brain, scientists have been able to link metabolic activity in different regions of the brain to particular functions (e.g. occipital regions to processing perceptual stimuli; frontal region to executive functions and decision making). The 86 billion neurons and approximately the same number of non-neuronal cells that make up the brain (Azevedo et al., 2009) are connected in organised subsystems (Bassett & Gazzaniga, 2011) to participate in different brain functions through exchanging electrical and chemical signals. Connectivity between brain regions and localised activations have been identified as key to brain functioning (P. T. Fox & Friston, 2012). Individual processes occurring in the brain are extremely difficult to characterise, and the brain is studied at the level of neural systems. Importantly, the brain is perpetually active even when considered “at-rest”, it does not simply shut down when the mental functions are not active. This highlights the complexity of the brain (Székely, 2001).

Motor output tends to be considered separate from mental functions and brain activity, yet it is the “final common output” of all brain processing (Sherrington, 1906). The body has received less interest amongst cognitive scientists who focus on mind-brain interactions, yet it contributes to mental functions and brain activity does not occur in a vacuum, detached from the body. The body is also a high-dimensional system, containing more than 650 muscles, 206 bones connected by joints, and includes muscles, bones and joints with different physiological properties. Computationally, it would be too challenging to map out how the body is coordinated to achieve a particular function. Yet this problem is solved when a new motor skill is learnt (Bernstein, 1967), and parts of the body work in synchrony in time and space to achieve the function. This is thought to be achieved by initially coordinating groups of muscles and joints as a rigid whole, because this reduces the number of possible configurations that could achieve the function resulting in a simpler computational problem for learning to proceed via trial-and-error. Therefore, reducing the available “degrees-of-freedom” in the body is both a learning strategy, as well as an outcome of learning - as von Foerster (2003) accurately describes, “*order is the arrival of redundancy in a system, a reduction of possibilities*” (p. viii). This highlights the complexity of the body, and the importance of considering the brain and body as one system.

The brain and the body together can be considered a complex dynamic system (A. Clark, 1998; Van Gelder, 1998). Complex systems refer to such high-dimensional systems with a great number of elements and functional interactions (M. Mitchell, 2009). While there has not been a single definition of complexity, there are properties that are common to such high-dimensional systems that are ubiquitous in nature (M. Mitchell, 2009). First, relative to the larger system, simpler components can be identified within the system. Second, these components interact in non-linear ways. This means that the activity of individual components cannot be summed up simply, and the output of the system is not proportionally equivalent to the input. This is due to the intrinsic interactions in the system, activity of individual component does not usually occur in isolation, but leads to another which can generate feedback or feedforward that alters the initial activity, and this effect ripples throughout the system. Third, the system shows emergent behaviour, that is the “collective outcome” of the system cannot be described by what individual components are doing, but shows new forms more complex than the components involved. For example, the activity of a single neuron does not tell us about the mental function it is involved in; and the movement of a single finger during a reach-to-grasp movement does not tell us about the function it achieves. Fourth, related to the third point, the system shows a hierarchical organisation. This results from emergent behaviour at all levels. At lower micro levels, the coordinated activity of smaller components within individual levels make up "coordinative structures" at a higher, macro-level which can interact with other components at that level. For example, neuronal activity makes up neural systems which then work together to achieve a function; and muscular activations make up gaze and arm movements which then work in concert to track a movement towards a moving object. Fifth, also related to the third point, the activity within complex systems do not result from a central controller, but *self-organises*. This means that there is no instruction on what form the system will eventually take but the interactions between parts in single levels eventually leads to organisation at a higher level.

The fifth point regarding complex systems is central in the study of infant development, understanding "*how something more can be created from something less"* (L. B. Smith & Thelen, 2003, p. 343). This has led to the dynamic systems theory of development (E. Thelen & Smith, 1998), a theory that recognises the dynamic interactions within developing systems, and between the internal and external environment, play a central role in how increasingly complex skills are achieved. This perspective grounds infants' brain development in the brain-body-environment interaction. Seeing the brain and body as a complex system that interacts with the environment, there is still a role of developed neural systems in mental and physical functions. However, mental skills enabled by neural systems still need to be understood in the context of bodily and environmental constraints. Additionally, in this view, developing neural systems do not simply mature to enable new capacities, they are themselves shaped by both biological constraints and ongoing experience.

2.11. Dynamic systems theory of development

Esther Thelen first conceptualised motor development as the result of complex interactions within the body (Thelen, 1995). She viewed motor skills as new motor forms resulting from the coordination of parts of the body. These patterns of coordinated activity emerge from the body's continuous interactions with the environment, as well as under physical, neurobiological, and contextual constraints. In particular, Thelen (2005) provided a convincing account of how infants' early interactions with the environment can lead to reaching abilities. She highlighted how the confluence of early constraints, early motivations in mouthing objects and biases in looking, and bias to grasp, provide the substrate for interactions with the environment to lead to reaching behaviour. Specifically, the drive to seek oral stimulation that is present from birth, and the perceptual bias to look at new and interesting objects along with the ability to grasp when the hand receives tactile stimulation, lead to a feedback loop which enable learning the pleasurable outcome of their arm movements when their movements lead to encounters with objects.

In particular, Thelen's early work challenged the notion of motor skills as the maturation of pre-programmed neural circuits. One of her seminal works was in explaining the puzzling disappearance of the newborn stepping reflex (Thelen & Fisher, 1982). The prevailing explanation at that time was that the stepping reflex disappears when cortex develops and the central nervous system exerts inhibitory influences on lower spinal circuits which generate these reflexes (Adolph, 2002). Thelen and colleagues proposed that the stepping reflex need to be understood not just from the neural circuits involved, but also the influence of the environment and biomechanical constraints as infants grow physically. Thelen and colleagues suggested that the reason infants do not show stepping movements was simply because their legs were too heavy. They provided evidence through astute observation and empirical manipulations, they showed that during the period when stepping movements supposedly disappear, manipulating the influence of gravity as well as augmenting infants' leg strength (Thelen et al., 1991) enabled infants to produce these movements. Crucially, they demonstrated in infants who were stepping stopped doing so when weights were added to their legs (Thelen et al., 1984).

L. B. Smith (2005) proposed that dynamic systems theory is compatible with the "embodiment hypothesis" and applied this to understand cognition. Combining both perspectives, interactions with the environment alongside neural development leads to relationships between brain, body and environment. Cognition is the emergence of these relationships, and is embedded in and inseparable from the real-time interactions involving sensorimotor functions and higher order capacities such as perception, attention, memory and action. She tested this hypothesis empirically in understanding infants' emergence of object permanence. Object permanence was initially conceptualised as a fixed representation of the idea that objects exist even when they cannot be sensed, a concept gained when infants have experienced the world sufficiently in Piaget's "sensorimotor phase" of intelligence (Piaget, 1952). Object permanence can be tested using the A-not-B task (Piaget, 1952). In this task, infants are first shown a toy hidden in location A and then given the chance to search for the toy, and normally do so in A. After repeated "A" trials, infants are shown a toy in location B instead and the experimenter observes where they search. Infants who have gained object permanence normally search correctly in location B, while infants who have not appear to persevere in reaching, this time incorrectly, in location A. Smith and colleagues (L. B. Smith et al., 1999) considered and manipulated the processes occurring in real-time to achieve a successful search in the B trial and were able to recreate an error in infants 8 to 10 months who usually do not make the error, or elicit a successful reach at B. For example, they identified literature showing that infants were more successful if location B was visually distinct from A, when the delay was shortened, or if infants paid more attention to B. Experimentally observing the trials where infants shifted their gaze to A after observing hiding at B, they also found that these trials led to more errors – perturbing gaze to A or B during the test trials could also bias infant performance towards error or success. Crucially, the error was dependent on previously formed memories of the reach to A, that is in part body-based. By manipulating the posture during B trials, these memories become weaker in biasing reaches to A. As such infants who were trained while sitting, and tested while standing made less errors (L. B. Smith et al., 1999). Instead of purporting cognitive representations, they parsimoniously focused on the processes behind a successful goal-directed reach – the involvement of perception, attention and memory in reaching movements.

In summary, first applied to understand more complex motor behaviours, dynamic systems theory can also be applied to understand mental processes. This theory provides an alternative, parsimonious perspective of higher-level mental capacities, not as modular or symbolic representations that mature with experience and become permanently acquired functions, but made up of the temporal organisation of lower-level processes in play during interactions with the world. Therefore, dynamic systems theory can be seen as a framework to study how motor experiences influences mental functions: the brain is part of a dynamic system with the world where movement enables interactions between the biological body and the physical environment; through acting on the world, this leads to experiences contributing to learning and brain development, leading to more complex motor and mental skills.

2.12. Movement is a multilevel entity unfolding over time

In the previous section I showed that movement can be seen as the output of a complex, dynamic system, and how this perspective can help to understand how more complex abilities emerge during development. Within this theoretical framework, movement is the product of multiple components working at different levels and timescales, and contains organisation at more than one level and timescale. Here, I elaborate further on the temporal and multilevel organisation of movement.

Movement unfolds over time. Human movement unfolds in an organised way, with a characteristic kinematic form. For example, skilled point-to-point movements show a single acceleration and deceleration phase, producing an inverted U-shape velocity profile, presumably as this is an efficient way to move to a target accurately (Harris & Wolpert, 1998). Neurochemical processes generate kinematic accelerations and decelerations of a limb, but the movement of a limb is incompletely described by each acceleration or deceleration from millisecond to millisecond. The coordination of neurochemical processes in time produces particular patterns. Infant movement consists of the same underlying processes generating movement accelerations and decelerations, but are different from movements of a skilled adult, due to the way accelerations and decelerations are coordinated over time. Compared to smooth movements of a skilled adult, infant movements are less efficient, take a longer time and a longer path to reach its intended goal, and visually, appears "jerkier" due to directional changes resulting from these accelerations and decelerations (von Hofsten, 1991). Analysing each acceleration and deceleration on their own at the fast timescales they occur do not provide the entire picture of infant (or adult) movement. Movement is the result of coordinating neurochemical processes in specific ways over time and its temporal structure reveals important characteristics.

Movement is prospective (von Hofsten, 1993), meaning that it requires information on what might happen next, based on knowledge from the past and in the present moment. Ultimately, this information is conveyed to alpha motor neurons in the spinal cord and brainstem, the *final common output* of all brain processing (Sherrington, 1906). Each alpha motor neuron innervates skeletal muscle fibres and to form a motor unit, and movement is coordinated at this level to produce the desired forces by activating muscle fibres with different properties to varying extents (Cuevas et al., 2014). Movement needs to be monitored so that it can react to environmental changes. This may be automatic, such as in making slight postural changes using visual and proprioceptive information about the body, as well as voluntary, when perceived changes in the environment lead to selection of alternative set of movements (Marsden et al., 1972). In addition, when planning processes come into play, movement at the present time becomes tied to movement at a later time (Delafield-Butt & Gangopadhyay, 2013; von Hofsten, 1993). This shows that the output at the alpha motor neuron level contains the influences of sensorimotor integration and higher-level cognitive processes.

Behaviour entails motor action (Adolph & Hoch, 2019). The overall behaviour of the system is not simply the sum of the parts, but contains function that individual parts do not have. Movement can be characterised at different levels: the muscle level describing the specific patterns of activity over many muscles over space and time; the kinematic level describing the movement relative to space and time only; and the goal level which describes the outcome of the action such as the type of goal it achieves (Hamilton & Grafton, 2012). It has been argued that in motor development, the fundamental phenomena to be explained is not movement at the micro, muscular or kinematic, level, but how functional or adaptive behaviour at the macro level, resulting from moving components in specific ways and in specific contexts, is acquired. Analysis at the goal level focuses on the function of the movement, what goals and desires are achieved through the movement and how the movement enables this (Adolph & Hoch, 2019). However, I argue that the multilevel nature of movement does not mean that we can only study movement at highest level, but that it provides a window to the different timescales of neural processes, and levels of coordination between neural systems.

2.13. Quantifying movement signatures

In the Chapter 1, I introduced how motor development is typically measured by identifying the motor milestones achieved, relative to the "norm" for the child's age. Motor skills may also be assessed by task performance on standardised motor tasks eliciting different domains of motor function, such as balance, visuomotor coordination and manual dexterity. I also introduced how, taking a movement perspective of autism have led to a focus on micro-movements – the sub-second, minute characteristics in the continuous output of movement.

This has led to interesting findings that the movements made by autistic individuals, even if they achieve a task successfully, show different characteristics at that micro level. In this chapter, I showed that movement can be conceptualised as the product of a complex system, with large numbers of interacting components at different levels. This allows movement to be quantified in yet another way using the mathematics of complex systems, which describes the interactions within the system holistically.

In the previous section I outlined the importance of considering that movement evolves over time. Yet, in the psychological sciences, phenomenon is typically sampled through repeated measurement and scientists analyse only the summary statistic of the central tendency of the phenomenon. The rationale for this is that there is variability when in the psychological phenomenon of interest, and collapsing information gathered in the time domain can remove the variability due to noise. It is useful in that it provides a global picture, when we are interested in the most consistent state that the system takes, when conditions fluctuate constantly and inevitably. However, traditional statistical methods in psychology provides only a static picture. In contrast, analysing the dynamics of a phenomena such as human behaviour involves describing the changes in its output over time. This can encompass a description of the temporal and spatial patterns, frequencies at which changes occur, or equations that describe how changes occur. Movements observed with the same mean and standard deviation can have different dynamics. I will show in the next few paragraphs why examining the movement dynamics provides a window to the processes involved in producing movement. I will show, importantly, that analysing movement dynamics can reveal the different configurations of movements that the system is able to produce, and therefore its information content. This has been termed movement complexity, and is mathematically quantified using Entropy. I will also provide an overview of other methods that quantify other aspects of movement dynamics.

Movement is variable. Variability refers to the different states in which the system can take. When variability results from noise, this can impact task performance. This end-point variability, measured by range and standard deviation, is the type of variability typically considered in the study of behaviour, and are typically considered experimental disturbances, to be removed (Slifkin & Newell, 1998). However, researchers have highlighted that variability tells us more than just the success or failure in dealing with noise. A second type of variability, coordinative variability, refers to variations in the system output through coordinating the degrees of freedom in the system in many different ways, which all enable task completion (Bernstein, 1967; Latash, 2012; van Emmerik et al., 2016). Distinguishing these two types of variability is important and is illustrated in Arutyunyan and colleagues' (1968) experiment comparing accuracy in pistol shooting in expert and novice marksmen. To achieve precise marksmanship, the marksmen has to keep the gun barrel precisely aimed at the target with low end-point variability. This can be achieved through both low and high coordinative variability. In order to keep the pistol still, novices focus on keeping their shoulder and wrist rigid, to prevent disturbances to the pistol. In contrast, experts make use of the available degrees of freedom in their shoulder and wrist joints to maintain the pistol in the desired position, and this enables them to do so more effectively with lower end-point variability of the pistol. Bernstein (1967) famously described movement as repeated without repetition. Even when infants have learnt to make the same movement consistently to achieve a motor task, they perform each movement in a manner that is far from robotic. Examining the form of movement from one time to the next reveals subtle changes that is not simply attributable to random noise (Riley & Turvey, 2002). This temporal characteristic of movement variability has been termed movement complexity – and has mathematical underpinnings in *entropy.*

Entropy

The interactions within complex systems have been understood through statistical mechanics (Weaver, 1991). This framework developed from understanding the macro-properties of physical systems, from the micro-properties of the system using statistical methods and probability. For example, in the field of thermodynamics, to characterise a gaseous substance at two different temperatures, the substance at a higher temperature can be said to have a greater number of possible microstates, and hence more disorderly, than the other. This state characterising orderliness or disorderliness has been termed entropy, a mathematical quantity proportional to the natural logarithm of the number of microstates (M. Mitchell, 2009).

In information theory, entropy has been used to quantify the information content of a message. Information is related to uncertainty. A message conveying an outcome, given more possible outcomes (meaning that the outcome is more uncertain), will convey greater information. Shannon and Weaver (1949) first applied this in telecommunication to determine how messages of different information content can be communicated through a noisy channel successfully. Information theory applies more generally to any probabilistic system, as uncertainty is related to the probability of an event. In the simplest example of a fair coin, only two states are possible – heads or tails. On repeated coin flips, we find out more about the possible states of the coin which can be said to be an information source. We also find out that each coin flip provided half the information of the coin system, which contains two possible states, heads or tails. This quantity, representing two different facts, has been quantified as 1 bit of information. Shannon entropy, representing the amount of information communicated by the source, is defined based on the probabilistic outcomes of a system:

$$\mathrm{H(X)} = -\sum_{i=1}^{n} P(x_i) log_2 P(x_i)$$

In this way, the definition of Shannon Entropy captures how a system encoding more outcomes (a lower probability of each event), contains more information. A six-sided die containing six possible states generates more information on average, as observing consecutive die rolls provides us with knowledge of a more complex system – one containing more possibilities. This can be applied to complex systems – relative to a less complex system, a system with a greater number of possible micro-states characterising its macro-level property can also be said to provide us with more information on average as we find out about a greater number of possible states the system can take.

Uncertainty is also related to unpredictability. A complex system with high information content can be said to have high uncertainty in relation to what its next state will be, as there is a large number of possible configurations it can take. Therefore, a system with high entropy, or information content, can also be described as an unpredictable system. In thermodynamics, a system containing greater entropy describing the disorderliness of the system, also relates to greater unpredictability, as well as greater information content.

Fitts law

In Paul Fitts (1954) seminal work, he likened the motor system to an information source, generating a kinematic signature when completing a point-to-point movement. The motor system can produce a successful point-to-point movement in many possible ways, and "the greater the number of alternative classes, the greater the information capacity for a type of movement is" (Fitts, 1954, p.262). As each movement depends on integration of perceptual information, Fitts further found that perceptual characteristics of the goal, such as the target distance and the target width, influences the information content of the response. Fitts also discovered a proportional relationship was also demonstrated between the perceptual difficulty of the movement and the amount of time required to produce the movement. This relationship is famously known as Fitts Law:

$$MT = a + b\ log_2(\frac{2D}{W})$$

Where MT represents movement time, D the target distance, and W the target width. 2D/W represents the Index of Difficulty (ID).

Harris and Wolpert (1998) proposed that Fitts law results from noise in the motor system, which increases with the amplitude of the motor command (to enable the effector to cover a longer distance). The movement itself is also affected by biological or environmental noise that makes the motor command imperfect, and therefore requiring greater perceptual feedback to correct the movement. As such, further and smaller targets are more difficult to achieve accurately due to these biological and environmental constraints, and require longer movement time, related to the processing of perceptual information in the motor system to generate that type of movement.

2.13. Quantifying dynamics

Dynamics can be quantified in a number of ways. I summarise some methods in Table 2-1 (Rapp, 1994). Autocorrelation focuses on quantifying how much a value is related to a previously occurring one, and spectral analysis describes dynamics in terms of the sine waves that can be combined to produce it, based on Fourier transformation. Other methods focus on reconstructing the phase space of the dynamic system, which can represent all the states that the system can take and plotting the trajectory of state changes over time. In this section, I focus on entropy, which is based on quantifying the degree of irregularity or predictability of a signal, and recurrence quantification analysis, which is based on a visualisation of trajectories in phase space.

Table 2-1. Methods to quantify dynamics of a timeseries

Method	Description
Autocorrelation	Assesses the relationship between each data point and the next data point (autocorrelation). The scatter of points (x t+1 against x t) more closely lying along a regression line would mean that the points are highly correlated ie if the previous point had a particular value, the next point also tends to have a certain value. Plotting the autocorrelation with the second data point defined over a range of lags gives the autocorrelation function. For example, a sine wave characteristically is positively correlated over short lags but becomes negatively correlated over longer lags. A physiologic signal such as force variability over a constant force production task may have high and positive correlations at short lags but decreasing to zero at greater lags. A signal resulting from random processes would show no correlations across any lag, as the pattern of output at any one time is not related to previous values
Spectral analysis	Spectral analysis is the decomposition of a timeseries into its component sine waves. Fast Fourier Transformation (FFT) is a method to do so, and produces a periodogram describing the power spectrum of sine waves over a range of frequencies, which make up the signal.
Embedding dimension	Embedding dimension refers to the number of dimensions required to unfold the phase space of a dynamical system. Greatest False Nearest Neighbours analysis can be used to estimate the number of variables required to form a valid state space.
Maximal Lyaponov Exponent (LyE)	Max LyE measures how rapidly a system’s state trajectories over time diverge in phase space. This measures the stability of the system’s state, how small perturbations or variations in the system’s state can lead to different patterns of behaviour.

Entropy methods

Kolmogorov-Sinai entropy is a measure of the information in dynamic physical systems, and is based on the idea that a system is more unpredictable if it can take a greater range of states (Benettin et al., 1976). However, characterising all the states in biological systems is not practical and requires huge amounts of data. This motivated the development of Approximate Entropy (ApEn) (Pincus, 1991), which quantifies the regularity in the timeseries, the extent that patterns in the timeseries occur again in the same way. Mathematically, it quantifies the logarithmic probability that a sequence pattern of particular length (i.e., m data will also match for the next data point. This can also be said to measure how predictable the timeseries is, whether patterns evolve in the same way.

Algorithmically, ApEn is implemented by counting the number of matches for *m* consecutive data points, and the number of consecutive matches for *m+1* data points, over the whole timeseries. A match is considered even if the data points do not match exactly, provided they match within a similarity criterion r. The ratio of the number of matches for *m* points, and *m+1* data points is obtained and the natural algorithm is taken. ApEn can be defined mathematically as:

$$ApEn(m,r) = lim_{N\to\infty}[\Phi^m\,(r) - \Phi^{m+1}\,(r)]$$

$$\Phi^m\,(r) = (N-m+1)^{-1}\sum_{i=1}^{N-m+1}\log C_i^m\,(r)]$$

Where m is the length of consecutive data points considered in a pattern, i refers to the position of the element in the timeseries, N is the length of the signal, C_i^m is the count of patterns of m data points, and r is the tolerance range for two values to be considered similar.

Higher values of ApEn are obtained when there are few pattern matches, and therefore the signal is more irregular and unpredictable, while lower values indicate greater regularity and predictability. Sample entropy (SampEn) is a modification of the ApEn algorithm (Richman & Moorman, 2000), which excludes “self-matches” when identifying the number of pattern matches – this means that a pattern is counted only if it occurs again later. This addresses the

ApEn algorithm's bias towards computing greater regularity in the signal when there are more patterns identified, but the patterns do not actually repeat again.

The analysis of ApEn and SampEn is computationally demanding, as the algorithm has to go through each timeseries several times to count all the different patterns that could occur. The similarity criterion *r* is normally determined from a proportion of the standard deviation of the data, to allow for some variation in the occurrence of similar patterns. However, this can be problematic when the data is influenced by noise or artefacts, which increases the standard deviation. Richman and Moorman (2000) propose sensitivity analyses to determine the *r* parameter or carry out further analyses to ensure that the selection of *r* does not drastically alter the results. However, this adds to the computational demand of the method.

Permutation entropy is another method to quantify information content of the signal using pattern irregularities in the signal (Bandt & Pompe, 2002). Permutation entropy uses the same rationale as ApEn and SampEn, but instead of identifying patterns based on their values, focuses on permutations of the values. This means that the order of the values is used in the algorithm, but not the exact difference between the values (Bandt & Pompe, 2002). The strength of this algorithm is in its robustness to observational and dynamical noise and is less computationally demanding (Bandt & Pompe, 2002; Zanin et al., 2012). Other methods to quantify entropy include Fuzzy Entropy (Chen et al., 2007) and Wavelet Entropy (Rosso et al., 2001).

Multiscale entropy

Entropy has also been extended to Multiscale entropy (Costa et al., 2002, 2005). This was motivated by the observation that entropy algorithms are limited to quantifying entropy at the timescale corresponding to the sampling frequency. Yet, complex systems exhibit output acting at multiple timescales and it is likely that complexity should be exhibited at more than one timescale. Additionally, a limitation of the ApEn algorithm is that signals generated by white noise are assigned high entropy values, yet are not truly complex. To accurately describe the complexity of biological signals, complexity at multiple timescales should therefore be considered. Costa and colleagues demonstrated that Multiscale Sample Entropy differentiated between white noise and 1/f noise –1/f noise demonstrates dynamic characteristics such that one value is related to its history of values. MSE accurately characterises the presence of greater complexity in 1/f noise at higher timescales, relative to white noise. MSE also accurately showed that a physiological timeseries, produced by a complex system, has greater complexity than a surrogate of the physiological timeseries manipulated to randomly shuffle the order of values to destroy the temporal patterns.

To calculate entropy at higher, i.e., slower, timescales, the signal is *coarsegrained* by taking the average of *s* consecutive values to create a timeseries at the that scale factor (M. Costa et al., 2002, 2005). Coarsegraining reduces the length of the resulting timeseries, meaning that entropy computed at higher scale factors may be less reliable and the algorithm is not able to compute a value for Sample Entropy if no matches are found (S. De Wu et al., 2014). Further advances have been made to address this limitation, in the Composite multiscale sample entropy method, all the possible coarse-grained timeseries – using different starting points of the original data – are used to calculate entropy, and the average is taken. In the Refined Composite Multiscale Sample Entropy method, entropy is calculated from the total number of matches across all the possible coarse-grained timeseries, reducing the possibility that no matches are identified (S. De Wu et al., 2014).

Applications of entropy methods

Entropy has biomedical applications, found to distinguish movements in health and disease, and in aging. For example, applied to gait dynamics, stride-to-stride variability show lower complexity between healthy individuals and individuals with a Central Nervous System disease (Hausdorff, 2007); in older adults, lower postural complexity is associated with greater falls (Zhou et al., 2017). Such findings have led Goldberger and colleagues (2002) to propose that aging is associated with loss of complexity. Bisi and Stagni (2019) applied Multiscale entropy to show an increase in gait regularity between childhood to adulthood, characterising maturation patterns indicative of greater automaticity. However, when automaticity is disrupted in tandem walking when participants had to walk along a tapeline, complexity increased with age. This suggests that higher entropy cannot always be taken to be indicative of more advanced development or a healthy state - the task context used to elicit the signal inherently affects the amount of information processed by the system, transmitted by the signal and quantified using these indirect entropy methods.

To summarise, different methods, with particular strengths and limitations, have been used to analyse the entropy of dynamic data. These methods have been applied to physiological signals including movement, showing promise in biomedical research to understand what influences the output of the brain-body system.

Recurrence quantification analysis

"Similar situations often evolve in a similar way. Some situations occur over and over again." - Marwan and colleagues (2007, p. 240)

Observing the unfolding of movement or behaviour provides a window to the underlying system producing it. However, scientific experiments do not have the luxury of the time to observe sufficient instances of behaviour, if they happen infrequently, or unfold over a longer timescale. Methods to analyse entropy rely on having sufficient number of observations in a timeseries to obtain reliable estimates of entropy (Pincus, 1991). Although innovations in entropy analysis have enabled analysing of biological signals with relatively smaller amounts of data, these methods have been applied to phenomena occurring at short timescales. Kinematic patterns can be sampled easily, as their dynamics occur at the millisecond timescale. Gait patterns, for example, stride-to-stride dynamics, occur at a timescale no longer than around one second. However, behaviour and sequences of behaviour unfold at much longer timescales. For example, the function of an infants' reach is revealed only when the movement is complete – then the kinematics of that reach starts to make sense in terms of the behavioural function it achieves, e.g., why the infant has made a slow controlled deceleration towards the object in order to grasp it, or a less controlled movement to knock it over. Repetitive behaviours are a sequence of movements performed in a similar way, and common in development (Thelen, 1979), such as when infants bang objects repeatedly to create interesting sensory stimulations. Similarly, the repetitive nature of the movement has to be studied at the timescale which it unfolds.

Recurrence quantification analysis (RQA) is a method of nonlinear analysis that overcomes these limitations (Box et al., 2015). As its name suggests, RQA quantifies dynamics based on a fundamental property of complex dynamics systems - the recurrences of states. Recurrences are stretches of short and long repeating patterns (Wallot & Leonardi, 2018). Unlike a system relying on random processes, systems containing some level of order show recurrences, because the system repeats inherent processes to generate output, and thereby producing in similar patterns of output. Examining these patterns of recurrences provide information on how the system behaves.

RQA was developed in the physical sciences and is based on a graphical analysis of recurrences. Recurrences occur when the system revisits a previous state. For continuous timeseries, this phase space needs to be reconstructed in order to determine if a state is recurrent. Reconstruction of phase space is commonly achieved using time-delay embedding, as described by Takens Theorem (1981). Upon reconstruction of the phase space, recurrences are identified as states matching within a specified threshold. Recurrences are then plotted in a recurrence plot (RP) that allows the visualisation of the systems trajectory relative to its behaviour in the past (or future).

A RP is a two-dimensional graph identifying whether a system's state at one time (on the x-axis) matches its state at another time (on the y-axis). RPs contain a central diagonal corresponding the comparison of the same value against itself. Moving along the x- or y-axis away from the diagonal, any plotted recurrences depicts the time in the past or future when the same state occurred. Based on the geometric properties of recurrences identified in the plot, the dynamics of the system can be quantified (Zbilut et al., 2002). The most basic measure, percentage of recurrences (%REC) quantifies the extent that the system's behaviour occurs again given a behaviour has previously occurred. Determinism (DET) refers to the extent the systems' future state depends on its previous state, and %DET is calculated by computing the number of data points recurring as part of a sequence and as such form diagonal lines in the plot, parallel to the central diagonal. Shannon information entropy (ENT) can be computed based on complexity of structures in the RP. As the dominant structure in RPs of continuous data is the occurrence of diagonal line structures, ENT has been proposed to be calculated from the frequency distribution of diagonal line structures. The maximum diagonal line length refers to the longest length of repeating sequences, and captures the dynamic stability of the system, related to the largest Lyaponov Exponent – both characterise how long the system shows a predictable, stable, pattern.

The main strength of RQA is in its graphical approach (R. Dale et al., 2011). This makes it suitable for short timeseries (Zbilut et al., 2002). It also lends itself to intuitive interpretations applicable across different fields - in addition to the quantities described above, a range of other dynamic descriptors can be obtained where relevant to the research question. Further, it is applicable not just to variables on a continuous scale, but also categorical variables. Categorical variables can be said to represent the systems' state, and does not requiring a reconstruction of the phase space.

RQA is also extremely versatile and can describe the interplay between two systems, such as by analysing the repetition of coupled and non-coupled states in the timeseries produced by each system in Cross-RQA (R. Dale et al., 2011). RQA has proliferated in the cognitive and behavioural sciences due to these advantages (Port & Gelder; Guastello et al). It has been applied to gaze patterns (Anderson et al., 2013), coordination of gaze patterns between observers (D. C. Richardson & Dale, 2005; Kevin Shockley et al., 2009), movement analysis (Tolston et al 2014), postural synchronisation between two individuals (K. Shockley, 2005; Kevin Shockley et al., 2003). Beyond the motor domain, it has been applied to analysis of linguistic (R. Dale & Spivey, 2006) of coupled interactive states between mother and infant (Abney et al., 2017), motor synchrony and coordination between two individuals (Abney et al., 2015; Brick et al., 2018), as well as EEG (Acharya et al., 2011; Heunis et al., 2018).

2.14. Section summary

An embodied view of mental functions highlights that cognition and emotion are embodied but a prevailing question is how higher-level functions are achieved from seemingly different lower-level level functions. Dynamic systems theory, building on the principles of complex systems science, addresses this problem. This framework conceptualises movement as the product of multiple processes interacting in time. Observations and empirical studies have demonstrated that more complex abilities are enabled by, and builds on lower level skills, countering the cognitivist view that mental information processing are enabled by abstract symbolic representations. Instead, information processing can be seen as the processes within a complex, high-dimensional system, interacting across levels and timescales. New methods have enabled us to probe this. With these relatively recent theoretical and methodological advances in mind, I now introduce the focus of this PhD thesis.

Section 3: Focus of the thesis

In the first chapter, I introduced how the development of socioemotional capacities is key to engage with others and learn from social situations, cope well with emotional challenges, and as such key for overall wellbeing. When difficulties arise, this can have long-term consequences on school performance, building satisfactory social relationships and life chances. It can also impact family functioning and lead to a burden on services. Research tends to focus on socioemotional difficulties, yet overlook the role that early motor difficulties play. I further introduced the embodied mind perspective and showed how in autism this has made strides in understanding how movement affects socio-communicative difficulties, as well as in early identification. Next, I reviewed literature showing that preterm-born individuals are at risk of these negative outcomes, even when socioemotional difficulties are not severe enough to warrant a clinical diagnosis. Motor delays and difficulties are widely recognised, and precede socioemotional difficulties.

In this chapter, I highlighted how understanding the development of emotional self-regulation will enable a better mechanistic understanding of socioemotional difficulties, given its transdiagnostic nature, that it emerges early in development, and integrates a range of functions. I introduced definitions of self-regulation, showing that emotional self-regulation can be understood as involving "domain-general" processes to "domain-specific" emotional situations. This includes early developing attentional modulation, behavioural inhibition and activation processes which make up effortful control, as well as later developing and more complex cognitive abilities, collectively termed executive functioning. I also introduced theories and approaches to understand movement that complements the embodied mind perspective, crucially showing how lower level abilities can affect higher level ones. I highlighted how the conceptualisation of movement needs to go beyond motor skills to understand fully how movement unfolds over time to give rise to intentional behaviours.

The following studies examines the thesis that movement is associated with socioemotional development, with the aim of understanding what movement can tell us about socioemotional differences. I conducted three studies examining six research questions, examining movement at the level of sub-second motor kinematic patterns, and at the level of behaviour, focusing on behaviours related to emotional self-regulation. Based on the literature reviewed in Chapters 1 and 2, I define emotional self-regulation as involving domain-general attentional and behavioural processes specifically to emotional situations, and consider it one of the social cognitive capacities involved in successful social interactions, within the framework of socioemotional competence. I use the terminologies emotional self-regulation (from research in the neuroscience of emotion), and self-regulation of emotions (from developmental psychology) interchangeably, to refer to the application of voluntary, effortful, self-regulatory processes to modulate emotional states including affect and emotional behaviour.

2.15. Study 1: Developmental differences in subsecond movement patterns in autism and neurotypical children

My first study uses a previously collected dataset from Anzulewicz et al (2016) with the objective of analysing differences in subsecond movement patterns obtained through smart-tablet gameplay. Differences in subsecond movement patterns have been proposed to implicate social learning mechanisms, but there continues to be an ongoing debate on whether there are sub-second motor differences in autism. Concurrently, advances have been made to identify autism computationally through subsecond movement patterns but the developmental significance of movement patterns that distinguish between groups are unclear. This is because machine learning techniques train an algorithm to identify a combination of movement features that can distinguish between groups, but may not have strong justifications for why these features are important. I open the investigations in this thesis by addressing a contemporary issue in the autism movement perspective. This study will examine the research question:

Are sub-second movement kinematics and their developmental trajectories different between autistic and neurotypical individuals? (Chapter 4)

2.16. Study 2: Emotional self-regulation in preterm birth

My second study is set within an ongoing cohort study of preterm birth, the Theirworld Edinburgh Birth Cohort Study. The objective of the second study is three-fold: first, I will develop a new coding scheme (Chapter 3) and examine the validity of these new measures as an indicator of emotion regulation (Chapter 6); second, I will investigate differences due to prematurity in behaviours during emotional self-regulation (Chapter 5); third, I will investigate associations between these measures of emotional self-regulation with other developmental measures to understand the relationship between aspects of emotional self-regulation with biological constraints, motor and social development (Chapter 6-8). Specifically, I will address the following research questions:

Are there differences in the type or temporal organisation of emotional self-regulation behaviours between 9-month-old term and preterm-born infants? (Study 2A, Chapter 5)

What is the relationship between infant temperament and emotional self-regulation? (Study 2B, Chapter 6)

Are emotional self-regulatory behaviours influenced by motor skills at 9-months-old? (Study 2C, Chapter 7)

Does emotional self-regulation at 9-months-old predict autistic traits at 2-years old? (Study 2D, Chapter 8)

2.17. Study 3: Differences at multiple timescales of movement

My third study is also set in the same birth cohort study. The objective is to explore, as a proof-of-concept, if motor differences are sensitive to changes in the socioemotional context and the ways prematurity influences motor patterns during socioemotional contexts. This study will examine the research question:

What is (1) the effect of prematurity on infants' motor patterns during the still-face paradigm and (2) the effect of emotional stress or caregiver availability on motor patterns? (Chapter 9)

2.18. Summary of rationale

This PhD examines movement at two levels, subsecond motor kinematics and motor behaviours related to the self-regulation of emotions. The three studies I chose take a dual-approach to movement. First, I use a traditional approach that examines these two levels of movements separately, considering whether and what ways movement at each level is different between two groups that experience or are at risk of different socioemotional outcomes. In Study 1 and 3, respectively, I look at whether movement at the level of subsecond movement kinematics are different in autistic compared to neurotypical children, and in preterm-born and term-born infants. In Study 2, I examine whether movement, at the level of socioemotional behaviours, differ between the latter groups.

Second, I approach the association between movement and socioemotional development from an integratory perspective, as outlined in this chapter – that socioemotional capacities involve movement and movement unfolds over time. I use approaches from complexity science to study temporal patterns of behaviour in Study 2, and the different timescales of activity in movement in Study 3. This is based on the perspective that dynamics provide a window to the synergistic interactions underlying motor output. Again, I consider whether dynamic patterns are different between preterm and term-born infants. In Study 2, I further examine how the novel, dynamic measures are related to socioemotional characteristics measured using established, questionnaire approaches in developmental psychology (temperament, Study 2B), motor development (Study 2C) and socioemotional outcomes (autistic traits, Study 2D).

Overall, the rationale for the studies are to put old phenomenon in a new lens through applying novel technology and cross-disciplinary methods. The studies cut across two traditionally separate levels of investigation, and compare new phenomenon with established tools to further inform how an integratory systems' approach can tell us about socioemotional differences and outcomes.

3. Methodology

3.1. Dataset - swipe movements during tablet gameplay

The first study in this thesis uses a dataset previously collected by Anzulewicz and colleagues (2016), on finger "swipe" movements made during gameplay. Data was collected from 37 autistic children aged between 3 and 6 years old, and 45 age-matched neurotypical children, in specialist autism therapeutic clinics in Krakow, Poland. Autism was defined as a clinical diagnosis of ICD-10 Childhood Autism (World Health Organisation, 2004), by medical practitioners working in those clinics.

Children played two games on an iPad Mini 2 (Apple Inc, 2013, iOS version 7.0) - the "Sharing" and "Creativity" game. The components of the Sharing game involved tapping on a piece of food in a central location to divide it, and then moving food pieces to one of the four character avatars on the screen, who have a plate in front of them. Once all food pieces were distributed, the character avatars expressed positive facial expressions and vocalisations if the food were distributed equally, and negative facial expressions or vocalisations if not, and a new food piece appeared. The Creativity game had a less defined structure. The main components of the game involved selecting a shape by scrolling on a slider and tapping on a shape, outlining a shape by roughly following the dotted outline, selecting a colour a by scrolling on a colour wheel, and coloring the object by moving over the bounded area, although children could also colour in any location on the screen. Children were provided a 2-minutes practice period to familiarise with both games and then proceeded with 5-minutes of gameplay beginning first with the sharing game but with time divided equally between both games.

Touchscreen coordinates (x- and y- coordinates) of the swipe patterns, and data from the inertial movement sensor (including tri-axial gyroscope and tri-axial accelerometer) on board the iPad were acquired throughout both games and segmented to correspond to either the Sharing or Creativity game. Discrete movements were identified from the raw data and over 200 features characterising movement patterns were extracted from each movement. The extracted features from each game were then separately used to train a machine learning algorithm to predict an autism diagnosis.

For the purpose of this study, I used raw touchscreen data from the Sharing game, but focused only on movements that can be considered goal-oriented in the context of the gameplay. I processed the raw segmented data to identify discrete movements corresponding to movements moving the food pieces from a start area to the characters. I then calculated kinematic landmarks pertaining to each discrete movement, focusing on a small set of kinematic features previously identified in the literature to be sensitive to perceptual aspects of the goal, and as such would measure processes related to creating movement plans and executing a movement to reach the goal.

3.2. Theirworld Edinburgh Birth Cohort Study

The remaining studies of this thesis is set within the Theirworld Edinburgh Birth Cohort study (TEBC), a prospective longitudinal cohort study to investigate the developmental outcomes of infants born preterm (Boardman et al., 2020). Approximately 400 infants have been recruited to TEBC in Phase II of the study, of whom 300 infants are born preterm (<33 weeks of gestational age (GA)) and 100 infants born at term (>37 weeks of GA). Infants of women who attend the Simpson Centre for Reproductive Health (SRCH) at the Royal Infirmary of Edinburgh, NHS Lothian, UK, were included. The study excluded infants with congenital anomalies, defined as structural or functional anomalies occurring during intrauterine life (WHO definition) and infants who were not suitable to undertake a 3 Tesla Magnetic Resonance Imaging scan (Boardman et al., 2020).

3.2.1. Ethics and consent

This study is conducted in accordance with the principles of the International Harmonisation Tripartite Guideline for Good Clinical Practice (ICH GCP). Ethical approval was obtained from the National Research Ethics Service (NRES), South East Scotland Research Ethics Committee, and NHS Lothian Research and Development Committee. Consent for participation in the TEBC was sought by researchers with training in Good Clinical Practice and familiarity with procedures for research involving children and young people. Written consent was sought twice: initially for assessments during initial enrolment antenatally and for neonatal samples; and for follow-up assessments from discharge to 5 years (Boardman et al., 2020).

3.2.2. Materials

A range of biological and behavioural measures, and standardised developmental assessments are obtained at 7 timepoints: antenatal, birth, neonatal, 4.5 months, 9 months, 2 years and 5 years. Data used for this thesis were: antenatal data on demographics and socioeconomic status; 9-month video data from behavioural observation, and movement acceleration data from computational motor assessment (see section on computational motor assessment), obtained during the still-face paradigm (see section on Still-face paradigm); 9-month questionnaire data on development measured using Vineland Adaptive Behaviour Scales II (Comprehensive Interview Form at 9-months); 9-month questionnaire data on temperament measured using the Infant Behaviour Questionnaire Revised (short form) (IBQ-R), and 2-year questionnaire data on social development measured using the Quantitative Checklist for Autism in Toddlers. Additional information and procedure for collecting these measures are provided in the respective study chapters.

3.2.3. Participants

Participants included in this thesis were infants who attended their 9-month follow-up appointment up until March 2021, and participated in the still-face paradigm at the appointment, totalling 137 infants (74 born at term, 64 born preterm; 76 male, 60 female). Infants who additionally provided the relevant developmental data at 9-months or 2-years, on temperament measured using the IBQ-R (Study 2B), motor development measured on the VABS (Study 2C) or social development measured on the Q-CHAT (Study 2D) were included in the respective analyses. A subset of infants (n=25) attending their 9-month follow-up between July 2019 and March 2021 participated in computational motor assessment during the still-face paradigm, and were included in Study 3. Additional criteria relating to inclusion and exclusion for analyses are detailed in each study chapter.

3.2.4. Procedure

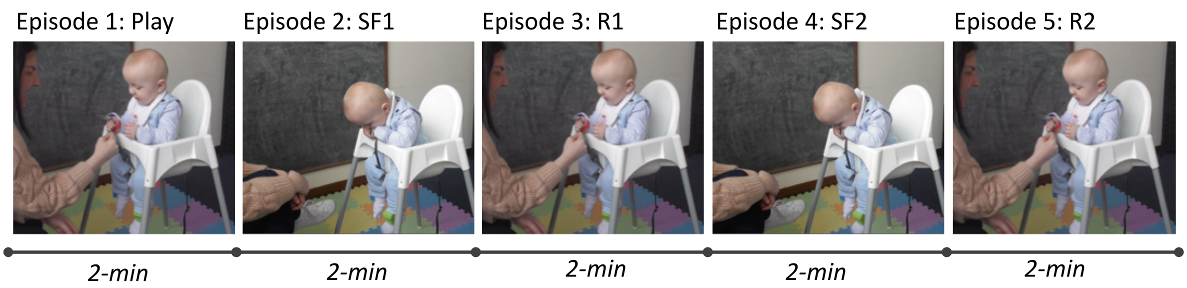
Follow-up at 9 months and 2 years of age was corrected for the degree of premature birth. For example, this means that an infant born 4 months preterm would be followed-up at 13-months chronological age. This approach endorses a biological maturational perspective, assuming that early in development proceeds consistently as a function of time since conception, and that preterm infants would catch-up to the developmental level of equivalent to their peers born at full-term after the complete maturation of the central nervous system. In contrast, when chronological age is used, this endorses an environmental perspective of development, where the effects of external factors on development (such as interactions with the physical and social environment) take precedence over biological factors (S. L. Wilson & Cradock, 2004).

Infants were contacted by a member of the study's research team to attend a follow-up appointment within 1-month before or after the date they turn 9-months-old or 9-months corrected age (or 2-years-old or 2-years corrected age). Behavioural assessments or researcher-administered developmental questionnaires were administered by a member of the research team and biological samples collected by a research nurse. Other questionnaires were completed by parents around the date of the follow-up appointment. Paper copies were returned by post. Since the COVID-19 pandemic, parents were emailed a link to complete questionnaires on the Jisc Online Surveys platform or a web-based administration platform provided by the questionnaire publisher.

3.2.5. Still-face paradigm

The still-face paradigm is an experimental procedure to evoke an emotional stress response in infants by violating expectations of normal social reciprocity (Mesman et al., 2009; Tronick et al., 1987). The still-face paradigm examines parent-child interactions in a structured sequence, comprising three main episodes: a baseline interaction episode where parent and child engage in normal playful interactions (Play); followed by a "still-face" (SF1) episode when the parent is asked to put on a neutral facial expression and stop responding to their child; and a "reunion" (R1) episode when the parent resumes normal interactions again and normally includes attempts to re-engage the child in play. In the TEBC, the still-face paradigm was carried out with an additional still-face (SF1) and reunion sequence (SF2) (Haley & Stansbury, 2003). As each episode was 2 minutes long, this "extended" modification of the still-face paradigm with 5 episodes lasted a total of 10 minutes. (see Figure 3-1).

Figure 3-1. The extended modification of the still-face paradigm



The still-face paradigm reliably elicits a "still-face" effect, characterised by an increase in negative affect and decrease in positive affect and social attention from baseline play to still-face, and a recovery in the three measures in the reunion phase (Adamson & Frick, 2003). The still-face effect is also characterised by a "carryover" or "reunion" effect where there is some recovery of affect but affect does not return to baseline levels. The extended still face paradigm was used as it appears to elicit a more robust "reunion" effect, where social attention also fails to return to baseline levels. Infants also show a greater negative affect in the second compared to first still-face episode (Haley & Stansbury, 2003). The still-face effect also appears to apply to heart-rate, where infants show increased heart-rate during still-face episodes and in line with its aims to evoke stress as cortisol increases after the still-face paradigm (Haley & Stansbury, 2003). Infants also show behaviours to self-soothe, such as self-clasping and mouthing.

The still-face paradigm was administered at the 9-month appointment and videos (1920 x 1080 pixels, 50 frames per second (fps)) of the caregiver and infant were obtained using Panasonic HC-W580 cameras stood on tripods.

Ethical issues pertaining to the still-face paradigm

The still-face paradigm was designed to elicit distress in infants and parents can also become distressed from observing the infants' distress. Parents were informed that they can stop anytime if they or their infants are too distressed. This was emphasised before starting the still-face paradigm. Researchers carrying out the still-face paradigm also stopped the experiment if the infant was crying continuously and inconsolably for over 30 seconds, including in both the caregiver-present and still-face phases. Following the appointment, parents were provided a debrief sheet including information on how the still-face paradigm serves as a standard laboratory procedure to enable researchers to study infants' response to stress.

3.2.6. Computational motor assessment

In Study 3, infants' arms, legs, torso and head movement were measured using tri-axial Inertial Magnetic Units (MTw Awinda) commercially available from Xsens. Each IMU contain a gyroscope (measuring angular velocity at ±2000deg/s), accelerometer (measuring acceleration at ±160ms-2) and magnetometer (measuring magnetic field at ±1.9 Gauss), each with an internal update rate of 1000Hz, as well as a barometer and thermometer (Paulich et al). Each weigh 16g and are of 47mm by 30mm by 13mm in dimension. Data from each IMU were transmitted wirelessly to an Awinda Station, which can receive data from up to 20 IMUs, up to 20m away within an enclosed space, and up to a maximum of an update rate of 120 Hz for one to five IMUs. This drops to 100Hz for six to nine IMUs. IMUs connected wirelessly to the Awinda station are time-synchronised to within 10µs. Data recording was initiated and stopped using the MT Manager software (version 4.6) which provides a user interface for setting up the wireless network and IMU connected to the network. The Strap-Down Integration (SDI) protocol is integrated on board the sensor to provide calibrated data, including accounting for the influence of ambient temperature and low pass filtering of the accelerometer and gyroscope data at 184Hz. Calibrated data from the IMU was then transmitted wirelessly.

Synchronising IMU with video and audio data

IMU data was synchronised to video data, to enable segmentation of IMU data (i.e. obtaining data corresponding to segments of behavioural data of interest). Two Raspberry Pi computers (version 3 B+) were used to achieve this synchronisation. The Awinda station contains the functionality and ports to send or receive TTL pulses (between 0-3.3V) and the

Raspberry Pi contains General Purpose Input Output ports (GPIOs) that respond to different patterns of electrical signals. Synchronisation was achieved by communicating a Transistor-transistor logic (TTL) pulse between the Master Raspberry Pi and the Awinda station. The Master Raspberry Pi then communicates via a Bluetooth connection with a second Raspberry Pi fitted with a Pi camera board (v1.3, 5 megapixels) to obtain a video feed (1024 x 768 pixels, 25 fps), and a microphone connected via USB, to obtain audio data (44.1 kHz).

The Awinda station is connected to the Master Raspberry Pi GPIO responding to a falling voltage of 1.8 to 0, and the Sync Out function was used. This was configured using MT Manager, to send a falling voltage signal on starting the sensor recording, and a rising edge signal on stopping the recording. Programs were created in Python to start and stop the video and audio feed accordingly based on these electrical signals, and communicating the signals between the first Master Raspberry Pi and the second Camera Raspberry Pi doing the recording of the video and audio. The program used the pybluez library to establish a bluetooth connection between the two Raspberry Pis. In the Master Raspberry Pi, the program used the gpiozero library to access the GPIOs states responding to TTL signals from the Awinda station. Bluetooth signals were sent to the Camera Raspberry Pi to start or stop the camera module, and start or stop streaming audio frames from the microphone (using python pyaudio and wave libraries). After recording was completed, the program on the Camera Raspberry Pi combined the video and audio files into a single file (.mp4), using the ffmpeg library.

Attaching IMUs to the body

Straps designed for adults were available from Xsens to attach IMUs to the body. For this study, for using the IMUs with young infants, bespoke pockets for the sensors were created and sewn on to commercially available socks, wristbands, bibs and headbands. IMUs were inserted into these pockets before the clothing were put on the infant. Therefore, IMUs were attached to infants' ankles, wrists, torso and head. Pockets of different colours were used for each body location, and the corresponding colour of fabric attached to the IMU designated for measuring movement for that body location (Figure 3-2). Using the same sensor for measuring movement at each location makes it easier to manage the data file (see next paragraph on data export)

Figure 3-2-a: IMUs used for computational motor assessment

Figure 3-2-b: IMU size relative to a pen

Data export

Data export was also done using the MT Manager software. Following data recording, data is saved to a designated folder. This data file contains the raw sensors data from all the sensors used during the recording. Opening this data file in MT Manager applies the Xsens Kalman Filter algorithm to estimate the orientation of the IMU, which then enables calculation of movement acceleration from the raw acceleration data by removing the influence of gravity (Paulich et al., n.d.). Data from each IMU including three-dimensional (3D) acceleration, angular velocity and magnetic field, as well as 3D free-acceleration (with gravity subtracted from acceleration output) and other data of interest, can then be exported to a range of file formats. Each IMU has a designated digital name which is used to label the data during export.

Pilot and modifications

This procedure to obtain motor data using IMUs was piloted with infants age 9 months old participating in the TEBC. Sensor attachment was piloted with one infant, and following this, a new set of bespoke clothing was created (as described above) which enabled a secure and comfortable fit for infants. Sensor attachment procedure, with obtaining synchronised sensor and video data were piloted with three infants. Technical issues during deploying the Raspberry Pi cameras were tested and fixed.

Infants were observed to be distracted by wearing a headband and the first two infants who wore a headband removed or attempted to remove it during the still-face paradigm. As such, the headband was removed from subsequent use, meaning that only movement of the arms, legs and torso were measured. Infants appeared to be distracted by the wristsbands and subsequently, infants either wore a plain long sleeve white top provided by the researcher to hide the wristbands and bib containing the sensors, or the wristbands were hidden under infants' own long-sleeved clothing.

Observations during data collection

Suitability of using sensors were reviewed during data collection. One infant removed the wristbands, but for this infant, the sensors were placed on the inner side of the wrist (palm-faced-up side), instead of the outer side (palm face-down side). Infants were least distracted by sensors in the socks, but some infants interacted with the clothing or sensor pockets by pulling at them. New pockets were made to make the sensor pockets a neutral white colour, but were not implemented for this study.

Synchronised audiovisual and sensor data were obtained for 9 infants. Due to data loss in video, audio or sensor data sampling, synchronisation resulted in drift in video data relative to sensor or audio data. For each minute of sensor data, video data was 0.014s (SD=0.01) longer, and for each minute of video data, audio data was 0.08s (SD=0.18) shorter. This means that by the end of 10 minutes of recording, video data could be lagging behind sensor data, on average for 0.14s. Audio data would occur ahead of sensor data for 0.8s on average.

Researchers part of the follow-up team faced technical issues occasionally with the bespoke Raspberry Pi camera set-up, and for some infants synchronised video data could not be obtained. This may be due to Raspberry Pi not charged up, starting the recording before Bluetooth connections were completed, or turning off the Raspberry Pi before the audio and video files were combined.

Due to these ongoing challenges, other synchronisation methods were explored, using videos of the still-face paradigm. Manual synchronisation, using movement landmarks, was achieved by identifying a characteristic repetitive movement (e.g. 15 cycles of repetitive leg kicking, or rocking) in video, and searching for this movement signature in the sensor data. Manual synchronisation could also be achieved by observing the start of the sensor recording in the video, if the laptop running the MT manager can be seen in the video and the moment when the researcher clicks the recording button can be observed. Finally, synchronisation was attempted using an additional sensor connected to the wireless network and therefore synchronised to the other sensors. This additional sensor was attached to a clapperboard, and a movement artefact was created using the clapperboard when the clapperboard is placed in front of the video cameras capturing mother and infant behaviours during the still-face paradigm. Data from the three infants in the pilot phase where sensor data was collected were also included in the final sample using one of these methods of synchronisation.

3.3. Development of a video coding scheme

3.3.1. Dynamic-systems framework to analyse emotional self-regulation

Despite being, fundamentally, a dynamic process, emotion regulation tends to be quantified using aggregate measures, discarding time information to produce a snapshot in time.

Researchers desire to study emotion regulation in isolation from emotion and careful efforts have been made to specifically define emotion and emotion regulation (Eisenberg & Spinrad, 2004; Thompson, 1994), yet the two processes are difficult to disentangle in practice due to their interaction in time. Emotionality or emotional reactions, has been defined neuro-scientifically as coupled neurophysiological and behavioural responses linked to evocative stimuli (Damasio, 1999). In contrast, emotion regulation refers to higher-level control processes, not directly triggered by the evocative stimulus, that are recruited to modify the intensity and duration of emotional reactions (Thompson, 1994). There has been attempts to identify the effects of emotion regulation on the emotional profile. For example, emotional sensitivity, or reactivity, is identified as the initial steepness in emotional intensity (in the earlier parts of the emotional response) while emotion regulation is said to influence how it off-sets to reach a neutral baseline (Koole, 2009). Yet, the purpose of emotion regulation is not always to return to a neutral baseline and emotion regulation can upregulate or downregulate emotion, towards adaptive goal behaviours. In Gross's process model and extended process model, the leading cognitive model of emotion regulation, it is recognised that emotion regulation can have different and evolving effects in anticipation of, during or after the presentation of evocative stimuli. This makes it even more problematic to singularly identify when emotional expression ends and regulation begins (Cole et al., 2004).

Some theorists have gone a step further to posit that "emotion and regulation are one" (p. 23), because emotional expression can have regulatory effects, triggering feedback loops that then alters the initial emotional response (Kappas, 2011). Researchers broadly agree with this idea, that ultimately, emotion regulation is a continuum between conscious, effortful and top-down controlled, to unconscious, effortless and automatic (Nancy Eisenberg & Spinrad, 2004; Gross & Thompson, 2007). However, they have argued against the usefulness of a broad definition of emotion regulation as it enables almost any behaviour to be considered emotion regulation (Eisenberg & Spinrad, 2004), proposing that the solution is to specify the which kind of emotion regulation is of interest. Because what researchers are typically interested in are the self-generated, voluntary, controlled, goal-directed aspects of emotion regulation, Eisenberg & Spinrad (2004) proposed a sharper definition of emotion-related self-regulation that precludes the regulatory effects of emotionality:

Emotion-related self-regulation is the process of initiating, avoiding, inhibiting, maintaining or modulating the occurrence, form, intensity or duration of internal feeling states, emotion-related physiological, attentional processes, motivational states, and/or the behavioural concomitants of emotion in the service of accomplishing affect-related biological or social adaptation, or achieving individual goals.

Nevertheless, researchers have recognised that it is also difficult to tease out in practice which processes are voluntary or involuntary. In development, this is even more complicated. Infants may be voluntarily producing or persisting in behaviours, such as fussing or kicking to elicit caregiver's attention and care; or testing if they are effective in terms of successfully downregulating emotions (Ekas et al., 2013, 2015). These behaviours are usually considered automatic reactions to emotion and are usually the target of emotion regulation (Nigg, 2017).

Due to the existing limitations in defining and studying emotion regulation, new approaches have been proposed. Firstly, researchers can focus on the dynamic features of emotional responses, the intensity, timing and modulation of it due to emotional regulatory processes. Secondly, researchers could simply focus on measuring the processes involved in emotion regulation. As a result of the latter, researchers studying the development of emotion regulation have identified effortful control as a way to study emotional self-regulation due to: first, its involvement during emotional situations to purposefully redirecting attention and behaviour - including to modulate automatic emotional responses; second, the fact that it is top-down self-initiated, and third, that it is an early emerging capacity (Rothbart & Bates, 2006).

In this section, I apply dynamic systems theory to develop the second approach further to study *processes* in emotion regulation, with the aim to inform our understanding on how prematurity affects emotional self-regulation.

Within a complex dynamic systems framework, emotion regulation can be seen as the product of lower level processes interacting to produce what is observed at higher level. Emotional self-regulation can therefore be seen as the coordination of several meso-level abilities – particularly attention and cognition which are then integrated with the motor behavioural system to express emotion and enact purposeful self-regulatory responses. These meso-level abilities in turn rely on lower, micro-level interactions over space and time such as in the coordination of sensorimotor structures (e.g. muscular activation to generate eye movements), abstract cognitive concepts built from perceptual leaning.

A metaphor for a dynamic system is an energy landscape containing all the possible states that the system can achieve (L. B. Smith & Thelen, 2003). The states at a particular level of analysis are characterised by coordination at lower, levels, a specific organisation of the system's many degrees of freedom. The landscape includes attractor states, low-energy, preferred states which the system returns to repeatedly and frequently over time (M. J. Richardson et al., 2014). This energy landscape is not fixed, but evolves, as development alters the organisation of the system over time. Complex biological systems contain inherently many high degrees of freedom that become coordinated during learning, and differences in coordination produces differences in the temporal output. Using this metaphor, the behaviours produced by infants in an emotional context can be said to be the attractor states of the emotion regulation system, mediated by integratory lower level processes.

Thelen and Smith (1994, 1998) identifies four steps in dynamic systems analysis: first identifying a "collective variable", an observable behaviour reflecting the state of the system – characterised by the interrelationships among lower-order components; second, identifying the attractor states that the variable shifts between over time; third, quantifying the temporal stability and change of the variable; fourth; considering changes that characterise phase transitions, when the system shifts from one attractor state to another. The fifth and sixth step proposed - investigating what leads to phase shifts and experimentally manipulating the factors that might lead to phase shifts - may be of interest depending on the aims of the research.

Following from Chapter 2, analysing the temporal patterns or dynamics of a system's output provide a window to the organisation of the system. Three main descriptors have been proposed to describe the dynamics of a system (van Emmerik et al., 2016). Firstly, stability describes how long a system remains in a particular state. This may indicate that the system is too resistant to change, persisting for prolonged periods in the same state. It may also indicate the extent of learning, for example if a learnt behaviour is selected for the situation and therefore maintained for a period of time, in contrast to states occurring by chance and assembled only transiently. Secondly, variability describes the range of states available, and may indicate that the system has the potential to produce more regulatory states. This could indicate that the system has access to more types of behaviours and can therefore adapt to different demands, however it may also indicate stages in learning as variability leads to specificity of useful strategies. Finally, complexity describes the number of temporal patterns in which the system transits between states. It indicates how fluidly the system can access different states, mediated by the organisation of the interacting components.

Complexity is thought to indicate flexibility and adaptability as greater complexity might mean that the system is able to shift between states to suit task demands (Van Emmerik et al., 2004). However, it must be noted that the interpretation of these descriptors is speculative at present. This is especially so in the context of dynamic developmental systems which shift between orderliness and complexity, stability and relative instability, variability and specificity. Development is an iterative process of periods of destabilisation that makes one form less preferable and stabilisation that makes new or alternative forms more preferable; variability and complexity when new forms are tried and tested, specificity and orderliness as some forms are selected and used more than others, and complexity again as the system diversifies and finds different forms of the same solution (Hadders-Algra, 2010).

3.3.2. Procedure

With the aim of investigating infant's emotional self-regulatory behaviours, dynamic analysis can proceed by identifying the attractor states of this collective variable and their changes over time - the second step of the framework of dynamical systems analysis (Thelen & Smith, 1998; Thelen & Smith, 1994). This was done by developing a video coding scheme from reviewing the range of behaviours used by infants in the still-face paradigm, a situation which elicits distress in infants. In a dynamic systems framework, emotional self-regulation can be seen as the output of a dynamic system during an emotional context, the macro-level behavioural output resulting from processing across more than one neural subsystem. A review of the targets of emotional regulation highlighted that its effects can be distinguished in attentional, knowledge and cognition and bodily expression domains (Koole, 2009). Therefore, behaviours previously defined in the research using the still face paradigm were organised by identifying the function of the behaviour, guided both by the target of the process as well as how developmental researchers defined them previously.

These behaviours were identified from research on behavioural observations of infant regulatory behaviours during still-face. This body of research has produced a number of behavioural coding schemes, notably the Infant Self-Regulatory Scheme (Jean & Stack, 2012), and Infant and Caregiver Engagement Phases (Weinberg & Tronick, 1999). Other video coding schemes have adapted existing schemes (Montirosso, Borgatti, et al., 2010; Yaari et al., 2018), or quantified other aspects infant behaviour during the still-face paradigm (Ekas et al., 2013; Planalp & Braungart-Rieker, 2015; Rothbart et al., 1992).

Researchers have widely agreed that gaze aversion, distancing, hand clasping and mouthing behaviours are used for emotional self-regulation, as they display a classic still-face effect, i.e., occurring more during the still-face phase when infants are displaying negative affect. Gaze aversion and has been defined in terms of gaze, the extent of postural movements used to turn away from the caregiver (sideways), and attending to objects in the proximal or distal environment. Infants also purposefully turn away to get away from the caregiver, defined as distancing. Other researchers have also argued that high intensity repetitive movements, such as kicking and banging, are expressions of negative affect, and that infants may be purposefully using them and testing their usefulness, even if they may in fact upregulate negative affect (Ekas et al., 2013).

To capture the whole range of behaviours, no assumption was made on whether they are effective. Instead it is assumed that these behaviours are emotional self-regulatory behaviours in that they were: (1) occurring in the context of emotional distress, and (2) are self-initiated and/or are subjected to modification by top-down cortical activation or inhibitory processes.

Version 1 of the video coding scheme was developed from exploratory viewing of two videos of the behaviours defined in existing coding schemes still-face paradigm, and from feedback from a second experimenter with experience of video coding of infant's behaviour during the still-face paradigm. 40 videos were coded in a pilot before making minor refinements the categories in the final coding scheme (Version 2).

3.3.3. Operational definitions

Five emotional self-regulatory behavioural states were defined in the final coding scheme.

Self-comforting behaviours was adapted from the "self-comforting regulatory" and "self-comforting exploratory behaviours" defined by Jean and Stack (2012). The authors distinguished the two states based on the criteria of whether gaze was on the location of touch. Organising this based on the function of movement and the target system, I have defined self-comforting behaviours as regulatory behaviours acting on the oral or tactile sensory systems. While the ICEP and IRSS both identify two-hands clasp as a self-comforting behaviour, Bigsby and colleagues (1996) identified that this was a midline behaviour that becomes more common with increased motor development. Therefore, this scheme also included foot-bracing, another midline behaviour, although involving the feet instead of the hands.

Self-comforting (SC) behaviours were therefore defined as *"movements where the function of infant's movement is to obtain oral or tactile stimulation; Infants is using own body to provide oral self-stimulation, exploring manipulating objects on self, or touching their own body, for 1s or longer". Examples include mouthing hand or objects, manipulating clothing, clasping hands, bracing feet or touching head.*

Figure 3-3: Examples of self-comforting behaviours

Following from Jean and Stack (2012) definitions, and recognition that infants use objects to direct attention, *object exploration/distraction behaviours* was the second behavioural state defined in the scheme. Jean and Stack considered interaction with objects to be either regulatory or exploratory based respectively, on whether gaze was on the object during the interaction. However, it may be argued that when infants are not gazing at the object, the "regulatory" function of the behaviour is difficult to determine, for example if infant is indeed touching the object to seek tactile stimulation, or is just resting or holding the object with attention elsewhere. Therefore, to be conservative, only object interactive behaviours with an exploration/distraction function characterised by manual manipulation and gaze at object, were defined.

Object exploration/distraction (OBJ) behaviours were therefore defined as *"movements where the function is to provide attentional distraction by exploring the perceptual properties of objects. Infant is reaching towards and/or using fine motor behaviours to move towards and/or manipulate objects not on self, for 1s or longer. Infants' gaze must be directed towards the object."* Examples include playing with chair belt or exploring chair surface.

Figure 3-4: Examples of object exploration/distraction behaviours.

Social interaction/monitor behaviours were defined because of the social nature of the still-face paradigm and in development infants use behaviours, gestures and gaze to solicit and engage in social interaction. Due to the difficulty in defining what is considered social intention, social intention was defined as movements that lead to increased proximity, movement resulting in touch, and gestures/behaviours with clear social meaning in the infants/caregiver's cultural context. In version 2, only arm movements meeting the first two criteria were considered social interactive behaviours, as infants often lean towards the mother to look over the chair during the still-face paradigm.

Social interaction/monitor behaviours (SOC) were defined as *"movements where the function of infant's movement is to engage in or solicit social interaction. Infant is attending to the caregiver's face for 1s or longer, or using gestures or motor behaviours containing social interactive intention. Social interactive intention is defined as (a) infant-initiated arm movements, such as reaching, which must result in increased proximity or touch of any part of the caregiver, and (b) gestures or behaviours with social meaning."* Examples include reaching towards caregiver, clapping, pointing.

Figure 3-5: Examples of social interaction/monitor behaviours

Social interaction/monitor

Repetitive movement is recognised in the coding of still-face behaviours but is usually considered a form of emotional expression, such as during negative engagement states defined by the ICEP (e.g. *fussing)*. Yet they can occur during both positive and negative arousal. Repetitive motor behaviours are highly common over the course of development, and are meaningful to investigate especially because repetitive motor behaviours are highly common in neurodevelopmental conditions where they appear to have a motor stimulatory function when individuals are experiencing positive or negative affect. The definition for repetitive motor behaviours was based on "repetitive movement episodes" used in an earlier coding scheme (Purpura et al., 2017). In this scheme, the time criteria was expanded to allow repetitive behaviours occurring twice within three seconds to be included. This was to capture repetitive behaviours occurring at a lower frequency, not just high intensity ones repeating within one second based on the definition by Purpura and colleagues (2017). Finger movements, wrist rotations and ankle rotations were not included in the scheme, because they were rare and where present, they tend to occur continuously and it is difficult to define when the episode starts or ends.

Repetitive movements (RME) were defined as "movements where the function of infant's movement is to provide motor self-stimulation. Infant is using repetitive movements of the torso, arms or legs, defined by an identical pattern of flexion, extension, rotation, abduction, adduction or elevation in all possible directions, at least two times consecutively within a 3 second or smaller window". Examples: banging, leg kicking, body rocking, arm waving, clapping (clapping is assigned two behavioural functions)

Figure 3-6: Examples of repetitive movements. Left: infant is kicking both legs; Right: infant is banging the chair with their right arm

Repetitive movements

Distancing behaviours have been defined by Weinberg and Tronick (1999) in the ICEP scheme, and included in this scheme. Distancing (DIST) behaviours were *"movements where the function of infant's movement is to increase their physical distance from the caregiver. Infant is trying to escape or get away from the caregiver by twisting, turning away from the caregiver, without engaging an object, for 1s or longer"*.

Despite the aim of this scheme to be as comprehensive as possible, it is not possible to characterise every kind of movement. Therefore, *other spontaneous movement or no movement* was the final behavioural state defined, where the emotion regulation function/intention is not apparent from the scheme's definition. In version 2 of the scheme, no movement was not differentiated as infants show movements, however slight, most of the time. This state was redefined as Other or no apparent emotional regulation behaviours (MOV), where "*the function of infant's movement for emotion regulation is not apparent. Infant is not moving or is engaging in motor activity that cannot be described by other emotion regulatory function"*.

Concurrent behaviours. Infants show highly complex movements, and behaviours may overlap in time. In this scheme, behaviours that are concurrent in time were coded as a concurrent behavioural state.

There appears to be a general consensus that infant's behaviour during emotion regulation can be characterised along three dimensions: gaze, affect and self-regulation. Some coding schemes analysed behaviour that combines two dimensions (eg., gaze and affect characterises states defined in the ICEP) and along each of the three dimensions separately. Here, gaze was considered a motor behaviour used to redirect or seek perceptual input, this scheme combines the dimensions of gaze and self-regulation. Yaari and colleagues (2018) attempted to code gaze on a 9-point scale based on the amount of sideways head and torso movements directed away from the caregiver. The authors eventually reduced this scale to a binary measure of gaze aversion whether gaze was on or away from mother. Due to these challenges in capturing the different postural extents of gaze aversion, only gaze aversion via engaging an object was coded in the first version of the coding scheme because this is a developmentally relevant skill. In version 2 of the scheme, the decision was made to include sustaining gaze at caregiver's face in the scheme, as part of the social interactive/monitor state, in line with Yaari and colleague's (2018) measure of gaze at mother or away.

In version 2, a one second time criterion was also included in some of the definitions, to exclude behaviours that were brief or accidental and unlikely to have an emotional regulatory function. Behaviours with social interactive intent were excluded from the time criterion because proximity-seeking reaching movements may end within one second.

3.3.4. Interrater reliability

Inter-rater reliability was computed from approximately 10% of the videos included in the final analysis sample. This resulted in a sample of 11 infants with data from both still-face phases (for an analytic sample of 113 infants). Of these infants, 5 infants also had data on play and reunion phases (coded during the pilot phase or coded for Study 3) and were included for analysing reliability scores.

Two measures of interrater reliability were used. Firstly, percentage agreement, defined as the percentage of the 120s period where both coder's rating matched within 1 second in either direction, provides a reliability measure pertinent to timeseries analysis of the resulting behavioural timeseries. Secondly, Cohen's kappa statistic, provides a reliability measure that accounts for the base rate of occurrences of different types of behaviours. Cohen's kappa ranges from -1 to +1 where values below 0 indicates worse than expected agreement, 0 indicates no agreement and a maximum of 1 indicates perfect agreement. Cohen's kappa may also be interpreted as the proportion of "correct" data and the proportion of "errors", with a value of at least 0.60 proposed to indicate adequate agreement (McHugh, 2012). Both measures were calculated for each phase segment and then averaged across all segments.

Coding of behaviours concurrent in time meant that two coders may not agree on the occurrence of both behaviours in each one second period. This would skew the reliability scores, even if the coders agreed on one, but not additional behaviours occurring in the period. As such, partial agreement was defined as agreement within 1-second in either direction on at least one behavioural state.

A second coder was trained by coding two training sets comprising data equivalent to two videos. Instead of coding the full video from 2 infants, phase segments from 5 infants were selected, so that the full range of behaviours can be observed during training. The first training set was used to allow the second coder to familiarise with the video coding scheme by observing examples of each behaviour state coded by the first "master" coder (two segments); and for coding the segments together (three segments). The second coder then coded the second training set independently. Percent agreement and Cohen's kappa were calculated for the resulting codes from the second training set, and the second coder proceeded with coding the 10% subset of video only if at least 90% agreement and 70% Cohen's kappa was achieved, if not a third training set would be selected. 91% agreement was and 0.88 Cohen's Kappa was obtained from the second training set.

Results

The coding scheme had a reliability score of 91.6% agreement and 0.89 mean Kappa for the still-face phase, meeting the requirement for adequate agreement. In Table 3-1, these results are further broken down into caregiver-present (play and reunion phases) and caregiver-absent (still-face phases). The reliability scores for partial and complete agreement are also provided. In caregiver-present phases, concurrent behaviours, particularly behaviours occurring together with social attention, were more prevalent. As expected, complete agreement affected caregiver-present phases more than caregiver-absent phases. However, Kappa scores for complete agreement also showed adequate agreement.

Table 3-1. Interrater reliability of the Function of Movement and Behaviour video coding scheme – percentage agreement and Cohen's kappa

	Partial agreement	Complete agreement

	Mean % agreement	Mean kappa	Mean % agreement	Mean kappa
SF1, SF2 (N=11, 22 phases)	92.39	0.89	78.48	0.70
P, R1, R2 (N=5, 15)	90.50	0.87	69.78	0.61
SF paradigm (N=5, 25 phases)	91.00	0.88	72.37	0.63
All coded videos (N=11, 37 phases)	91.62	0.89	74.95	0.66

4. Developmental Differences in the Prospective Organisation of Goal-Directed Movement Between Children with Autism and Typically Developing Children: A Smart Tablet Serious Game Study

4.1. Abstract

Movement is prospective. It structures self-generated engagement with objects and social partners and is fundamental to children's learning and development. In autistic children, previous reports of differences in movement kinematics compared to neurotypical peers suggest its prospective organisation might be disrupted. Here, we employed a smart tablet serious game paradigm to assess differences in the feedforward and feedback mechanisms of prospective action organisation, between autistic and neurotypical preschool children. We analysed 3926 goal-directed finger movements made during smart-tablet ecological gameplay, from 28 children with Childhood Autism (ICD-10; ASD) and 43 neurotypical children (TD), aged 3-6 years old. Using linear and generalised linear mixed-effect models, we found the ASD group executed movements with longer Movement Time (MT) and Time to Peak Velocity (TTPV), lower Peak Velocity (PV), with peak velocity less likely to occur in the first movement unit, and with a greater number of Movement Units After Peak Velocity (MU-APV). Interestingly, compared to the TD group, the ASD group showed smaller increases in PV, TTPV and MT with an increase in Age (ASD x Age interaction), together with a smaller reduction in MU-APV and an increase in MU-APV at shorter target distances (ASD x Dist interaction). Our results are the first to highlight different developmental trends in anticipatory feedforward and compensatory feedback mechanisms of control, contributing to differences in movement kinematics observed between autistic and neurotypical children. These findings point to differences in integration of prospective

perceptuomotor information, with implications for embodied cognition and learning from self-generated action in autism.

4.2. Introduction

Children move to engage the world of people and objects, and to learn from those experiences (Delafield-Butt, 2018; Reed, 1996; Colwyn Trevarthen & Delafield-Butt, JonathanDelafield-Butt, 2017). They test the world with action and learn its responses (Baldwin, 1895; Piaget 1953). From the infant's first simple movements (banging, sucking, smiling) to the serially organised complex projects of young children (grasping, stacking, climbing, playing), self-generated movement forms the bedrock of psychological experience on which learning, cognition, and social understanding develops (A. Clark, 1999; Delafield-Butt, 2018; Koziol et al., 2012; Pezzulo et al., 2008; Pezzulo & Castelfranchi, 2009; Colwyn Trevarthen & Delafield-Butt, JonathanDelafield-Butt, 2017; M. Wilson, 2002).

Efficient prospective control of actions is crucial to the structure of sensorimotor experiences. Each must be guided with an anticipation of its future effect (Bernstein, 1976) as it moves experience from 'where one is' to 'where one wants to be' as they bring the person usefully forward in time (von Hofsten, 1993, 2007). Movement, and the motor system on which it depends, enables development of a 'sensorimotor intelligence' that underpins all experience, learning and social interactions (Delafield-Butt & Trevarthen, 2015; Piaget, 1952, 1954). This early, self-generated learning is evident in the fine detail of movement from birth (Delafield-Butt & Gangopadhyay, 2013), and high-precision analysis of its particular motor form can indicate developmental risk . Disruption to movement in early childhood can thwart learning. Early childhood motor delays or difficulties are predictive of later socio-communicative difficulties (MacDonald et al., 2014) and can be the first sign of neurodevelopmental disorder (Gillberg, 2010).

Recent evidence of a subtle, but significant motor disruption associated with Autism Spectrum Disorder (ASD) has led to a growing body of research on sensorimotor difficulties and differences in ASD at the kinematic, action and behavioural levels, from impairments in motor coordination (Fournier et al., 2010) and motor planning (Gowen & Hamilton, 2013), to differences in action imitation (J. H. G. Williams et al., 2004) and its affective expression (Casartelli et al., 2020). Movement differences in ASD have implications on how we understand the development of socio-communicative difficulties (Bhat et al., 2011) and making sense of the world in shared engagement with others (Trevarthen & Delafield-Butt, 2013).

In this chapter, I advance a multiple-process model of goal-directed aiming following a comprehensive framework for analysis of goal-directed movement kinematics (Elliott et al., 2010, 2017). Movement kinematics are directly related to the neuro- and psycho-motor processes underlying movement generation, including perception, planning, feedforward and feedback control (Bootsma et al., 2004; Fitts, 1954; Kawato, 1999; Lee, 2009; MacKenzie et al., 1987; Wolpert et al., 1995; Wolpert & Ghahramani, 2000; Woodworth, 1899).

Kinematics variables describe the movement and reflect its motor plan. For example, 'peak velocity', 'time to peak velocity' and 'peak velocity of the first movement unit' reflects the execution of an efficient food-to-plate movement using feedforward control, and kinematics such as the 'percent time after peak velocity' and the number of movement units reflects the recruitment of feedback control, while overall movement time reflects the speed-accuracy trade-off in generating efficient and accurate goal-directed movements (Elliott et al., 2010, 2017).

Differences between individuals with ASD and neurotypical individuals (TD) at the kinematic level, the most basic level in which movement is organised to achieve goals (Hamilton, 2009; Pezzulo, 2012), may indicate differences in prospective control (Colwyn Trevarthen & Delafield-Butt, 2013), in other words, difference in the processes involved in predicting, anticipating and achieve goals in the near or distant future (von Hofsten, 1993). If the prospective organisation of movement on which embodied experience and learning is predicated (von Hofsten, 2007), then those embodied experience and their learning will also be disrupted (Delafield-Butt and Trevarthen, 2017; Trevarthen and Delafield-Butt, 2013).

Movement kinematics in autism

Compared to neurotypical individuals, atypical movement kinematics have been reported in autism in a variety of tasks, including longer movement times (Campione et al., 2016; Forti et al., 2011; Glazebrook et al., 2006, 2009; Mari et al., 2003; Stoit et al., 2013; Yang et al., 2014) as well as lower peak velocities (Forti et al., 2011; Glazebrook et al., 2006; Mari et al.,

2003) and longer times to peak velocity (Campione et al., 2016; Glazebrook et al., 2006, 2009), all of which point to differences in feedforward control. However, some studies did not find evidence of group differences in movement times (Dowd et al., 2012; Fabbri-Destro et al., 2009; Papadopoulos et al., 2012) or peak velocities (Campione et al., 2016; Dowd et al., 2012; Yang et al., 2014). One study has suggested, to the contrary, that individuals with ASD execute movements with greater peak velocity than neurotypical individuals (Cook et al., 2013). In addition, peak acceleration, also thought to be associated with feedforward control (Elliott et al., 2010), was found to be lower in young adults with ASD compared to neurotypical controls (Glazebrook et al., 2006). However, this kinematic variable has not been widely studied and group differences in peak acceleration were not found in children's reaching movements (Campione et al., 2016) or simple point-to-point movements (Dowd et al., 2012).

Few studies have investigated differences in kinematics related to feedback control and the direction of differences between ASD and TD populations remain unclear. Three studies investigated the relative duration of the deceleration phase, quantified as the percentage of movement time after peak velocity occurred, and did not find differences between ASD and TD groups (Campione et al., 2016; Glazebrook et al., 2006; Rinehart et al., 2006). However, there is some evidence that individuals with ASD may require a greater extent of feedback processing to control movement, as their movements may be jerkier (Cook et al., 2013; Yang et al., 2014) and comprise more movement units (Forti et al., 2011; Yang et al., 2014) compared to controls.

A gap in the literature is in the consideration of developmental changes in movement kinematics. Firstly, differences between ASD and TD populations in how the kinematic organisation of movement develops can obscure group differences, or change the direction of effects observed at different ages. Secondly, in children, movement kinematics are still maturing and can develop significantly across the span of months. Earlier investigations of movement kinematics studied children of different ages, matching groups for age during sampling (Campione et al., 2016; Dowd et al., 2012; Forti et al., 2011; Mari et al., 2003; Rinehart et al., 2006) or including it as a covariate in the analysis (Dowd et al., 2012). However, including a mix of ages in the study design as large as a 5-year range in Dowd and colleagues' (2012) study can introduce substantial within-group variability on top of within-individual movement variability inherent to the motor system and particularly when motor skills are developing. This means that in these earlier studies, differences between ASD and TD groups may have been confounded or obscured in the presence of variability due to age, in their relatively small study samples.

More importantly, developmental changes in the kinematic structure of movement provide insight into the development of goal-directed movements, and differences between ASD and neurotypical populations have yet to be investigated. Like in adults, infant reaches are structured into phases of acceleration and deceleration or "movement units", including a dominant movement unit covering the most distance to the target – the primary transport unit (von Hofsten, 1991). With development, the number of movement units decreases, the peak velocity or primary transport unit occurs earlier and covers an increasing proportion of the target distance (Berthier & Keen, 2006; Konczak et al., 1995, 1997; Newman et al., 2001; von Hofsten, 1991). Reach trajectories become straighter (Berthier & Keen, 2006; von Hofsten, 1991). By the end of 2 years, adult-like movements with a single bell-shaped velocity profile start to be produced predominantly (Berthier & Keen, 2006; Konczak & Dichgans, 1997) but the quality of reaches continue to improve throughout childhood, including reduced variability in reach endpoint (Contreras-Vidal, 2006; King et al., 2012). This body of research, conducted in neurotypical populations, suggest that with development, there is a reduced reliance on later corrective feedback movements, as the initial planning phase becomes more efficient (Deutsch & Newell, 2005), potentially through the development of more accurate motor plans. If this developmental process is altered in ASD, this could indicate that differences in motor planning or execution can have downstream effects on motor control processes recruited for producing efficient goal-directed movement.

In this chapter, I employ a smart tablet serious game to computationally examine preschool children's goal-directed movement to test for differences in feedforward and feedback kinematic parameters. Tablet-based technology has become more widely available as accessible research tools, and used to study movement kinematics in children with ASD (Dowd et al., 2012; Papadopoulos et al., 2012; Rinehart et al., 2006), but the developmental significance of the movements studied using these tools is often overlooked. Specifically, movements made on a tablet surface are usually part of a two-step movement: first to bring the finger or pen to the tablet surface, before making the desired movement within the tablet environment. Research using new technology and smart-tablet technology in particular should consider that devices do not just provide a virtual environment within their workspace, but are also objects situated in the real-world environment.

Current study

In summary, recent theoretical advances from an embodied cognition framework highlight the role of early sensorimotor differences in the development of socio-cognitive differences between ASD and neurotypical individuals. Movement kinematics provide a window into the processes involved in the control of movement and differences at this level have been reported in ASD compared to neurotypical individuals. Differences in developmental trends indicate if motor control processes are recruited to different extents with development, and may obscure group differences in earlier studies. Smart-tablet technology has provided easy access to the recording of movement kinematics, but to date little consideration has been given to the developmental significance of such movements.

In this study, kinematic analysis was conducted on goal-directed movements made by 3- to 6-year-old children during smart-tablet gameplay, involving moving food pieces within a start area onto plates within an end area (Anzulewicz et al., 2016). The food-to-plate movements in this study is considered to be conceptually equivalent to the second step of a two-step movement where the target-distance from food-to-plate modulates the difficulty of the movement, preceded by a movement to bring the finger onto the food area of the touch screen. Two-step actions such as a reach-to-place task have been used to investigate prospective control (Gottwald et al., 2017) and kinematics of the second step were sensitive to changes in task demands, relating to differences in planning and prospective control of the second movement step (Gottwald, 2018).

This study approached the investigation of differences between ASD and TD groups in the kinematic organisation of movement in two steps. First, I explored the validity of kinematic variables proposed in the multiple process model, as indicators of feedforward and feedback control in the context of smart-tablet gameplay. Peak velocity (PV), peak velocity of the first movement unit (PV1), and time to peak velocity (TTPV) were selected *a priori* as kinematic variables related to feedforward control; movement units (MU), percent time after peak velocity (i.e., the deceleration phase, %Dec) related to feedback control; and movement time (MT) related to both feedforward and feedback control. Movement units after peak velocity

(MU-APV) and a binary variable, whether peak velocity was found in the first movement unit (PV1-b), were further explored as potential indicators of feedback and feedforward control respectively. Next, I investigated the relationship between ASD diagnosis, target distance and age on selected movement kinematic variables. I hypothesised that (1) children with ASD will differ from children in the control group in the extent of both feedforward and feedback control (Effect of ASD); (2) in how kinematics relating to the feedforward and feedback processes develop with age (Interaction effect of ASD x Age); and (3) how they alter kinematics in relation to target distance, an indicator of goal difficulty (Interaction effect of ASD x Dist).

4.3. Methods

Sample

Data from Anzulewicz and colleagues (2016) on finger movements during smart-tablet (Apple Inc., iPad mini, iOS version 7.0) gameplay of the "Sharing" game was analysed. The dataset consists of 82 children aged between 3-6 years old, including 37 children had a clinical diagnosis of ICD-10 Childhood Autism (ASD) and 45 typically developing (TD) children, recruited from specialist therapeutic centres in Krakow, Poland. The "Sharing" game involved moving food pieces presented in a central area towards one of four plates in the game scene. Participants were given two minutes of practice to familiarise with the task before five minutes of data collection during gameplay. Further description of the sample can be found in the report by Anzulewicz and colleagues (2016). This study conforms to the ethical principles set out in the Declaration of Helsinki and was approved by the University of Strathclyde Ethics Committee. Informed consent for children's participation in the study were provided by their parents. Data had been anonymised prior to access by the first author for the present investigation. Apart from participant age, no other personal information was linked to the touchscreen movement data.

Goal-directed finger swipes were included for analysis in this study. Unlike paradigms on point-to-point movements, the "Sharing" game did not have specific start and end-points; therefore goal-directed swipes were defined as swipes beginning in the food area and ending in the target area (food-to-plate swipes, see Figure 4-1). I excluded swipes not suitable for kinematic analysis: swipes made with multiple touches (where more than one gesture was registered at the same time) were excluded, as a unique swipe path could not be distinguished; and swipes consisting of less than 5 data points were excluded to permit velocity derivatives using a five-point stencil (see Procedure).

To increase the validity of the analysis to goal-directed swipes, I further restricted the analysis to swipes likely to be performed according to the task-demands. I excluded: firstly, food-to-plate swipes from participants who made at least 10% of food-to-plate swipes out of the total swipes made during gameplay; secondly outliers of food-to-plate swipes based on movement time (>2.0s) and target distance (>70mm) as these are unlikely to be swipes aimed at reaching a single goal location efficiently; finally, swipes with a straightness index (ratio of distance moved to target distance) greater than 1.5. This criteria for straightness index was selected as it excluded most of the outliers, based on visual-inspection of a box-plot and was guided by reports that straightness ratio of reaching movements decrease to about 1.4 by 3 years of age (Berthier & Keen, 2006).

Figure 4-1: "Sharing" game showing food-to-plate swipes from 1 participant. Participants made swipes from food presented in different locations within the food area, to locations within the end area. Participants predominantly ended their movement in the plate areas, but the game mechanics regarded a "successful" swipe as one that moved the food to a plate or to the location of any cartoon characters. This figure shows examples of the successful food-to-plate swipes (red) and unsuccessful swipes (blue) excluded from the analysis in this study.

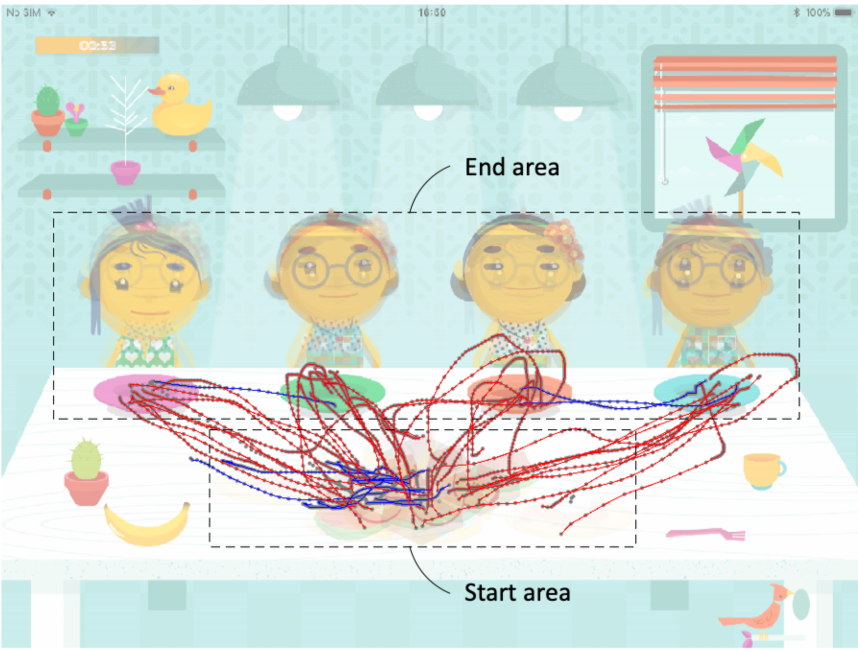
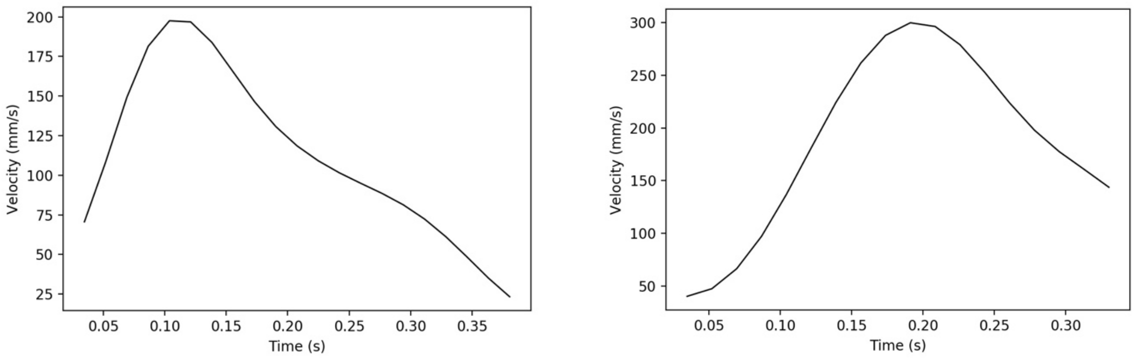
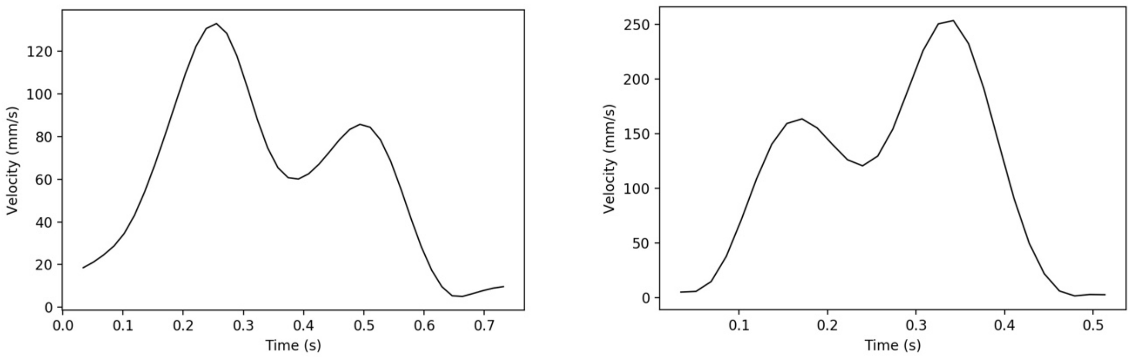


Figure 4-2: Representative swipe profiles. Each participant may execute a mix of these profiles, and although relatively few, may execute swipes with more than 3 movement units

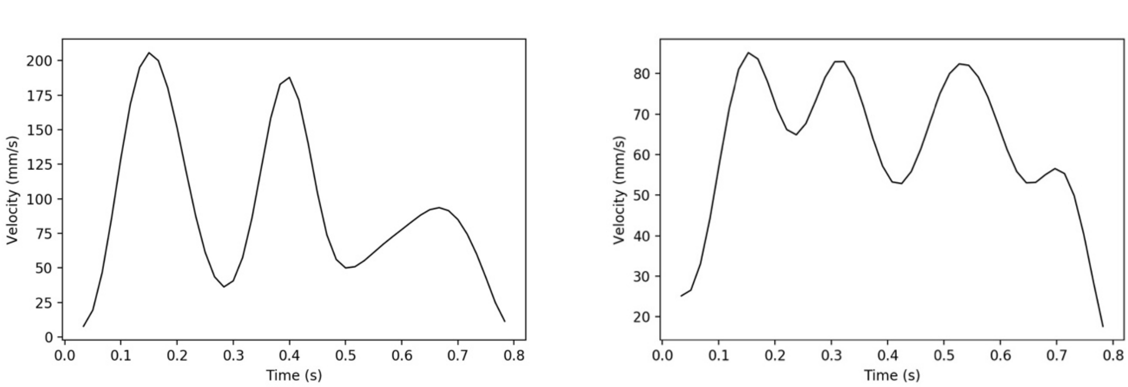
a) 1 Movement Unit (ASD50 swipe13, TD43 swipe16)



b) 2 Movement Units (ASD57 swipe44, TD79 swipe85)



c) 3 Movement Units (ASD13, swipe78, TD67 swipe21 - Last movement unit did not meet criteria for an acceleration and deceleration phase each resulting in a velocity change ≥8mm/s and therefore merged with adjacent movement unit)



Kinematic variables (a priori)

Movement Time (MT) was defined as the time from touch begun to touch end.

Movement units (MU) was a count variable defined as a velocity maximum comprising an acceleration and deceleration phase cumulatively resulting in a velocity change of 8mm/s or more. Velocity maxima were included only if they were greater than 5% of peak velocity. Swipes were visually inspected to ascertain that this criterion excluded small changes in velocity in the count of movement units (Achermann et al., 2020; von Hofsten, 1991). The start of the first movement unit was defined as the acceleration phase where velocity increases from the first velocity minimum or from the time touch was detected, to a velocity maximum. The end of the last movement unit was defined as the deceleration phase, where velocity decreases from a velocity maximum to the last velocity minimum, or the touch was detected to end.

Peak Velocity (PV) was the value of the greatest magnitude of velocity resulting from the movement.

Peak Velocity of the first movement unit (PV1) was the value of the maximum velocity of the first movement unit.

Time to Peak Velocity (TTPV) was the time from touch begun to the time PV was reached.

Deceleration Phase (%Dec) was the ratio of time after PV to movement end, expressed as a percentage.

Kinematic variables (exploratory analyses)

Movement units after peak velocity (MU-APV) was the number of movement units occurring after PV

Peak velocity of the first movement unit (PV1-b) was a binary variable, whether PV1 was found in the first movement unit

Predictors

ASD diagnosis (ASD), defined as clinical diagnosis of ICD-10 Childhood Autism, and participant age (Age), measured in months, were included as predictors of kinematic variable at the cluster level.

Target distance (Dist), defined as the displacement between the start and end position of the swipe, was included as a predictor of the kinematic variable at the swipe level. This was an ordered categorical variable in 10mm intervals.

Data preprocessing

Data consisting of timestamps and positional coordinates recorded in Apple Developer's UITouch object was pre-processed in Python 3.7. Movement start was defined as the time when a touch was detected (UITouch=0). Movement end was defined as the time an ongoing touch was detected to end (UITouch=3). Invalidly recorded swipes, without a touch detected, moved (UITouch=1), and end structure, were excluded from analysis.

Movement x- and y- position vectors were filtered using a fourth order, zero-phase shift, 8hz low pass Butterworth filter. 4-8 Hz frequency filters are commonly used in human movement analysis (Bartlett, 2007) and an 8 Hz filter was chosen based on comparison of 100 randomly chosen position vectors filtered at 4, 6 and 8 Hz. Filtering at 8hz had minimal or no perceptible distortion of signals, and reducing the frequency further to 6Hz and 4Hz led to perceptible and increasing distortion of coordinate profiles. After filtering x and y position vectors, x and y velocity vectors were obtained through numerical differentiation using the five-point stencil (Abramowitz & Stegun, 1964). This method allows more accurate derivatives as noise in data can be amplified as a result of finite differentiation, and has been applied to finger movement position data (Rachaveti et al., 2018).

Finally, velocity magnitude was calculated as the vector sum of x- and y- velocity vectors and kinematic outcome variables were calculated for each swipe according to the definitions described.

Data analysis

Data analysis was conducted in R (version 3.6) and RStudio (version 1.2). Mixed effect models were fitted using the lme4 (D. Bates et al., 2015) and glmmTMB packages (Brooks et al., 2017).

A chi squared test was conducted to test if there was a difference in the number of swipes excluded from TD and ASD participants. Descriptive statistics (mean, standard deviation and range) was obtained for participant age cross-tabulated by ASD and TD groups, at the subject level. Number of swipes made for each category of Dist, was cross-tabulated by TD and ASD participants. Group differences in means and standard deviations of participant age was tested using a T-test, and group differences in median Dist category was tested using a Mann-Whitney test. The distribution of each swipe kinematic outcome by ASD diagnosis was inspected using violin plots for continuous or count variables, and a barplot for the binary variable PV1-b.

To account for the nesting of swipe data by individual, linear and generalised linear mixed models were fitted for each swipe kinematic outcome with Dist centred to the median category (30-40mm), and Age was scaled to years and mean-centred (4.7 years). Linear regression models were fitted for five outcome variables: PV1, %Dec; and log-transformed variables MT, TTPV and PV. General Linear regression models (Zero-truncated Poisson log-link models) were fitted for MU. As exploratory analyses, following model diagnostics for the a priori kinematic variables, we fitted generalised linear mixed models for kinematic variables PV1-b (Logistic regression) and MU-APV (Poisson log-link regression). Finally, I computed pairwise correlations between all the kinematic outcomes considered in the study to strengthen the interpretation of the movement kinematic as indicators of feedforward and feedback control.

Model building and diagnostics

The procedure recommended by Zuur and colleagues (2009) was followed. I considered random intercepts to account for the non-independence in swipes made by the same subject as part of our experimental design, but additionally included random slopes for all kinematic variables as improved the models (Supplemental Table 4). For multivariate conditional models, ASD, Dist and Age were included as hypothesised fixed effects, but interaction effects were only included in the final model if they improved the model, to be able to estimate relevant parameters more accurately and precisely to answer the experimental questions. As part of experimental hypotheses, we tested for the effect of ASD x Dist and ASD x Age. An interaction effect of Dist x Age was also considered, to control for Age effects on the slope of Dist. No interaction effect of Dist x Age was found for all models except for PV1 (Supplemental Table 5).

A top-down model building approach was used, first fitting the full model with all random intercepts, random slopes and fixed effects (including interaction effects) (Model Re1). In Step 2, using the full model, I determined if a random slope should be included, both fitted using the REML estimator (Model Re2). A random slope was included if AIC criteria was lower in Model Re1. In Step 3, using the random effects structure optimised in Step 2, the fixed effects structure was optimised by fitting models using the Full Information Maximum Likelihood estimator with an interaction effect removed at each step and nested models compared using a likelihood ratio test (Models Fe1-4). Inclusion of interaction effects was guided by effect estimates and likelihood ratio tests. Models fitted in the model building procedure (Re1-2, Fe1-4) are reported in the Supplemental Tables 4 and 5.

Finally, parameter estimates with 95% confidence intervals and p values were obtained by fitting the final model using the REML estimator for Linear Models and ML estimator for General Linear Models and applying Type III ANOVA Satterthwaite and Wald's approximation to degrees of freedom for Linear and General Linear Models respectively.

Models were tested for residual normality, homogeneity of variance and linearity, by examining residual q-q plots, scatter of residuals against fitted values, and scatter of residuals against observed values, respectively. MU was visually inspected to follow a Poisson distribution and the final model was checked for overdispersion. Due to non-normally distributed residuals obtained from modelling the raw outcome variable, and positively skewed outcome distributions (Figure 4-4), PV, TTPV and MT were log-transformed and re-fitted using the same model building procedure.

Exploratory kinematic variables

Movement units after peak velocity (MU-APV). As fixed effects explained only 1% of the variance in %Dec, we sought to identify another kinematic variable indicative of feedback processing, that was less susceptible to variability in whether the peak velocity occurred in the first movement unit. I derived a count variable, movement units after peak velocity (MU-APV)

Peak velocity of the first movement unit (PV1-b). Due to heteroscedasticity in residual variance found in the model fit for PV1 and because the swipe movement profile varied in whether the largest peak in velocity occurred in the first movement unit (Figure 4-2), I derived a binary variable indicating whether peak velocity was found in the first movement unit (PV1-b).

Sensitivity analyses

I reran the final models (for MT, TTPV, PV, PV1-b and MU-APV only) on a stricter dataset, which further excluded swipes that did not meet the criteria of <5mm distance covered before first minima and <5mm distance covered after last minima, if applicable. This was to exclude: (1) movements that decelerate over a significant proportion of the target distance upon contacting the touchscreen surface before making the food-plate swipe, which would invalidate the Dist category; and (2) movements resulting from a strategy to slowly reduce the distance to the goal, before quickly accelerating towards goal while lifting the finger off the touchscreen surface, which do not have the same kinematic form as accurate goal-directed movements even if they achieved the task-demand in the context of smart-tablet gameplay.

Data availability

Derived and analysed kinematic data, Python scripts used to generate kinematic data from raw touchscreen data, and R scripts used to generate kinematic data analysis are available on https://osf.io/xjdf8/.

4.4. Results

Analysis sample

A total of 4917 food-to-plate swipes were made by 82 participants. Among these, 159 (3.2%) swipes were not suitable for the present analysis as they resulted from 'multiple touch' where more than one swipe was registered at the same time (n=118, 2.4%), containing less than 5 data points (n=7, 0.1%), or resulted in swipe distances shorter than the shortest food-plate distance (n=34, 0.7%). After exclusion, 3926 swipes from 71 participants (43 TD, 28 ASD), formed our sample of goal-directed food-to-plate swipes. 2593 swipes (66.0%) were made by TD participants and 1333 swipes (34.0%) were made by ASD participants. ASD diagnosis did not influence whether swipes were more likely to be excluded (χ^2 (1) = 0.385, p value = 0.535). See Supplemental Table 1 for a breakdown of the excluded swipes.

The mean number of goal-directed swipes made per individual was 66 swipes, and on average this was 20 swipes greater for TD participants (73 swipes) than ASD participants (55 swipes) (T(69)=2.99, p=0.004).

Participants' age ranged from 2.8 years to 6.6 years, with a mean of 4.7 years (s.d = 0.905). Means and variance of age were not different between ASD and TD groups (T(69) = -0.184, p = 0.855; F(42,27)=1.10, p=0.801). Swipes made by TD participants and ASD participants had displacement ranging from 13.5 mm to 70.0 mm, leading to 6 ordered categories of 10mm intervals from 11 mm to 70 mm. Proportions in respective categories of Dist were marginally significantly different between TD and ASD groups (χ^2 (5) = 11.2, p =0.047). Proportionally, ASD participants performed marginally more swipes in the 30-40mm category and marginally less swipes in the 10-20mm and 20-30mm category. The median Dist was 30-40mm. See Table 4-1 and Figure 4-3 for details.

Table 4-1-a. Swipes excluded and analysed

Food-to-plate swipes	Total (N=4917)	TD (N=3233)	ASD (N=1684)	p value
Swipes excluded	991 (20.2%)	640 (19.8%)	351 (20.8%)	0.406
Analysis sample	3926 (79.8%)	2593 (80.2%)	1333 (79.2%)	

Table 4-1-b. Analytic sample: Participant age and swipes per individual, by ASD diagnosis

Participants	Total (N=71)	TD (N=43)	ASD (N=28)	p value
Sex				
Male, N(%)	47 (66.2%)	30 (69.8%)	17 (60.7%)	0.431
Female, N(%)	24 (33.8%)	13 (30.2%)	11 (39.3%)	
Age, years				
mean (sd)	4.7 (0.9)	4.7 (0.9)	4.7 (0.9)	0.855
range	2.8 - 6.6	3.0 - 6.2	2.8 - 6.6	n.a
Swipes per participant				
mean (sd)	66.0 (27.0)	73.3 (25.6)	54.8 (25.4)	0.004
range	11 - 145	18 - 145	11 - 96	n.a

Table 4-1-c. Analytic sample: Characteristics of goal-directed swipes by ASD diagnosis

Swipes	Total n(%)	TD n(%)	ASD n(%)	p value
Total	3926 (100%)	2593 (66.0%)	1333 (34.0%)	n.a
Target distance				
10-20mm	232 (5.9%)	172 (6.6%)	60 (4.5%)	
20-30mm	1207 (30.7%)	808 (31.2%)	399 (29.9%)	
30-40mm	743 (18.9%)	467 (18.0%)	276 (20.7%)	0.0468
40-50mm	851 (21.7%)	552 (21.3%)	299 (22.4%)	
50-60mm	643 (16.4%)	429 (16.5%)	214 (16.1%)	
60-70mm	250 (6.4%)	165 (6.4%)	85 (6.4%)	

Figure 4-3. Violin plot showing distribution of participant age by ASD diagnosis (Black: TD, Red: ASD)

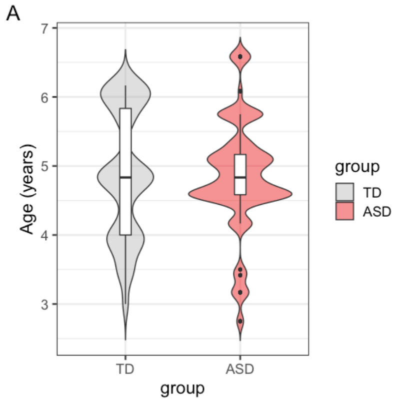


Figure 4-4-a. Descriptive plots of kinematic variables (a priori) across the analytic sample of 3926 swipes. From A-F: Violin plots of MT, PV, TTPV, MU, PV1, %Dec, by ASD diagnosis (Black: TD, Red: ASD)

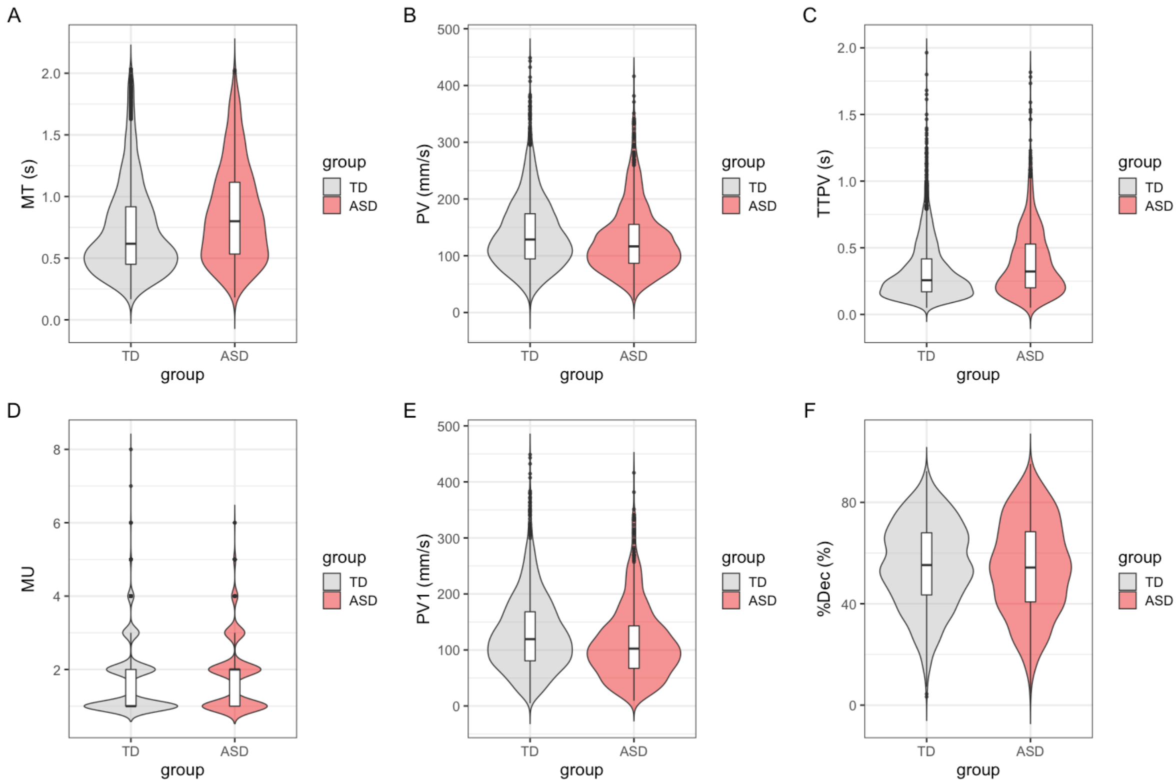
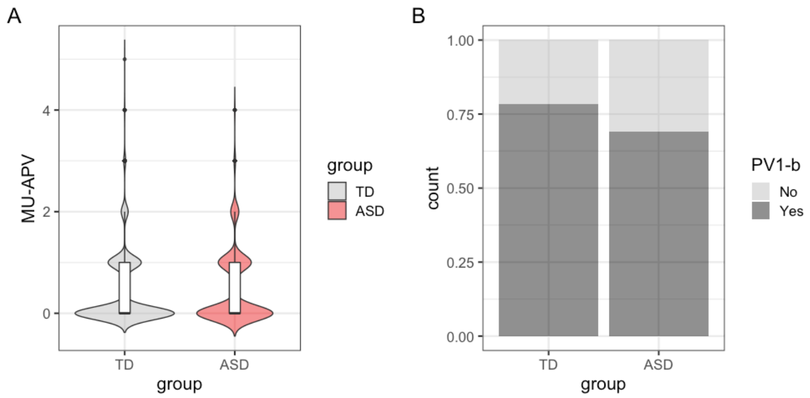


Figure 4-4-b. Descriptive plots of kinematic variables (exploratory) across the analytic sample of 3926 swipes. A: Violin plot of MU-APV by ASD diagnosis (Black: TD, Red: ASD); B: Barplot of PV1-b showing proportions (relative counts) of Peak Velocity occurring in the first movement unit (Yes) or occurring in subsequent movement units (No), for swipes made by each group



Linear and Generalised-Linear Mixed Effect Models

In this section I report on the final linear and generalised-linear mixed effect models for log-transformed variables MT, PV, TTPV, and variables PV1-b and MU-APV (Table 4-2-a, fixed effect; Table 4-2-b, random effects). Assumptions of normality of residuals, homogeneity of variance and linearity were met following log-transformation (Appendix II, Supplemental Figure 1) and MU-APV was not overdispersed (dispersion ratio=0.902). The total variance explained ranged from 26.9 – 73.6%, with fixed effects explaining 12.5 – 35.3% of the total variance (Table 4-2-b). Exponentiated (multiplicative) coefficients are reported for log-transformed variables MT, TTPV, PV, odds ratios (OR) for PV1-b and incidence rate ratios (IRR) for MU-APV (Table 4-2-a). Predicted marginal effects of ASD, Age and Dist, are shown in Figures 4-5 and 4-6.

Models for MU, PV1 and %Dec are reported in Supplemental Table 2.

Table 4-2-a. Final Models. Linear, Logistic and Poisson Mixed Effect Models. Fixed effects with exponentiated coefficients for Movement Time, Peak Velocity, Time to Peak Velocity; odds ratios for Peak Velocity 1MU-b and Incidence Rate Ratios for Movement Units APV. Fixed effects were calculated at the median Dist category (30-40mm) across all swipes and mean age (4.7 years) across all participants.

	MT (s)	PV (mm/s)	TTPV (s)	PV1-b	MU-APV
Fixed effects	*Coefficient (95% CI)*	*Coefficient (95% CI)*	*Coefficient (95% CI)*	*Odds Ratios (95% CI)*	*Incidence Rate Ratios (95% CI)*
Intercept	0.70 *** (0.63 – 0.77)	114.11 *** (105.96 – 122.88)	0.28 *** (0.25 – 0.32)	4.45 *** (3.43 – 5.78)	0.29 *** (0.24 – 0.35)
Dist	1.10 *** (1.09 – 1.12)	1.17 *** (1.15 – 1.18)	1.13 *** (1.11 – 1.15)	0.75 *** (0.70 – 0.81)	1.33 *** (1.26 – 1.41)
Age	0.71 *** (0.64 – 0.79)	1.25 *** (1.16 – 1.35)	0.74 *** (0.65 – 0.83)	1.89 *** (1.52 – 2.35)	0.61 *** (0.51 – 0.72)
ASD	1.13 (0.96 – 1.33)	0.92 (0.82 – 1.03)	1.20 * (1.00 – 1.44)	0.56 ** (0.38 – 0.82)	1.36 * (1.01 – 1.83)
ASD x Age	1.33 ** (1.11 – 1.60)	0.88 (0.77 – 1.00)	1.21 (0.99 – 1.48)	n.a	1.35 * (1.02 – 1.80)
ASD x Dist	n.a	n.a	n.a	n.a	0.91 * (0.84 – 0.99)

* *p<0.05* ** *p<0.01* *** *p<0.001*

Table 4-2-b. Final Models. Linear, Logistic and Poisson Mixed Effect Models. Random effects coefficients for residuals, intercept, slope, and correlation between intercept and slope, marginal/conditional R2; Intra-class correlation, Deviance statistic and AIC criteria.

	MT (s)	PV (mm/s)	TTPV (s)	PV1-b	MU-APV
Random effects	*Estimates*	*Estimates*	*Estimates*	*Estimates*	*Estimates*
σ^2	0.08	0.09	0.21	3.29	1.17
τ_{00} Subject	0.13	0.06	0.14	0.62	0.30
τ_{11} Subject. Dist	0.00	0.00	0.00	0.03	0.01
ρ_{01} Subject	-0.48	-0.32	-0.11	-0.52	-0.86
ICC	0.61	0.41	0.40	0.16	0.20
Marginal R^2 / Conditional R^2	0.296 / 0.729	0.350 / 0.614	0.201 / 0.517	0.123 / 0.263	0.166 / 0.331
Deviance	1544.434	1861.133	5398.459	3946.211	6083.565
AIC	1586.130	1905.410	5438.311	3960.211	6101.565

Effect of Dist, Age and ASD

I found strong evidence of an effect of Dist and Age on all kinematic outcomes (p<0.001). Increase in Dist led to longer MT (OR: 1.10, 95% CI 1.09-1.12), larger PV (OR: 1.17, 95% CI 1.15-1.18) and longer TTPV (OR: 1.13, 95% CI 1.11-1.15). Increase in Dist also led to lower odds of PV1-b (OR: 0.75, 95% CI 0.70-0.81), and greater incidence rate of MU-APV (IRR: 1.33, 95%CI 1.26-1.41). (Table 2). In other words, compared to shorter swipes, there were fewer swipes with peak velocity in the first movement unit amongst longer swipes. Additionally, on average, there were more movement units after peak velocity in longer swipes.

Increase in 1 year of age led to swipes with shorter MT (OR: 0.71, 95% CI 0.64 – 0.79), larger PV (OR: 1.25, 95% CI 1.16-1.35), shorter TTPV (OR: 0.74, 95% CI 0.65 – 0.83), greater odds of PV1-b (OR: 1.89, 95% CI 1.52-2.35), and reduced the incidence rate of MU-APV (IRR: 0.61, 95% CI 0.51 – 0.72).

I found evidence of an effect of ASD for MT, PV, TTPV and MU-APV, along with interaction effects of ASD x Dist and ASD x Age. At the median Dist of 30-40mm and mean age of 4.7 years, ASD participants had longer MT (OR: 1.13, 95% CI: 0.96 – 1.33), TTPV (OR: 1.20, 95% CI 1.00-1.44), lower PV (OR: 0.92, 95% CI 0.82 – 1.03), and greater incidence rate of MU-APV (IRR: 1.36, 95% CI (1.01 – 1.83) compared to TD participants. Compared to the TD group, the ASD group had half the odds of PV1-b (OR: 0.56, 95% CI 0.38-0.82).

Interaction effects

ASD x Dist. I found evidence of an ASD x Dist interaction for MU-APV (IRR: 0.91, 95% CI 0.84-0.99), indicating a smaller effect of ASD at longer Dist and a smaller effect of Dist for the ASD group compared to the TD group.

ASD x Age. I found evidence of ASD x Age interactions for MT, PV and MU-APV, which show that the effect of ASD became larger with an increase in age and the effect of age was smaller for the ASD compared to TD group. Compared to the TD group, the age-attributed reduction in kinematic outcome for the ASD group was smaller for MT (OR: 1.33, 95% CI 1.11 – 1.60), TTPV (OR: 1.21, 95% CI 0.99 – 1.48) and MU-APV (IRR: 1.35, 95% CI 1.02 – 1.80); and age-attributed increase in PV was smaller (OR: 0.88, 95% CI 0.77 – 1.00).

Figure 4-5. Predicted Marginal Effects of Mixed Effect Models. *Top to Bottom:* MT, TTPV, PV. *A, B, C:* Effect of Target Distance by ASD diagnosis at grand mean of age (4.7 years). *D, E, F:* Effect of Age by ASD diagnosis at grand median category of target distance (30-40mm). No effect of ASD x Dist was found (A, B, C) but ASD x Age cross-over interaction effects show diverging trends in these movement kinematics and differing effects of ASD diagnosis (D, E, F).

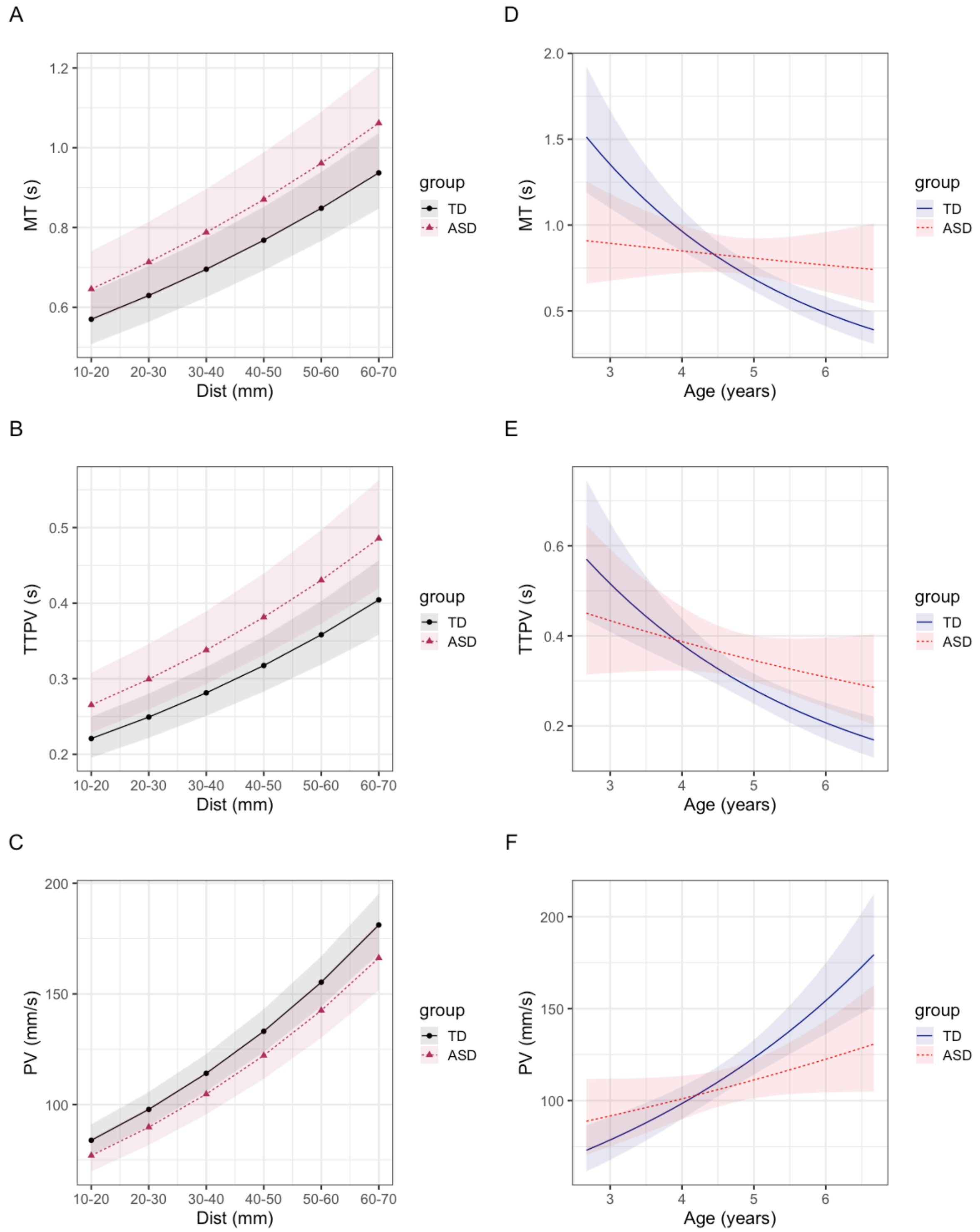
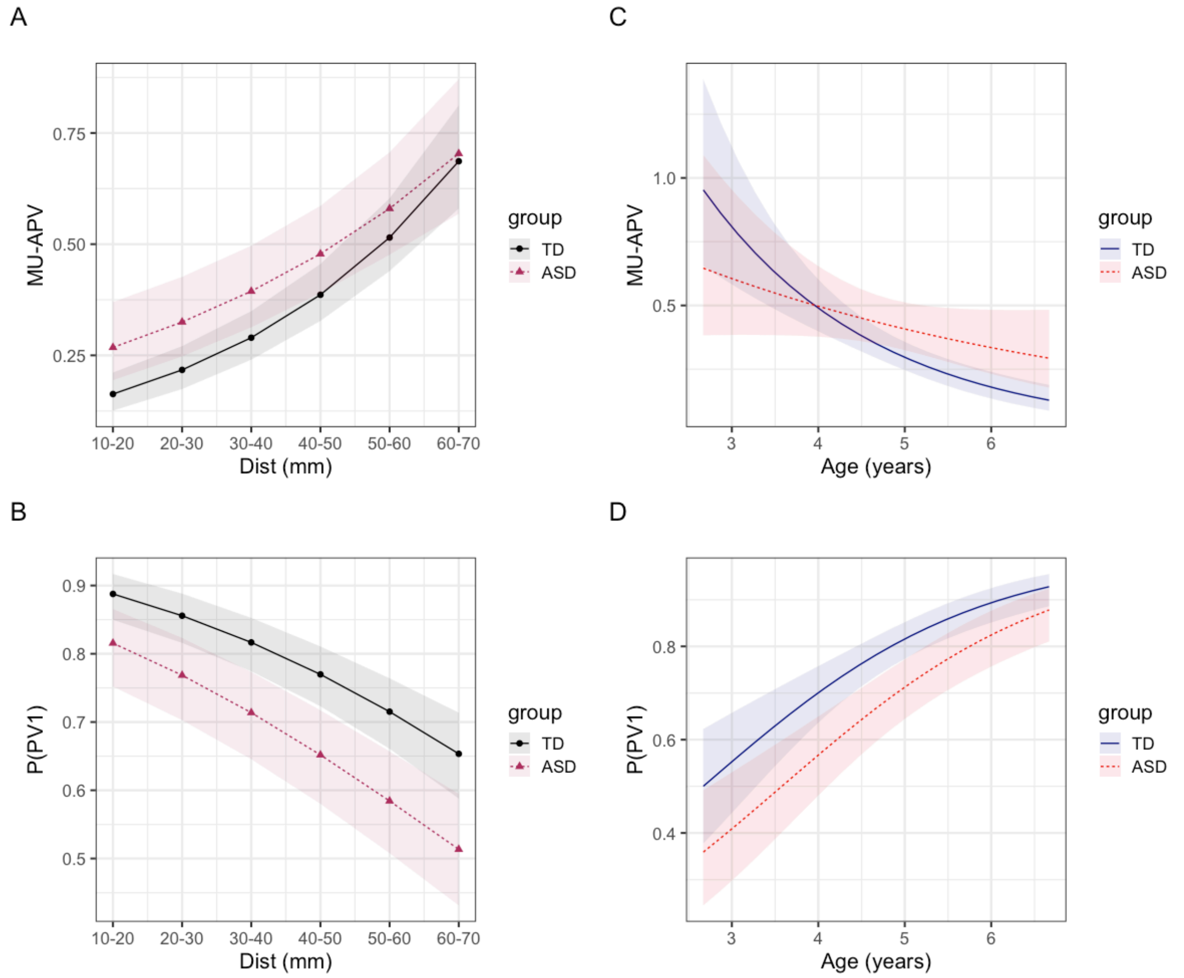


Figure 4-6. Predicted Marginal Effects of Mixed Effect Models. *Top:* MU-APV (Expected value); *Bottom:* PV1-b with predicted probabilities. *Left:* Effect of Target Distance by ASD diagnosis at grand mean of age (4.7 years). *Right:* Effect of Age by ASD diagnosis at grand median category of target distance (30-40mm). The ASD x Dist for MU-APV show that for further targets, the ASD group did not show an increase in number of MU-APV to the same extent as the TD group, while ASD x Age effect shows that the ASD group execute movements with greater MU-APV, but this effect is only seen amongst older children (A, C). No interaction effects were found for PV1-b, indicating that the effect of ASD does not change with Age or Dist (B, D)

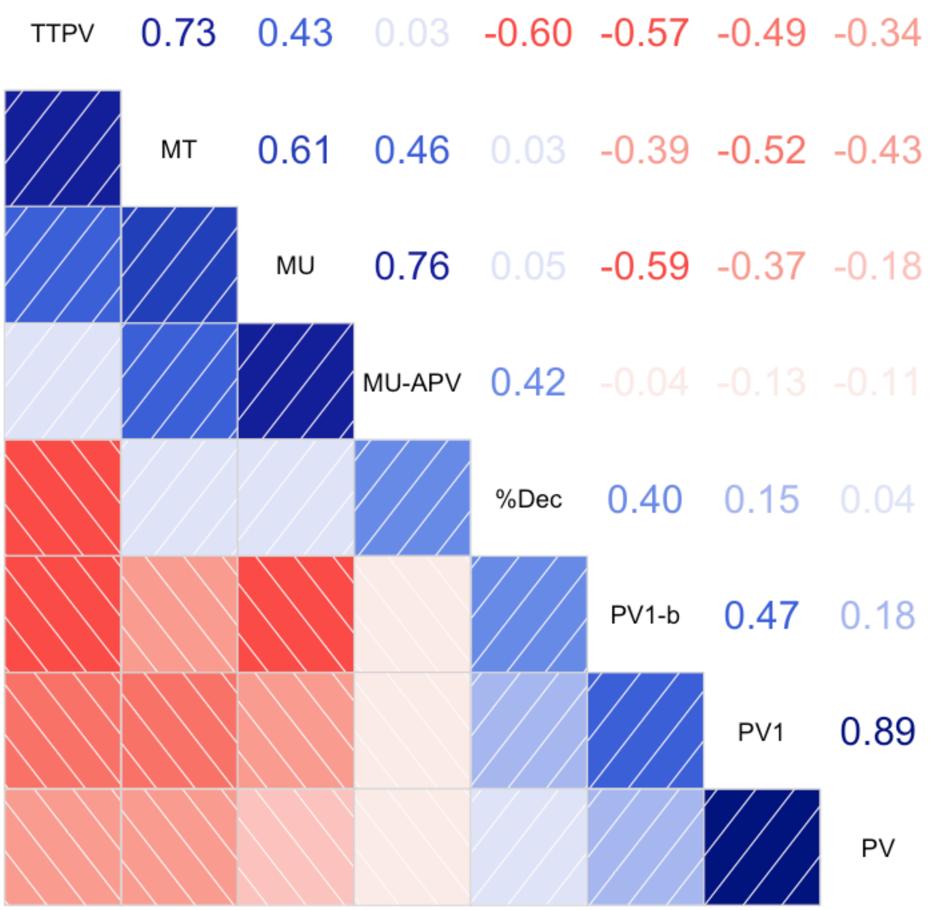


Correlation analysis

PV1 was strongly positively correlated with PV (r= 0.87) and showed the same patterns of correlations: negatively correlated with TTPV, MT and MU, and weak to no correlation with %Dec. MU was more strongly correlated with PV1 (r= -0.40) than PV (r= -0.19). PV1-b was positively correlated with PV1 (r= 0.51) but only weakly correlated with PV (r= 0.19), and otherwise showed the same pattern of correlations with PV1. MU-APV was positively correlated with MU (r= 0.75), %Dec (r= 0.46), and MT (r= 0.51), and showed no correlation with TTPC, PV1 and PV. PV1-b was not correlated with MU-APV. (Figure 4-7)

MU and MT were strongly positive correlated (r= 0.72) and showed the same pattern of correlations with other kinematic variables: positively correlated with TTPV and MU-APV, no correlation with %Dec, and negative correlations with PV and PV1. (Figure 4-7)

Figure 4-7. Correlation matrix for a priori kinematic outcomes TTPV, MT, MU, %Dec, MU-APV, PV1-b, PV1, PV, ordered by Principle Component Analysis. Pairwise Pearson correlations are shown in the right-diagonal panel and direction/strength of correlation in the left-diagonal panel. Blue indicates positive correlations and red indicates negative correlations, and greater saturation indicates stronger correlations.



Sensitivity analysis

A total of 3684 swipes (93.8% of the analysis sample), 2435 (93.9%) and 1249 (93.7%) from ASD and TD group participants respectively, met the stricter criteria for sensitivity analysis. Analysis of this dataset produced comparable coefficient estimates (Supplemental Table 3). The ASD x Age effect reduced slightly for MU-APV (IRR: 1.26, 95% CI 0.94 – 1.69) and increased slightly for PV (OR: 0.82, 95% CI 0.72 – 0.93).

4.5. Discussion

This is the first kinematic analysis of movements made within an ecological, serious game smart device paradigm. This study advances understanding of the kinematics associated with motor planning and adjustment in the final step of a two-step movement to achieve a desired goal. I demonstrate how these can be analysed in the context of ecological touchscreen gameplay to assess both feedforward and feedback control processes computationally. Target distance, which manipulates goal difficulty, was found to influence both early phase (feedforward) and late phase (feedback) kinematic variables.

In line with my hypotheses, I found evidence that (1) children with an ASD diagnosis differed from neurotypical controls in movement kinematics of goal-directed movements, (2) that, with the exception of PV1-b, these group differences become larger amongst older children, and (3) that ASD diagnosis influenced the relationship between target distance and movement kinematics related to feedback control.

Swipe kinematics and motor control processes in smart-tablet gameplay

I selected movement kinematics variables commonly investigated in the literature indicative of feedforward and feedback control (MT, TTPV, PV, PV1, and %Dec), and derived two additional kinematic variables (PV1-b and MU-APV) more suitable for movements in the context of our study's touchscreen gameplay.

Movement kinematics reflect the two-step (1) reach-to-food and (2) food-to-plate movement. The kinematic structure of swipe movements contains a primary transport unit in which peak velocity occurs, the magnitude of which relates to feedforward movement planning to cover the target distance; but whether peak velocity occurred in the first movement unit (and hence resulting in a greater PV1) depended on successful action chaining – i.e., whether the movement plan was available following the initial reach-to-contact to next immediately execute the second food-to-plate movement. Feedback processes act later to produce corrective movements altering the movement plan, appearing in the kinematic profile as movement units after the peak velocity.

%Dec. This kinematic variable is typically used to analyse smooth movements consisting of a single movement peak. The model of %Dec explained only 15.6% of total variance in %Dec, with only 1.2% of the variance explained by the predictors (Supplemental Table 2). This suggests that the model only explained variation between individuals in %Dec and were unable to account for the residual variation – that potentially resulted from random noise at the movement planning, execution, and correction influencing movement time before or after peak velocity, and the movement unit in which peak velocity occurs, and which normalisation by overall movement time did not sufficiently resolve.

PV1-b. The binary variable PV1-b, measuring whether peak velocity was found in the first movement unit, was based on the above reasoning on the kinematic structure of the two-step movement. Correlation patterns indicate good candidate measure of successful action chaining. PV1-b was only weakly correlated with PV suggesting that it is distinct from processes involved in generating the feedforward movement plan.

MU-APV. This variable was a count of the number of movement units after peak velocity, derived to capture feedback control processes, where the movement is set within an action chain of more than one movement step. This variable was positively correlated with %Dec and MT, suggesting that it is related to decelerative processes towards the movement goal that increase overall movement time; it was not correlated with variables associated with feedforward planning and control processes (PV, PV1, PV1-b, TTPV).

Movement kinematic differences between ASD and TD

In the remaining discussion, I refer to the results of the mixed-effect models of MT, PV, TTPV, PV1-b and MU-APV.

In line with the general trend reported in previous work (Campione et al., 2016; Forti et al., 2011; Glazebrook et al., 2006; Mari et al., 2003; Yang et al., 2014), I found longer movement time and time to peak velocity in autistic children compared to neurotypical controls, and also lower peak velocity and fewer movement units in swipes made by autistic children. Further, we found moderate to strong evidence of an interaction effect of ASD with Age that revealed a larger extent of kinematic differences between ASD and TD amongst older children, and moderate evidence of an interaction effect of ASD with Dist.

There are a number of reasons why previous studies reported no group differences, or different findings compared to ours. Firstly, my findings may be specific to autistic children with more severe difficulties, as our sample comprised children presenting at specialist clinics. In contrast, some studies which did not find group differences in peak velocity or movement time included only children with high functioning autism or Asperger's Disorder (Papadopoulos et al., 2012), or specifically excluded individuals with low cognitive functioning (Campione et al., 2016; Yang et al., 2014). This explanation is supported by evidence that group differences in peak velocity between ASD and controls was modulated by level of functioning (Mari et al., 2003), and peak velocity was positively correlated with IQ in both groups (Forti et al., 2011). Secondly, insufficient power could explain why group differences was not found in other studies. Movements, particularly in childhood are characterised by variability (Thelen & Smith, 1994), and our data support this (Figure 4-2). There is high within-individual variability as children do not always perform movements with the same kinematic characteristics. Including a large range of ages in relatively small sample sizes (Dowd et al., 2012), or used a two-step task can introduce further between-individual variability that makes it difficult to detect group differences. In contrast, variability is likely less problematic in studies of young adults, which found group differences (Glazebrook et al., 2006). Thirdly, our study suggests that developmental changes amplifies group differences, as indicated by the ASD x Age interaction in our study. This can explain why there was only a trend towards lower peak velocity in ASD compared to TD children in Forti and colleagues (2011) study of young children age 3-4 years old. Finally, task differences test different movement strategies and may alter group differences. Although Cook and colleagues (2013) found greater peak velocity and shorter movement time in young adults with ASD, this is likely restricted to the context of repetitive unconstrained arm movements they investigated, in contrast to our study and the majority of work on ASD movement kinematics which focused on goal-directed movements.

Modulating control processes with task difficulty. In line with motor control theory, increase in Dist and hence task difficulty leads to an increase in MT and PV, as well as a decrease in TTPV and PV1-b in both groups. Target distance is thought to have little influence on feedback control processes in studies of smooth movements in adults which typically consist of a single movement peak (Bootsma et al., 2004; MacKenzie et al., 1987). I present new evidence that the number of MU-APV in children's goal-directed swipes increases with increase in target distance. One explanation may be that greater target distance increases the opportunity for error and therefore greater use of corrective movements. However, every 1-year increase in age also halves the number of MU-APV in children's goal-directed swipes. This suggests that development of successful feedforward control with age reduces the need to recruit subsequent feedback processes. Further, the ASD x Dist interaction suggests that at smaller target distances, the TD group is able to use predominantly feedforward control and rely less on corrective feedback movements, unlike the ASD group. These group differences disappear at longer target distances as the TD group recruits similar extents of feedback control as the ASD group to overcome the greater task difficulty. Our findings suggest that feedforward control processes are intact in ASD children, but less effective than TD children, thereby resulting in a greater reliance on feedback control.

Developmental differences in movement kinematics. Reduction in MT, TTPV and MU-APV, and increase in PV in TD children is consistent with what is expected with motor development. With development, feedforward processes becomes more efficient and accurate, as represented by increasing dominance of a single, primary transport unit and fewer subsequent feedback phases to correct the trajectory to the target (Berthier & Keen, 2006; von Hofsten, 1991). I also found that with every year increase in age, peak velocity was 1.5-2.3 times more likely to occur in the first movement unit. This indicates that action-chaining becomes more consistent with motor development. Interaction effects show that showed a smaller reduction in MU-APV in the ASD group with increase in age compared to the TD group alongside lower PV, longer TTPV and longer MT. This study supports an explanation proposed previously for why ASD and TD groups have different movement kinematics, that autistic children develop different movement strategies compared to neurotypical controls (Glazebrook et al., 2006; Mari et al., 2003). Research using a computational perspective suggest that reducing the magnitude of PV is an optimal strategy to compensate for noise during motor execution, thereby reducing the error resulting from feedforward control processes (Harris & Wolpert, 1998). An earlier study focusing on variability in feedforward processes also supports the idea that autistic individuals reduce peak velocity to minimise the effects of noise on the ongoing movement (Glazebrook et al., 2006). This study further shows that autistic children with more severe difficulties develop strategies that rely more on feedback processes, i.e., using corrective sub-movements to reach the movement goal while high-functioning autistic children may do the opposite, to avoid the need for feedback processing (Mari et al., 2003).

Sensorimotor integration. The findings of group differences in the developmental trends of feedforward and feedback movement kinematics may be attributed to differences in the development of sensorimotor integration. Integration of vision and proprioception with ongoing movement is important for planning movement as well as to direct the movement towards its goal as the movement unfolds. Proprioceptive functioning improves substantially around age 4-5 years (Chicoine et al., 1992; von Hofsten & Rösblad, 1988) and continues during childhood (King et al., 2010). This can, in turn, contribute to improved integration of visuo-proprioceptive information relating the body to the movement goal to enable more accurate predictive and online control processes (Babinsky et al., 2012). I found that compared to controls, children with ASD showed a smaller increase in peak velocity, as well as a smaller reduction in movement units after peak velocity, which is in line with what we would expect if the development of sensorimotor integration was disrupted in ASD. Indeed, research appears to be converging on a disruption in sensorimotor integration in ASD (Gowen & Hamilton, 2013; Hannant et al., 2016), affecting how multisensory information is used for motor execution and online control (Glazebrook et al., 2009; Schmitz et al., 2003), and motor learning (Haswell et al., 2009; Izawa et al., 2012; Marko et al., 2015; Sharer et al., 2016), together with sensory perception, which influences motor planning and execution (Paton et al., 2012).

Action chaining. In the ASD group, movements were roughly half as likely to contain the primary transport unit as the first movement unit than in the TD group. This supports earlier reports that action chaining is affected in ASD, such that each second action step is more likely to be performed independently of the first (Cattaneo et al., 2007; Fabbri-Destro et al., 2009). This may be because individuals with ASD fail to incorporate the intention of the final motor act within an action chain (Cattaneo et al., 2007; Fabbri-Destro et al., 2009). However, we also found that increase in target distance reduced the action chaining performance of both groups to the same extent, in line with evidence that ASD children were able to modulate grasp height of the first movement step based on the target height (Ansuini et al., 2018). At first glance the latter finding appears to contradict existing explanations that differences in the kinematics of chained actions are due to differences in incorporating the intention of the final motor act. In fact, this finding may indicate more subtle differences in planning processes to achieve movement goals – specifically, that individuals with ASD are able to incorporate (low-level) visuospatial characteristics of the goal successfully in action chaining even if they fail to incorporate other contextual aspects of the final goal.

Given limited research on action chaining in ASD, this explanation highlights an important area for future research. Ansuini and colleagues' (2018) study was the only one which included a task to investigate whether modulation of the first movement step was influenced by the social context, i.e. the partners' intention. However, their task was not sensitive enough to detect modulation of movement in neither the TD nor ASD group. Further research is needed to clarify the extent of disruption in action chaining in ASD, whether the difficulty lies in incorporating contextual and intentional information about the final goal rather than low-level visuospatial aspects. This can also inform whether differences in movement kinematic organisation might have implications beyond the motor domain to affect intentional anticipation and intentional understanding in social contexts, potentially contributing to the socio-cognitive difficulties seen in ASD (Cook, 2016; Colwyn Trevarthen & Delafield-Butt, 2013).

Strengths, limitations and future directions

This is the largest study of movement kinematics in autism, facilitated by assessment using smart devices and ecological gameplay. While ecological gameplay allows for behavioural variability, this was balanced by the ability to acquire a large number of repeated measurements across participants and a range of target distances to enable a high-powered analysis in a mixed-effects regression model. This study embraced the benefits of smart-tablet technology for its ease of large-scale data collection and use outside an experimental environment; however, this is not without compromise, and the findings should be considered in light of its limitations.

Importantly, the "Sharing" game did not have an explicit speed or accuracy requirement: children moved food pieces to within the perceptual boundaries of the plate and the task was considered successful as long as movement ended within the end area. Although these food-to-plate movements still showed a speed-accuracy trade-off indicating that children followed the task demands to make movements efficiently and accurately, we may have underestimated differences between ASD and TD children. This is because children with ASD may still be able to complete the task without being as accurate – in earlier studies, differences between ASD and TD in movement units was greater when the task required greater accuracy (e.g. to smaller targets) (Forti et al., 2011), and in an unconstrained movement task, adults with ASD showed greater movement velocity, but tended to overshoot more (Cook et al., 2013).

Using a commercially developed game also meant that I could not incorporate experimental parameters of interest. Firstly, I derived target distance from the recorded properties of the resulting movement, i.e., the straight-line distance between the point at which a touch began, and the point at which touch ended. However, to account for the possibility that the resultant movement can deviate from the initial movement plan, I increased the validity of our definition of target distance using categories of target distance. Secondly, I was unable to assess endpoint accuracy in our study, which would have helped to evaluate whether the different kinematic strategies between ASD and TD also had different levels of success. This was because children were able to complete the task by finishing the movement within the plate and cartoon character area. This meant that, even though they were likely to be aiming at the clearly demarcated plate boundaries, control errors during the movement were tolerated by the gameplay design.

Our study only used a cross-sectional design to study age trends, but has highlighted the importance of investigating the longitudinal development of movement kinematics in motor development. Finally, while this study was in-part aimed at assessing the suitability of kinematic analysis on movements sampled during smart-tablet gameplay and effects should be considered in light of this exploratory aspect, our study shows the feasibility of sampling goal-directed movements as well as the potential of conducting kinematic analysis in a large dataset, which is easier to acquire in a gameplay context. This approach is particularly suitable for studying movements in young children with ASD as it does not require extensive instructions and can be used outside strict laboratory environments, such as in schools and clinics (Anzulewicz et al., 2016; Millar et al., 2019).

Finally, the motor kinematic, feedforward and feedback difference identified here now need to be placed within context in terms of autism symptomology and psychosocial development. Disruption to efficient prospective movement will affect learning the outcomes of one's own self-generated actions. Its motor structure informs learning and cognition. Future research is required to further map the precise relationship between the detail of prospective motor organisation, autism symptomatology, and psychological development.

4.6. Conclusions

This study demonstrates the use of kinematic analysis on movements sampled on a smart device touchscreen, during ecological serious gameplay. I show differences in the movement kinematics of children with ASD compared to neurotypical controls, of longer movement time and time to peak velocity, lower peak velocity, fewer occurrences of peak velocity in the first movement unit, and greater number of movement units. I further report age-dependent differences in movement kinematic organisation between the two groups, as a result of different developmental trends. From these findings, I conclude that Autism Spectrum Disorder affects the involvement of both predictive feedforward processes and corrective feedback processes to achieve efficient goal-directed movement. These findings suggest that feedforward control processes are intact, but less effective in ASD children than in TD children, resulting in a greater reliance on feedback control. This points to fundamental differences in the underlying neuromotor organisation and integration of perceptuomotor information to anticipate, prepare and enact a self-generated movement to achieve a desired goal, with implications for children's cognitive development, and learning.

5. Differences in behavioural patterns during emotional self-regulation between term and preterm infants

5.1. Introduction

The development of emotional self-regulation is important to understand the socioemotional outcomes of children born preterm

In Chapter 1, I reviewed literature on the socioemotional outcomes of children born preterm. Although the survival of preterm infants has improved dramatically, children born preterm remain at risk of socioemotional difficulties, including 3 to 4-fold greater risk for psychiatric disorders particularly ADHD, autism and anxiety (S. Johnson & Marlow, 2011), and subclinical attentional, social and emotional difficulties related to these conditions. Alterations to socioemotional development due to early life stress and brain injury has been highlighted as a pathway implicating these difficulties (Montagna & Nosarti, 2016).

Emotional self-regulation is the modulation of neurophysiological and behavioural states related to emotional experience and expression (Nigg, 2017). In Chapter 1, I identified self-regulation as a key component of social cognition within a framework of social-emotional competence. In Chapter 2, I emphasised that understanding emotional self-regulation may be especially important for understanding socioemotional outcomes because it is implicated in a range of difficulties (Nancy Eisenberg et al., 2010). I also showed that self-regulation may be seen within a temperamental framework and involving attentional and cognitive processes – specifically the flexible modulation of attention, behavioural activation and inhibitory control. The integration of these processes in the service of regulating emotions have been termed effortful control, as it requires conscious, resource-intensive processes to produce adaptive behaviours in response to emotional stimuli, in the face of automatic, competing, possibly less adaptive behaviours (Mary K. Rothbart & Derryberry, 1981). I showed in Chapter 1 that preterm infants show internalising and externalising behavioural difficulties including behaviours indicative of emotional dysregulation.

This early ability draws on the attentional network as it matures and infants integrate attentional functions served by the parietal cortex to modulate affect and behaviour (M. I. Posner & Petersen, 1990). I showed in Chapter 2 that within the first year of life, infants begin to use goal-directed intentional actions in emotional contexts, enhancing their ability to cope using internal resources, and become less reliant on their caregiver. The early developmental trajectory of emotional self-regulation makes it susceptible to the effects of preterm birth. In Chapter 1 and 2, I showed that preterm infants are at risk of early self-regulatory difficulties related to maintaining alert and calm behavioural state when faced with sensory and emotional stimuli. I showed that there are different ways to measure self-regulation and that these methods have shown that attentional and inhibitory processes crucial for emotional self-regulation may be affected in preterm birth.

Therefore, the rationale for investigating emotional self-regulation in preterm infants are: first, its importance in socioemotional functions; second, its susceptibility to the effects of prematurity as it develops early and third that there is evidence of self-regulatory difficulties and differences in the attentional and inhibitory processes underlying self-regulation in preterm infants.

Gap in understanding of emotional self-regulation in preterm birth

In the past decade, preterm infants' ability to self-regulate emotions have been studied using the still-face paradigm, an established developmental paradigm that elicits distress during a social situation when normal expectations are disrupted. The still-face paradigm is a structured parent-child play interaction involving three main episodes (Tronick et al., 1987). Following an initial "play" episode of normal face-to-face interaction with their child, the caregiver is asked to maintain a neutral expression, look away and stop responding to their child during the "still-face" episode, and then resume normal interactions again in the third "reunion" episode. During the still-face episode, infants tend to show greater levels of negative affect as well as self-regulatory behaviours (Adamson & Frick, 2003).

Compared to term peers, infants born preterm appeared to use fewer self-directed comforting behaviours at 3-4 months (Provenzi et al., 2017; Yaari et al., 2018). However, the opposite has been reported in infants 3-4 months old (Chiodelli et al., 2021) and no difference was observed at around 6-9 months in self-comforting (Atkinson et al., 2021; Jean & Stack, 2012;

Montirosso, Borgatti, et al., 2010) or object exploration behaviours (Jean & Stack, 2012). Additionally, at 3-months, preterm showed fewer social attention-seeking behaviours (Provenzi et al., 2017) and social orientation (Chiodelli et al., 2021), but no difference in attention-seeking behaviours were observed at 5.5-months (Jean & Stack, 2012). By 18-months, preterm infants showed fewer attention-seeking behaviours, although this difference was not significant (Atkinson et al., 2021). No difference in escape behaviours and 5.5 months (Jean & Stack, 2012), but preterm infants showed more distancing behaviours at 6-9 months (Montirosso, Borgatti, et al., 2010). No difference was found in the time spent looking away from the mother from 2-6 months (Hsu & Jeng, 2008; Jean & Stack, 2012; Yaari et al., 2018) or the amount of excessive motor activity (Chiodelli et al., 2021).

The effect of gestational age provides further indication of the impact of prematurity, but this is unclear from existing studies. Relative to those born very preterm (28-31w gestation), infants born extremely preterm (<28w gestation) showed fewer self-comforting behaviours (Yaari et al., 2018) and no difference in gaze aversion. However, a trend in the opposite direction was observed at 6-8 months: infants born extremely preterm showed more self-comforting behaviours, more gestures towards their mother, and lower extent of gaze aversion (Maclean et al., 2009). Gestational age did not affect self-comforting behaviours or escaping behaviours at 3-months, though this was amongst late preterm infants (32-37w gestation) (Fuertes et al., 2022).

Limitations of existing studies

Age-related changes in the development of emotional self-regulatory behaviours (de Weerth et al., 1999) may have affected the identification of group differences. By 3-months, infants are able to self-soothe through thumb sucking and self-touch. With the development of the orienting network and increased awareness of arousal states, infants are able to voluntarily modify arousal using attentional strategies. In line with this, during emotionally arousing experimental situations, term infants use fewer self-comforting strategies with increased age from 3 to 13.5 months (M.K. Rothbart et al., 1992) and from 5.5 – 18 months (Atkinson et al., 2021). Infants also spend more time looking away from the caregiver from 3-4 months, and increasingly use this gaze aversion strategy until at least 7-months (G. A. Moore et al., 2001; M.K. Rothbart et al., 1992; B. Shapiro et al., 1998; Toda & Fogel, 1993). Use of attention distraction techniques appears to decrease after the first year of life (Atkinson et al., 2021). At the same time, infants are gaining new motor skills, and stimulation-seeking motor behaviours such as kicking and banging are observed in from 3-months, potentially increasing til 6 months (Ekas et al., 2013; M.K. Rothbart et al., 1992), but subsequently decline after 10-13 months (M.K. Rothbart et al., 1992). Around 5 months, infants begin to focus less on human faces and more on objects, in line with the development of reaching and grasping skills (Kaye & Fogel, 1980). Intentional communicative behaviours develop at around 9-months in term infants (Bretherton & Bates, 1979; Kopp, 1982). Mother-directed social-seeking behaviours appear to develop from 5 to 12-months and continue to increase to 18-months (Atkinson 2021). MacLean and colleagues (2009) suggests that greater social gestures in preterm birth, which was accompanied by lower gaze aversion, may indicate a lower ability to disengage from the stress-inducing stimulus. However, it has also been suggested that, later in development, social gestures represent a dyadic-strategy for emotion regulation by seeking interaction (Atkinson, 2021). Compared to 5-months, gaze aversion strategies at 12 and 18-months were more likely to be toy-oriented while self-directed behaviours including self-comforting and motor overactivity appeared be lower at older ages (Atkinson, 2021).

Considering the developmental trajectory of emotional self-regulation, existing studies may not provide a complete picture of prematurity-related differences in emotional self-regulation during the still-face paradigm. This is because studies have tended to focus only on a subset of emotion regulation abilities even though infants begin to use an increasingly varied repertoire of strategies (Atkinson 2021). Self-soothing and gaze aversion strategies were the most commonly investigated as they are known to be effective in reducing negative affect. Notably, responses that have been labelled “maladaptive”, particularly motor responses tend to be neglected in the still-face literature (Ekas et al., 2013), analysed only as indicators of negative or positive affect (Chiodelli et al., 2021) or autonomic activity (Feldman, 2009). Yet these responses are useful to examine as they provide a regulatory function (Ekas et al., 2013; M.K. Rothbart et al., 1992) even if they may be less effective in that they upregulate negative affect. Atkinson (2021) analysed motor behaviours, but analysed them together with other self-comforting strategies (labelled “self-directed” comforting behaviours). The differences in developmental trajectories of emotion regulation strategies, and the different functional significance of behaviours highlights the need to examine the whole range of behaviours shown by infants during the still-face paradigm. This is in accordance with early studies of the still-face paradigm suggesting that infants demonstrate a range of coping strategies appropriate to their age and development (Weinberg et al., 2008).

Behavioural dynamics during emotional self-regulation

In the Chapter 3 (Methodology), the methodological framework of dynamic systems theory was highlighted due to the potential insights we can glean into the processes underlying emotional self-regulation, at a systemic level. This conceptualises emotional self-regulatory behaviours, at the macro-level, as the result of coordination by lower level meso- and micro-level interactions that integrates attentional, socio-cognitive, linguistic and motor-behavioural systems.

As an inherently dynamic paradigm, the still-face paradigm is well-suited to probe the dynamic nature of emotional self-regulatory behaviours. While behaviours identified in the still-face paradigm are typically coded on a second-by-second basis, this temporal information is typically removed to analyse the total or percentage of time using these behaviours. Recent advances in dynamic analytic approaches make it timely to address this gap in research using the still-face paradigm. The State Space Grid methodology (Hollenstein, 2013) proceeds by identifying all the behavioural states that the system resides in and then quantifying measures related to stability, variability and complexity. Recurrence Quantification Analysis (RQA) (Webber & Zbilut, 1994, 2005) is another similar approach that quantifies dynamics based on the state the system resides in in time. This method is based on the idea that recurrences, stretches of repeating patterns of various lengths, are a feature of dynamic systems, both living and non-living. The repetition of patterns tells us something about the system's organisation as a system that produces the same pattern of output are more orderly, returning to the same processes over time, while repetition of patterns in slightly different ways each time indicates complexity as processes are invoked in slightly different ways to produce a similar output. Originally applied to continuous signals in the physical sciences, RQA has since been applied to categorical data (Webber & Zbilut, 2005) and has also been extended to Cross-RQA to accommodate analysis of recurrences in two different systems coupled in time, as well as chromatic-RQA which permits analysis of coupled states (states that are characterised by the activity of both systems) (Xu et al., 2020). While both methods can be applied to analyse attractor states of dynamic systems, the versatility of RQA makes it highly adaptable to different experimental needs (Marwan & Meinke, 2004; Zbilut et al., 2002).

Using State Space Grids, infant-caregiver dynamics during the still-face paradigm have been analysed (Sravish et al., 2013). Only one other study has similarly used nonlinear techniques on behavioural data from the still-face paradigm (Montirosso, Riccardi, et al., 2010). Both studies found a difference. The authors used Sample Entropy as a measure of complexity, selecting a high sampling frequency of 5 Hz in order to obtain data of sufficient length for analysis. This meant that the measure of complexity pertained to processes occurring at 5 Hz, but may not, in fact, match the level of analysis of interest - the behavioural level, likely mediated by coordinative processes from different parts of the brain, working together over extended timescales. An extension of sample entropy, multiscale entropy, enables researchers to compute a measure of complexity corresponding to the multilevel structure of biological systems (M. Costa et al., 2002, 2005). However extensive periods of observation are required, especially where very low frequencies are of interest. In developmental psychology, researchers typically code behavioural state changes in 1s intervals where there is sufficient information to define distinct states. Concomitant with the advancement in nonlinear methods, this study will apply a promising approach, RQA, to analyse relatively short behavioural data in a widely-used developmental paradigm.

Current study

To improve the long-term socioemotional outcomes of preterm born infants, mechanistic understanding of how difficulties develop is imperative. Emotional self-regulation is a key process implicated in socioemotional behavioural difficulties, and there are early signs that prematurity can disrupt the processes enabling successful self-regulation. To date, there is incomplete understanding of the behavioural differences during the still-face paradigm, which elicits emotional self-regulation in infants. Furthermore, analysing the dynamics of behaviours during emotional self-regulation has the potential to reveal differences in the underlying interactions involved in producing emotional self-regulation. Temporal information about the unfolding of behaviours during the still-face paradigm is typically discarded in statistical analysis of the total or proportion of behaviours, even though there are methods that now enable us to probe these dynamics appropriately.

As described in Chapter 2, movement can be conceptualised as the output of a complex dynamic system. Movement during the still-face paradigm are related to emotional self-regulation and are therefore some movements will have an identifiable behavioural function. I showed in Chapter 3 that these can be characterised in relation to the perceptual, attentional, social and motor functions served by the behaviour.

This study will address the existing gaps in the literature to understand whether prematurity affects emotional self-regulation. This study aims to investigate, in 9-month-old infants, whether prematurity affects behaviour during emotional self-regulation during the still-face paradigm, focusing on two aspects of behaviour: (1) the type of behaviours, and (2) the dynamics of the behavioural response. I hypothesise that preterm infants show a different behavioural profile during emotional self-regulation, and also hypothesise specifically that prematurity alters behavioural dynamics, specifically, leading to lower behavioural complexity and disrupted dynamic stability.

5.2. Methods

Participants

Participants for the present study were term infants (born at 37 weeks or greater gestation age) and preterm infants (≤32 weeks gestation age) recruited to the Theirworld Edinburgh Birth Cohort Study (Boardman et al., 2020). Further inclusion and exclusion criteria were: (1) participation in the still-face paradigm at the follow-up appointment at 9-months chronological age (corrected age for preterm infants), before March 2021, and (2) data suitable for analysis. As a result of the COVID-19 pandemic, some dyads were not able to attend an in-person appointment and were not eligible for inclusion in this study. All caregiver-infant dyads were recruited at the Simpson Centre for Reproductive Health, and mothers provided consent for their and their child's participation. Consent was obtained by a researcher trained in Good Clinical Practice and familiar with procedures for research involving children and young people.

Based on these inclusion criteria, 137 infants were followed up and completed the still-face paradigm at 9-months chronological or corrected age. The final analytic sample excluded infants who were recalled late (n=1); who took part in the still-face paradigm but whose video was not recorded (n=1); or did not complete at least one still-face episode (n=4). Infants whose video quality was poor and affected the video coding process were also excluded from analysis (n=16). These "coding violations" were defined as obstruction of infant view such that 15% of the resulting codes were "estimated" or "un-scorable". According to this definition, 15 infants were excluded from analysis due to infants' legs being completely out of camera view. For infants who were partially obstructed by caregiver or legs were partially out of view videos were only excluded if they resulted in estimated or un-scorable codes above the 15% threshold (n=1). Infants were also excluded due to violations of the still-face procedure (n=3, see section on Still-face Paradigm which describes the violations).

After excluding those 26 infants, 111 infants made up the analytic sample. 61 infants were born at term age (mean=39 weeks, SD=1, 51% male) and 50 infants were born before 33 weeks of gestation (mean=29 weeks, SD =2, 58% female). A Chi-squared test did not reveal differences between term and preterm groups in the proportions included or excluded from analysis ($\chi^2(1)=1.83$, p=0.176). Infants were predominantly from a White European ancestry (92%) and from higher socioeconomic backgrounds (based on Scottish Index for Multiple Deprivation 2016 (SIMD, 79% of infants were in SIMD quintile 3 and above). 30% of the preterm group was from the lowest two SIMD quintiles, compared to 13% of the term group. 14 (28%) preterm infants and 1 (1.6%) term infant were part of multiple pregnancies. These infant characteristics are described in Table 5-1. Cross-tabulation of numbers and percentages are provided for categorical variables and means and standard deviation for continuous variables. The analysis sample comprised 105 infants and 6 infants who were part of three twin-pairs.

Table 5-1. Sample characteristics of infants meeting criteria for analysis

Infant characteristic	Overall, N = 111[1]	Term, N = 61[1]	Preterm, N = 50[1]
Age at visit	9.00 (0.48)	9.03 (0.40)	8.96 (0.56)
Gestation (weeks)	35 (5)	39 (1)	29 (2)
Birthweight (g)	2,557 (1,194)	3,562 (461)	1,330 (381)

Infant characteristic	Overall, N = 111[1]	Term, N = 61[1]	Preterm, N = 50[1]
Birthweight Z-score	0.38 (0.96)	0.66 (0.98)	0.03 (0.82)
Sex			
Male	60 (54%)	31 (51%)	29 (58%)
Female	51 (46%)	30 (49%)	21 (42%)
Ethnicity			
Any White background	99 (92%)	53 (91%)	46 (92%)
Any Mixed background	7 (6.5%)	4 (6.9%)	3 (6.0%)
Any Asian background	2 (1.9%)	1 (1.7%)	1 (2.0%)
SIMD (quintile)			
5	40 (37%)	26 (43%)	14 (29%)
4	30 (28%)	16 (27%)	14 (29%)
3	16 (15%)	10 (17%)	6 (12%)
2	16 (15%)	6 (10%)	10 (20%)
1	7 (6.4%)	2 (3.3%)	5 (10%)
Singleton			
Singleton pregnancy	96 (86%)	60 (98%)	36 (72%)
Multiple pregnancy	15 (14%)	1 (1.6%)	14 (28%)
9-month Height (cm)	72.0 (3.6)	72.6 (3.6)	71.4 (3.4)
9-month Weight (kg)	8.97 (1.18)	9.24 (1.16)	8.64 (1.13)

[1]Mean (SD); n (%)

Still-face paradigm

Infants and their caregivers took part in the extended modification of the still-face paradigm with five 2-minute phases (Haley & Stansbury, 2003), beginning with an initial play interaction and then alternating with still-face episodes in an A-B-A-B-A structure. As this study is aimed at investigating infants' self-regulatory abilities, only data from the two still-face phases was used, when the caregiver was unresponsive and infant had to rely on their own abilities to regulate distress. A Panasonic HC-W580 video camera positioned on a tripod each faced the infant and caregiver to record their facial expression and behaviour.

Figure 5-1. The still-face phases in the still-face paradigm

Violation of the still-face procedure ("still-face violations") was defined as early termination of the experiment, disruptive interruptions during the experiment, or when caregiver does not follow the procedure (for example, touches the infant during the still-face paradigm or does not maintain a still-face). In this study, phases in which the caregiver violated the still-face procedure were excluded from analysis. 1 infant was distracted by an experimenter in the same room when the experimenter was not hidden behind a screen and was excluded from analysis. Infants who terminated early, but had at least 1 SF episode, were not excluded from analysis as this may introduce bias, because these are the infants who tend to be the most distressed, and distress experienced may be associated with prematurity.

Variations in the procedure may result in potential violations of the still-face procedure. This includes when objects other than the infant chair/strap are introduced during the experiment (Object/Soother). A subset of infants wore Inertial Magnetic Unit (IMU) sensors integrated in clothing, though this was considered a potential violation only considered if infant removes the sensor or sensor clothing, or is distracted by the clothing. Videos with Object/soother or sensor violations were not excluded from temporal RQA analysis as the interest was in the temporal patterns of behaviour rather than the exact regulatory behaviour used, and excluding these infants would significantly reduce the sample size. The still-face effect was observed when infants were interacting with both mothers and fathers (Braungart-Rieker et al., 1998). Only a few infants participated with their grandmother, and therefore videos were not excluded based on the caregiver characteristic.

Study design

This was a repeated-measures, between-subject design. Two exposures (independent-variables) were considered a priori: a binary measure of prematurity (preterm or term-born) and a continuous measure of birthweight. Outcome measures (dependent variables) were infant's behavioural response during the still-face paradigm and the dynamics of the response, measured once in each still-face phase.

Exposures

Prematurity. Infants born preterm (<33 weeks gestational age) were compared with a control group born at term age (>37 weeks gestational age)

Birthweight. Birthweight measured in grams was used as a predictor to assess the dose-response effect of prematurity.

Prematurity with birthweight. Due to the effect of birthweight and the trend towards an effect of prematurity (see next section), this variable was derived to provide joint information of prematurity and birthweight within one variable. Preterm infants were further categorised to include birthweight information (e.g., in Hediger et al., 2002). Gestation age correlates with birthweight and all preterm infants in the sample also fall into low birthweight category (<2500 g) and only 1 term infant was considered low birthweight. Less than 10 infants were considered extremely low birthweight (<1000g). Therefore, this exposure comprised a term-born control group, and two preterm groups - low birthweight (LBW, 1500-2500g) and very low birthweight (VLBW, <1500g).

Outcomes

Still-face behavioural response

Emotional self-regulation. Measures of infant's emotional self-regulation was obtained using a novel observational coding scheme (described in General Methodology). These were defined as the proportion out of 120s spent in each ER behavioural state (SC, SOC, OBJ, RME, DIST), as well as the overall emotional self-regulatory response (ER), defined as the proportion of time spent in any of the ER behavioural states.

Table 5-2. Operational definitions of the Function of Movement and Behaviour Phases video coding scheme

Behavioural state	Operational definition
Self-comforting (SC)	The function of infant's movement is to obtain oral or tactile stimulation. Infants is using own body to provide oral self-stimulation, exploring manipulating objects on self, or touching their own body, for 1s or longer. Examples: mouthing hand/objects, manipulating clothing, clasping hands, bracing feet or touching head.
Object exploration/distraction (OBJ)	The function of infant's movement is to provide attentional distraction by exploring the perceptual properties of objects. Infant is reaching towards and/or using fine motor behaviours to move towards and/or manipulate objects not on self, for 1s or longer. Infants' gaze must be directed towards the object. Examples: playing with chair belt, exploring chair surface
Social interaction/monitor (SOC)	The function of infant's movement is to engage in or solicit social interaction. Infant is attending to the caregiver's face for 1s or longer, or using gestures or motor behaviours containing social interactive intention. Social interactive intention is defined as (a) infant-initiated arm movements, such as reaching, which must

	result in increased proximity or touch of any part of the caregiver, and (b) gestures or behaviours with social meaning. Examples: reaching towards caregiver, clapping, pointing
Repetitive movement (RME)	The function of infant's movement is to provide motor self-stimulation. Infant is using repetitive movements of the torso, arms or legs, defined by an identical pattern of flexion, extension, rotation, abduction, adduction or elevation in all possible directions, at least two times consecutively within a 3 second or smaller window. Examples: banging, leg kicking, body rocking, arm waving, clapping (clapping is assigned two behavioural functions)
Distancing (DIST)	The function of infant's movement is to increase their physical distance from the caregiver. Infant is trying to escape or get away from the caregiver by twisting, turning away from the caregiver, without engaging an object, for 1s or longer.
Other or no apparent emotional regulation behaviours (MOV)	The function of infant's movement for emotion regulation is not apparent. Infant is not moving or is engaging in motor activity that cannot be described by other emotion regulatory function.

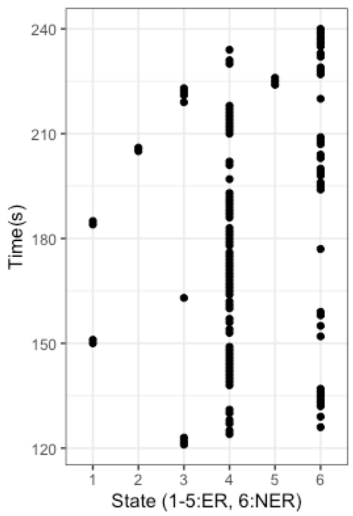
Behavioural indicators of affect. Data on infant negative affect was available from another doctoral study within the TEBC (Ginnell et al., 2021), obtained using observational coding with the ICEP scheme, revised Heidelberg version (C. Reck et al., 2009; Weinberg & Tronick, 1999). Negative affect was defined as negative engagement, during which the infant is showing negative facial expressions, is protesting or withdrawn, and was expressed as proportion of the total phase time. Due to the different methodology of the study, the proportion of time was calculated including from the entire still-face phase administered (including any extra periods beyond the designated 2-minute length of each phase which resulted from slight experimental inconsistencies).

Still-face behavioural dynamics

Recurrence quantification analysis

Each timeseries comprising infant's behavioural response over 120s of a still-face phase (Figure 5-2) was analysed for behavioural dynamics, in other words how the ER behaviours unfold or shift over time.

Figure 5-2. Example of a categorical timeseries of behavioural response during the 120s of the first still-face phase (120 – 240s of the whole still-face paradigm)



ER Behavioural dynamics were quantified using nonlinear measures obtained from Recurrence Quantification Analysis (RQA) (Webber & Zbilut, 2005). RQA characterises dynamics of a signal or time series using a key feature of all dynamic systems – *recurrences,* revisiting of a previous state in time. These recurrences are plotted graphically in a recurrence plot (Figure 5-4). In auto-RQA, a single timeseries is compared against itself. A recurrence is plotted at all the times (on the x-axis) the system's state matches itself at another time (on the y-axis, or vice versa). This produces repeating patterns of different lengths along the diagonal, horizontal and vertical lines in the plot. RQA quantifies these patterns in the plot.

In the implementation of RQA for continuous data, three free parameters are required: Radius (*r*), delay (*d*) and embedding dimension (*m*). The parameters delay and embedding dimension are used to, first, reconstruct the state space, before analysing if the state occupied by the system was recurrent. Based on Takens Theorem, reconstruction of the entire state space can be obtained from time-delay embedding of a timeseries output representing the observed states of the system over time. *d* refers to the number of shifted samples that a time-delayed replica of the original time series is created from. *m* is the number of dimensions to be used to reconstruct the phase space using the original and time-delayed copy of the timeseries; mathematically the embedding dimension specifies the multiplicative factor that the delay is applied to construct the time-delayed replica $x, x_d, x_{2d}, \ldots, x_{(m-1)d}$ (Coco et al., 2021). Due to noise and measurement error, states that recur do not normally recur exactly. Therefore, *r* specifies the extent that two points need to be similar in order to be considered a recurrent state.

In categorical RQA, reconstruction of the state space is not necessary as each category in the timeseries already defines a state within the state space. The free parameters delay and embedding dimension take the value 1, if no reconstruction of the phase space is required. Chromatic RQA is a modification of the original RQA algorithm, to obtain measures that can distinguish the different types of recurrent states of interest to the researcher (Xu et al., 2020). As the name indicates, this is done by colour-coding each type of recurrence defined by a combination of the state on the x-axis and the state on the y-axis. All the types of recurrences can be represented by a *chromatic state space* which plots all the possible combination of states.

In this thesis, the implementation of the algorithm for chromatic auto-RQA does not include functions for phase space reconstruction, as only categorical data was of interest. The original, unembedded, timeseries was used to identify recurrences. Recurrence was defined as a match of a type of behaviour later in time as defined in the chromatic state-space (Figure 5-3). For categorical states representing concurrent behavioural states (see Chapter 3, Methodology), a partial match of either one of the behaviours at another point in time counts as a recurrence. This is represented in the full chromatic state space in Appendix III.

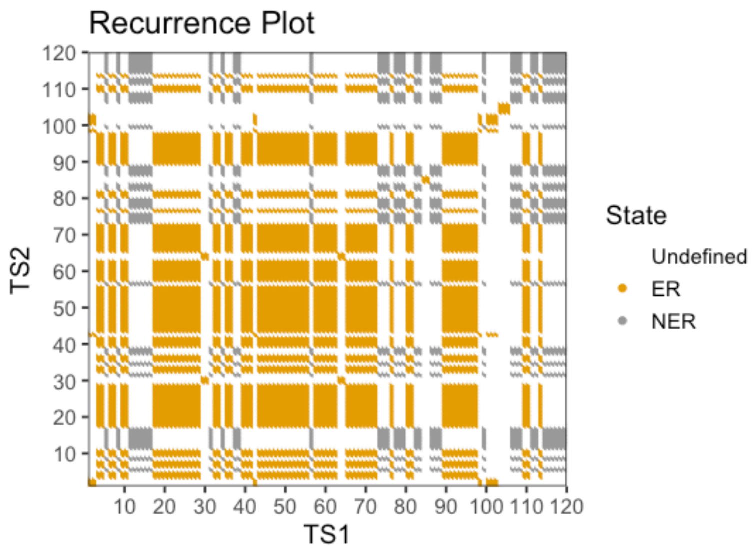
Figure 5-3: Simplified chromatic state space. States 1 to 5 correspond to ER states as defined in the video coding scheme (SC, SOC, OBJ, RME and DIST). State 6 corresponds to Non-ER states (MOV: Undefined/Other movement). Recurrences of States 1 to 5 later in time were considered an ER recurrence (coded in Orange). Recurrences of State 6 were considered a non-ER recurrence (coded in Grey)

	1	2	3	4	5	6
1	ER					
2		ER				
3			ER			
4				ER		
5					ER	
6						NER

After colour-coding each recurrence in the recurrence plot, measures specific to each chromatic can be computed accordingly. In this study, this method was applied in the auto-RQA context, to enable dynamics to be calculated from recurrences of emotion self-regulatory (ER) behavioural states only.

Categorical behavioural timeseries show a characteristic pattern in the recurrence plot, checkerboard-like patterns formed of rectangular structures (Leonardi, 2018). (see Figure 5-4). Therefore, the measures selected for this study were related to the vertical structures in the recurrence plot (or, equivalently, horizontal structures, because the recurrence plot is symmetric in auto-RQA).

Figure 5-4: Example of a recurrence plot.



Recurrence rate (RR). Recurrence rate was the overall percentage of recurrent points out of the whole recurrence plot. This was calculated using Webber and Zbilut's (2005) formula. The total number of recurrences of ER states on 1 symmetric half of the recurrence plot, excluding recurrences on the central diagonal, was obtained, divided by the total number of possible recurrences (total points on the symmetric half of the plot).

Laminarity (LAM). Laminarity was the percentage of recurrent points forming vertical structures of a minimal length *minL* in the recurrence plot. Low laminarity means that the recurrence plot contains more single recurrent points than laminar vertical structures or periods of stability (Curtin et al., 2017). Laminarity quantifies the extent of intermittency in the system, the alternation of long laminar phases with irregular turbulent phase changes (Manneville, 1980). For this study, *minL* was selected as three seconds, meaning behaviours that lasted three seconds or longer were considered more stable states, and behaviours lasting two seconds or less were considered intermittent.

Entropy of block structures (ENTb). Entropy was the average amount of information present in the block structures of the recurrence plot (Leonardi, 2018). Shannon information entropy (C.E Shannon, 1948) was calculated as the log of the sum of the probabilities of all possible rectangular block sizes (to the nearest integer). This was implemented algorithmically by obtaining a histogram of all possible block sizes and summing over the probabilities of each non-zero bin (Coco & Dale, 2014; Webber & Zbilut, 2005).

Trapping Time (TT) Trapping time, calculated as the average length of vertical line structures (of at least 2s in length), indexes the average time spent in a stable state (Marwan et al., 2002).

Statistical analysis

All statistical analyses were performed in R (version 4.02), on Rstudio (version 1.1).

Descriptive statistics

The Shapiro-Wilk test was used to assess for non-normality of all the behavioural outcome measures.

Experimental characteristics of the still-face procedure (number and percentage) tabulated infants in term and preterm groups, to provide an indicator of experimental consistency.

Due to non-normality of all outcome measures except for the total ER behavioural response, non-parametric correlation analysis was conducted. Spearman rank correlation coefficients were obtained for proportion of time in negative affective states with the proportion of total time spent in regulatory behaviours, each behavioural attractor strength, and each dynamic measure of behaviour. Spearman rank correlation coefficients were also obtained for the total ER behavioural response with each dynamic measure. All correlations were computed separately for SF1 and SF2.

Multivariate analyses

Using the *lme4* R package (D. Bates et al., 2015), linear mixed-effect models was conducted using prematurity as a predictor on temporal (RR, LAM, ENTb and TT) and overall amount of infants' self-regulatory behavioural response (MODELS A). Correlated data from twins was accounted for by considering twins as clustered within a family (Marston et al., 2009). However, a model with two random effects did not converge, likely resulting from low percentage of twin pairs (N=3, 2.7%) relative to the total number of clusters. As such, models were run by assuming that each infant's data was independent (Sauzet et al., 2013).

To explore if there was a dose-response effect of prematurity, I tested if there was a relationship between birthweight with SF ER behavioural and dynamic measures by analysing Spearman rank-sum correlation coefficients. Instead of running correlations between birthweight and each SF phase, data reduction was first employed, as Models A did not show an overall effect of SF phase on any behavioural/dynamic measures. The chosen data reduction approach was based on a combination of theoretical justification (that the SF paradigm was designed to elicit emotional distress) and descriptive statistics showing that in the sample, 1) negative affect was correlated with self-regulatory behavioural response – stronger and show significance in SF2, and 2) infants born preterm were different from term infants in negative affect in SF1. Therefore, data reduction proceeded in the following manner. Data from SF1 was used for all infants who showed negative affect in SF1. For infants who did not show negative affect in SF1, data from SF2 was used if they showed negative affect in the phase. If not, the mean of dynamic measures for SF1 and SF2 was used. Similarly, for infants whom no negative affect data was available, the mean of the two phases was taken. For infants whose experiment terminated early, only data from SF1 was used. Due to non-normality of each behavioural outcome variable (except for total behavioural response), spearman rank-sum correlation was applied.

As there appears to be associations between birthweight and outcome measures, each Model A was re-run using the joint effect of preterm delivery and birthweight as the exposure (MODELS B).

Descriptive statistics showed that the overall behavioural response was highly correlated with behavioural dynamics. As such, a linear mixed-effect model was conducted on the SF behavioural response to investigate whether the effect of prematurity was specific to the temporal structure of the behavioural response and not simply the overall behavioural response (MODEL C).

For all models, an interaction effect was considered between the Prematurity exposure and SF phase, and included only if it reached significance (alpha < 0.05). No interaction effects were included in the models as a result. Regression assumptions of normality, linearity and homogeneity of variance were checked by inspecting q-q plots (residuals against predicted quantiles from a normal distribution), graphical plots of observed values against residuals and residuals against fitted values, respectively. Homogeneity of variance was further checked using Levene's test as graphical plots showed a fanning out pattern at high fitted-values. These diagnostics checks and tests did not provide evidence that regression assumptions were violated.

Further analysis

Spearman's rank sum correlation coefficients were examined between the ER behaviours and ER behavioural dynamics that were found to be different between groups in multivariate analyses. This tests whether there is evidence of the influence of the amount of particular behaviours shown on dynamics.

Surrogate analysis

Additionally, to test the hypothesis that the dynamics observed in infant's behavioural data was not simply due to a random gaussian process, surrogate analysis was applied. Surrogate analysis can be applied through a "constrained realisation" approach, which generates surrogate data from the original data in a way that matches the sampling distribution other than the one being tested (Theiler et al., 1992). Random shuffling of the original data produces timeseries data with the same total behavioural response and recurrence rate, but destroys temporal order within the timeseries data. 100 surrogate time series were generated for each timeseries and RQA measures obtained for each timeseries. The null hypothesis that the value of each dynamic measure from the original timeseries came from a Gaussian process is then tested. The *casnet* R package (Hasselman et al., 2022), presently available in the development version, was used to implement hypothesis testing. The surrogate dataset is used to approximate the distribution of values and from this distribution, the rank order probability is obtained for the true value. For 100 surrogate time series, the null hypothesis was rejected at the 1% significance level - this tests whether the original data produced a value more extreme than the most extreme value in the surrogate distribution which comprises 100 values. 3 hypothesis tests were conducted for each time series (TT, ENTb and LAM). Therefore, Bonferroni correction was applied for three tests at 95% significance level, and a null hypothesis was rejected if $alpha<0.017$. Rejecting the null hypothesis would mean that the behavioural data is unlikely to be produced by a random Gaussian process.

5.3. Results

Descriptive statistics

Experimental variations of the still-face paradigm are described in Table 5-3 for the 111 infants in the analysis sample. 101 infants participated with their mother, 9 with their father, and 3 with their grandmother. 19 infants (12 term and 7 preterm) completed only one still-face episode. 6 infants who wore lightweight movement sensors during the experiment interacted with the sensor clothing.

Table 5-3. Descriptive statistics of still-face paradigm characteristics

Still-face experiment characteristics	Term, N = 61[1]	Preterm, N = 50[1]
Caregiver		
Mother	57 (93%)	42 (84%)
Father	3 (4.9%)	6 (12%)
Grandmother	1 (1.6%)	2 (4.0%)
Partial obstruction of infant view	10 (16%)	14 (28%)
Terminated early	12 (20%)	7 (14%)
Toy present	6 (9.8%)	3 (6.0%)
Soother present	2 (3.3%)	5 (10%)
Interruption	0 (0%)	5 (10%)
Experimental protocol		
New infant chair and experimenter behind screen	57 (93%)	48 (96%)
Old infant chair (with foot rest)	4 (6.6%)	0 (0%)
Old infant chair (with foot rest) and experimenter not behind screen	0 (0%)	2 (4.0%)
Sensor experimental protocol		
No sensors	50 (82%)	38 (76%)
Sensors present, no infant interaction	7 (11%)	10 (20%)
Sensors present, with infant interaction	4 (6.6%)	2 (4.0%)

[1]n (%)

Table 5-4 describes infant's behavioural response during SF1 and SF2, expressed in proportion of time. Term infants showed more negative affect than Preterm infants, but Wilcoxon rank sum test showed that the difference only reached significance in SF1 (W =

1786, p=0.013) and not SF2 (W=1044, p=0.536). Total ER behaviours refers to the proportion of time in any emotion regulatory behaviours as defined in the coding scheme, and both groups of infants showed ER behaviours for around half of each SF phase. The majority of infants did not show distancing behaviours (median (IQR) = 0 (0, 0)). Therefore, group differences in distancing behaviours were not analysed in regression models.

Table 5-4. Descriptive statistics of still-face behavioural response

	SF1		SF2	
Characteristic	Term, N = 61[1]	Preterm, N = 50[1]	Term, N = 52[1]	Preterm, N = 43[1]
ICEP_neg	0.16 (0.00, 0.39)	0.00 (0.00, 0.16)	0.58 (0.11, 0.75)	0.36 (0.06, 0.76)
Unknown	0	4	1	5
Total ER	0.54 (0.44, 0.66)	0.56 (0.38, 0.67)	0.52 (0.42, 0.67)	0.54 (0.43, 0.67)
SC	0.15 (0.08, 0.30)	0.16 (0.07, 0.28)	0.17 (0.07, 0.31)	0.18 (0.09, 0.33)
SOC	0.05 (0.03, 0.12)	0.08 (0.03, 0.14)	0.05 (0.03, 0.10)	0.07 (0.05, 0.12)
OBJ	0.07 (0.01, 0.13)	0.10 (0.05, 0.22)	0.03 (0.00, 0.15)	0.07 (0.00, 0.14)
RME	0.24 (0.16, 0.36)	0.17 (0.07, 0.36)	0.21 (0.12, 0.36)	0.13 (0.08, 0.32)
DIST	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)

[1]Median (IQR)

Table 5-5 shows the Spearman correlations of Negative affect with ER behavioural response, and Negative affect with behavioural dynamics. Negative affect was negatively correlated with total behavioural response (rho= -0.28, p=0.008), object-oriented regulation (rho = -0.40, p<0.001), repetitive movement episodes (rho= -0.27, p=0.025) and distancing (rho = 0.27, p=0.011) in SF2; but only object regulation (rho= -0.41, p<0.001) and distancing (rho= 0.20, p=0.03) in SF1. Negative affect was negatively correlated with all dynamic measures in SF2 (p<0.001), but evidence for correlations were only strong enough to reach significance in SF1 for LAM. Negative affect was not correlated with RR in SF1 (Spearman Rho = 0.01, p=0.914)

Table 5-5. Correlation between negative affect with behavioural response and behavioural dynamics

	Negative Affect	
	SF1, Rho	SF2, Rho
ER behavioural response		
Total ER	-0.01	-0.28***
SC	0.13	0.09
SOC	*0.16#*	0.00
OBJ	-0.41***	-0.40***
RME	-0.13	-0.24*
	Negative Affect	
	SF1, Rho	SF2, Rho
DIST	0.20*	0.27*
ER behavioural dynamics		
RR	0.01	-0.22*
ENTb	-0.12	-0.24*
LAM	-0.20*	-0.24*
TT	-0.14	-0.23*

*# p<0.1   * p<0.05   ** p<0.01   *** p<0.001*

Table 5-6 shows the Spearman correlations between the Total ER response with each measure of behavioural dynamics. The total SF behavioural response showed weak and moderate correlations with ENTb in SF1 and SF2 respectively, moderate correlations with TT, and strong and very strong correlations with LAM and RR respectively.

Table 5-6. Correlation between Total behavioural response and behavioural dynamics

	Total ER	
	SF1, Rho	SF2, Rho
ER behavioural dynamics		
RR	0.924***	0.904***
ENTb	0.368***	0.499***
LAM	0.655***	0.750***
TT	0.416***	0.536***

*# p<0.1 * p<0.05 ** p<0.01 *** p<0.001*

Models A – effect of prematurity and SF phase

There was no evidence that any of the emotional regulation behaviours or the dynamic outcome measures were different in SF2 compared to SF1. While non-significant at the 95% confidence level, there was a trend towards lower RR (Effect: -3.39%, 95% CI -7.47 – 0.68, p=0.106) and ENTb (Effect: -0.13 bits/bin, 95% CI -0.29 – 0.03, p=0.112) in the Preterm compared to Term group. There was also a trend towards a lower proportion of time spent using RME behaviours (Effect: -0.06, 95% CI -0.12 – 0.00, p=0.068) but no difference in any of the other behaviour types. There was a trend towards lower OBJ (Effect: -0.02 95% CI -0.05 – 0.00, p=0.060) and RME (Effect: -0.03 95% CI -0.05 – 0.00, p=0.086) in SF2 compared to SF1. (See Table 5-7 and Figure 5-5)

Table 5-7-a. Models A – effect of preterm birth and still-face phase on behavioural dynamics

MODEL A	RR	LAM	ENTb	TT
Fixed effects	Beta (95% CI)	Beta (95% CI)	Beta (95% CI)	Beta (95% CI)
(Intercept)	17.48 *** (14.58 – 20.39)	79.21 *** (76.00 – 82.42)	2.55 *** (2.43 – 2.66)	4.16 *** (3.64 – 4.69)
Preterm [Ref: Term]	-3.39 (-7.47 – 0.68)	0.14 (-4.12 – 4.40)	-0.13 (-0.29 – 0.03)	0.28 (-0.44 – 1.00)
SF2 [Ref: SF1]	0.10 (-2.10 – 2.30)	-0.51 (-3.74 – 2.71)	-0.03 (-0.14 – 0.08)	-0.09 (-0.56 – 0.38)
Random effects				
σ^2	61.63	135.37	0.16	2.88
τ_{00}	84.48 $_{ID}$	55.58 $_{ID}$	0.09 $_{ID}$	2.09 $_{ID}$
ICC	0.58	0.29	0.38	0.42
Marginal R^2 / Conditional R^2	0.019 / 0.586	0.000 / 0.291	0.018 / 0.391	0.004 / 0.423

N=111, Observations=206

$^{\#}$ *p<0.1*   * *p<0.05*   ** *p<0.01*   *** *p<0.001*

Figure 5-5-a. Models A – predicted effect of preterm birth and still-face phase on behavioural dynamics

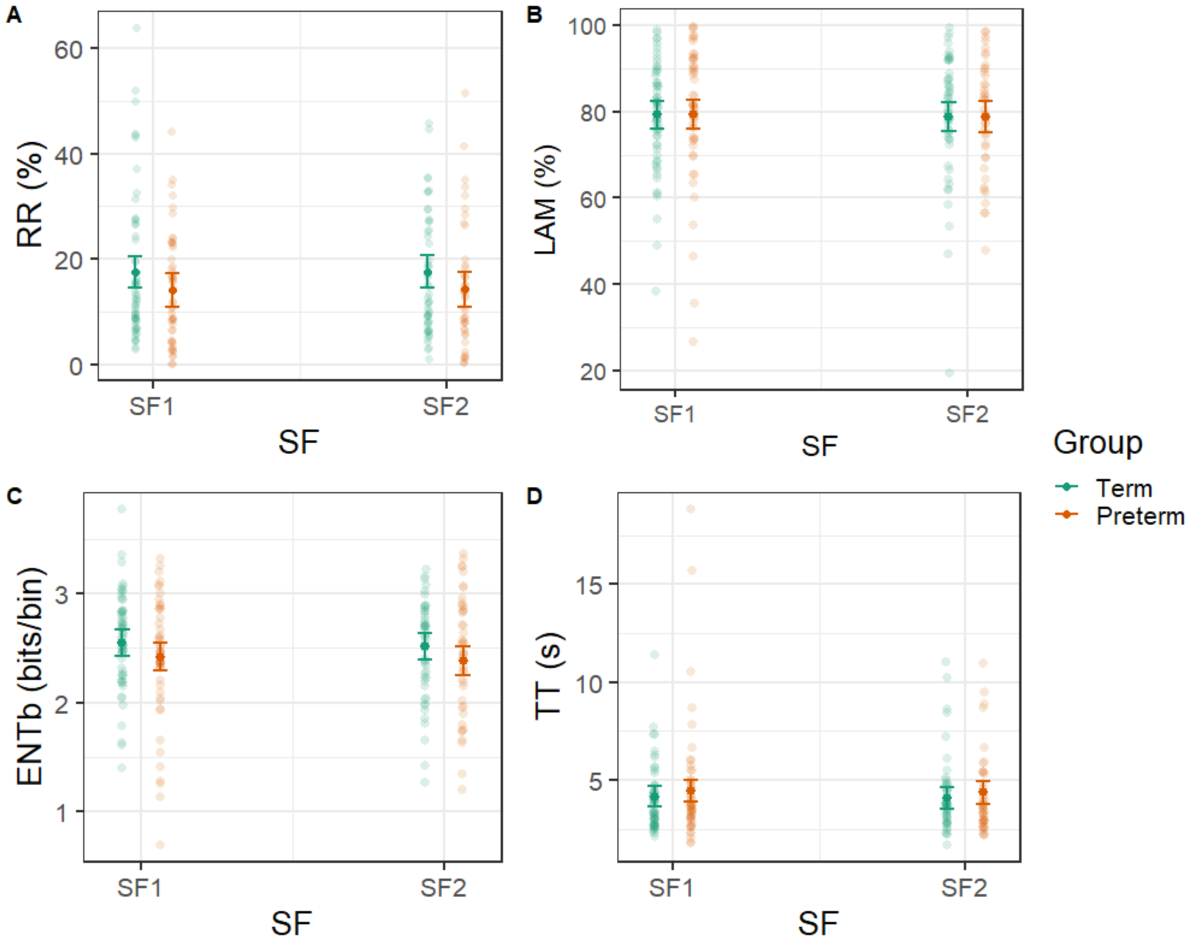


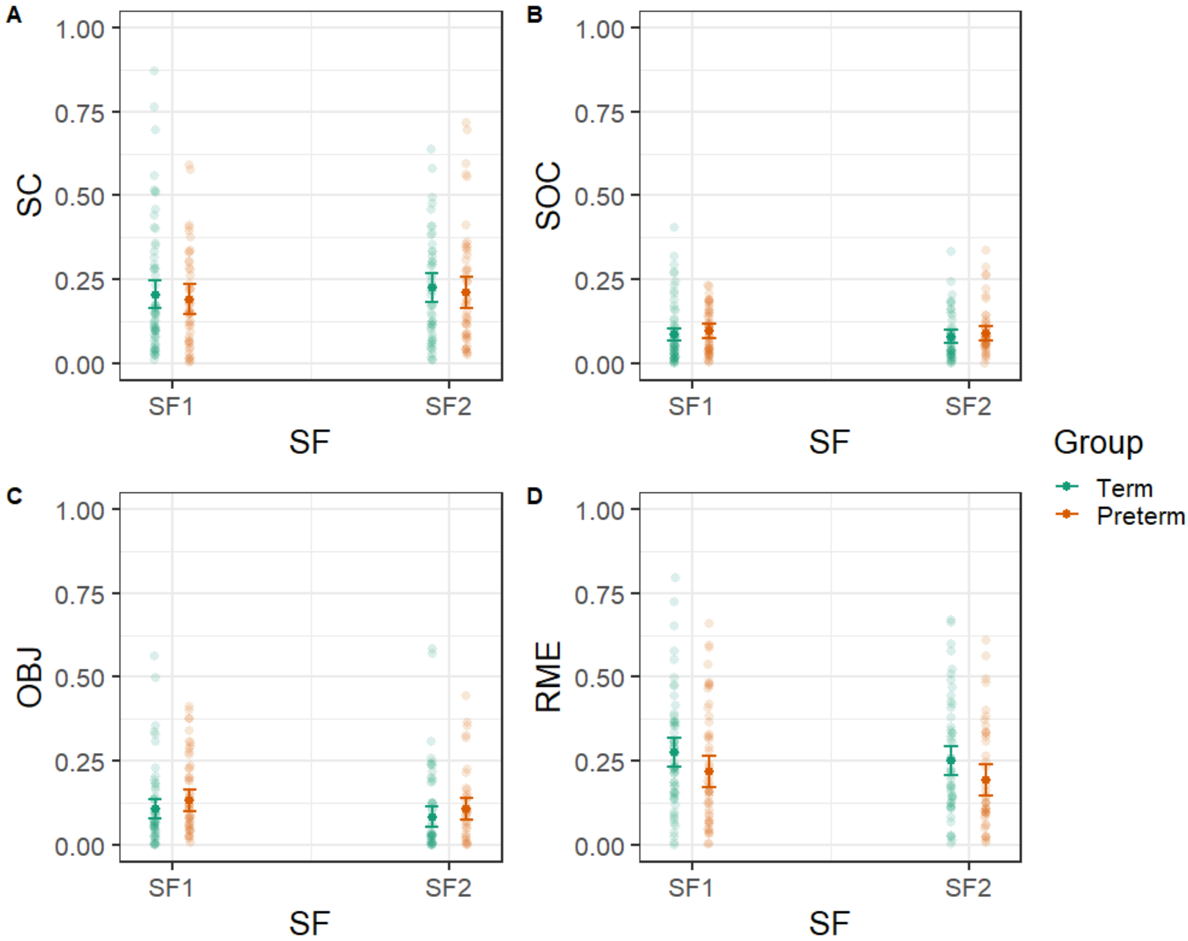
Table 5-7-b. Models A – effect of preterm birth and still-face phase on behavioural response

Models A	SC	SOC	OBJ	RME
Fixed effects	Beta (95% CI)	Beta (95% CI)	Beta (95% CI)	Beta (95% CI)
(Intercept)	0.21 *** (0.16 – 0.25)	0.09 *** (0.07 – 0.10)	0.11 *** (0.08 – 0.14)	0.28 *** (0.23 – 0.32)
Preterm [Ref: Term]	-0.01 (-0.07 – 0.04)	0.01 (-0.01 – 0.04)	0.02 (-0.02 – 0.06)	-0.06 (-0.12 – 0.00)
SF2 [Ref: SF1]	0.02 (-0.01 – 0.05)	-0.01 (-0.02 – 0.01)	-0.02 (-0.05 – 0.00)	-0.03 (-0.05 – 0.00)
Random effects				
σ^2	0.01	0.00	0.01	0.01
τ_{00}	0.02 $_{ID}$	0.00 $_{ID}$	0.01 $_{ID}$	0.02 $_{ID}$
ICC	0.57	0.48	0.45	0.66
Marginal R^2 / Conditional R^2	0.005 / 0.576	0.007 / 0.488	0.020 / 0.457	0.031 / 0.673

N=111, Observations=206

$^{\#}$ *p<0.1* * *p<0.05* ** *p<0.01* *** *p<0.001*

Figure 5-5-b. Models A – predicted effect of preterm birth and still-face phase on behavioural response



Correlation between birthweight and ER behavioural response and behavioural dynamics

Birthweight was positively correlated with RR (rho=0.21, p=0.029), ENTb (rho=0.25 bits/bin, p=0.009) and RME (rho=0.25, p=0.007). Although not significant at the 95% confidence level, birthweight was negatively correlated with OBJ (rho=-0.18, p=0.06). Birthweight was not correlated with any other emotional regulation behaviours or dynamic measures, or the total behavioural response. (see Table 5-8).

Table 5-8. Correlation between ER measures and birthweight

Correlation with Birthweight	Rho
RR	0.21*
LAM	0.13
ENTb	0.25**
TT	0.13
SC	0.14
SOC	-0.08
OBJ	*-0.18#*
RME	0.25**
Total ER	0.14

Models B - Joint effect of prematurity and birthweight

There was strong evidence of an effect of the joint prematurity and birthweight exposure on RR, ENTb, OBJ and RME. Contrasts shows that the VLBW group, but not the LBW group, was different from the Term group. Specifically, VLBW infants showed lower RR (Effect: -5.27%, 95% CI 10.03 – -0.51, p=0.032), ENTb (Effect: -0.23, 95% CI -0.42 - -0.04, p=0.017), greater OBJ (Effect: 0.05, 0.00 – 0.09, p=0.048) and lower RME (Effect: -0.11, 95% CI: -0.18 - -0.04, p=0.003). See Table 5-9 and Figure 5-6.

Table 5-9-a. Models B – joint effect of prematurity and birthweight on behavioural dynamics

Models B	RR	LAM	ENTb	TT
Fixed effects	Beta (95% CI)	Beta (95% CI)	Beta (95% CI)	Beta (95% CI)
(Intercept)	17.50 *** (14.61 – 20.39)	79.22 *** (76.01 – 82.44)	2.55 *** (2.43 – 2.66)	4.16 *** (3.64 – 4.69)
Prematurity [Ref: Term]				
LBW	-0.66 (-6.10 – 4.78)	1.57 (-4.14 – 7.28)	0.01 (-0.20 – 0.22)	0.32 (-0.65 – 1.28)
VLBW	-5.27 * (-10.03 – -0.51)	-0.87 (-5.91 – 4.17)	-0.23 * (-0.42 – -0.04)	0.25 (-0.59 – 1.10)
Still-face phase [Ref: SF1]				
SF2	0.06 (-2.13 – 2.26)	-0.55 (-3.77 – 2.67)	-0.03 (-0.14 – 0.07)	-0.09 (-0.56 – 0.38)
Random effects				
σ^2	61.55	134.78	0.15	2.88
τ_{00}	83.39 $_{ID}$	56.93 $_{ID}$	0.09 $_{ID}$	2.12 $_{ID}$
ICC	0.58	0.30	0.38	0.42
Marginal R^2 / Conditional R^2	0.034 / 0.590	0.004 / 0.300	0.042 / 0.402	0.004 / 0.427

N=111, Observations=206

# *p<0.1*   * *p<0.05*   ** *p<0.01*   *** *p<0.001*

Figure 5-6-a. Models B – predicted effect of joint preterm and birthweight factor on behavioural dynamics

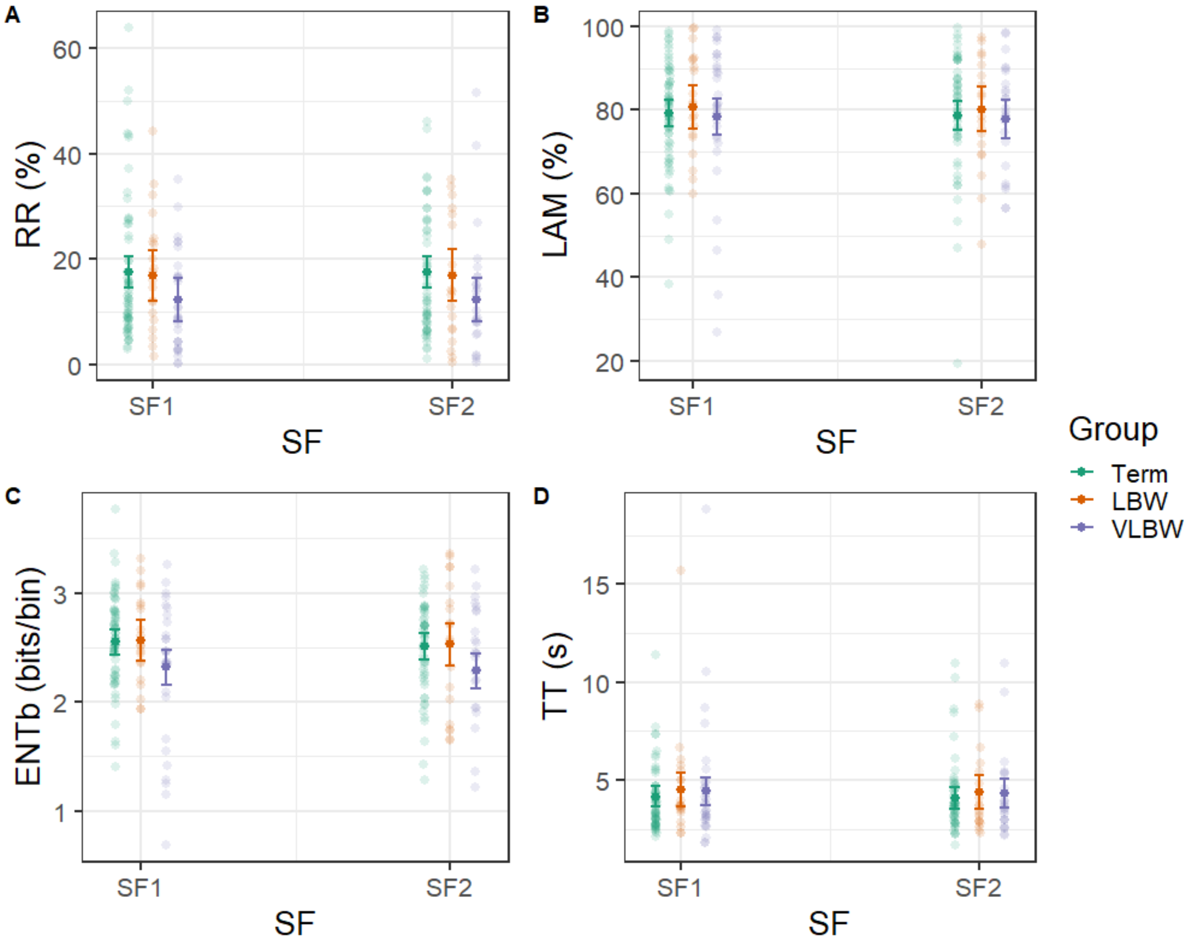


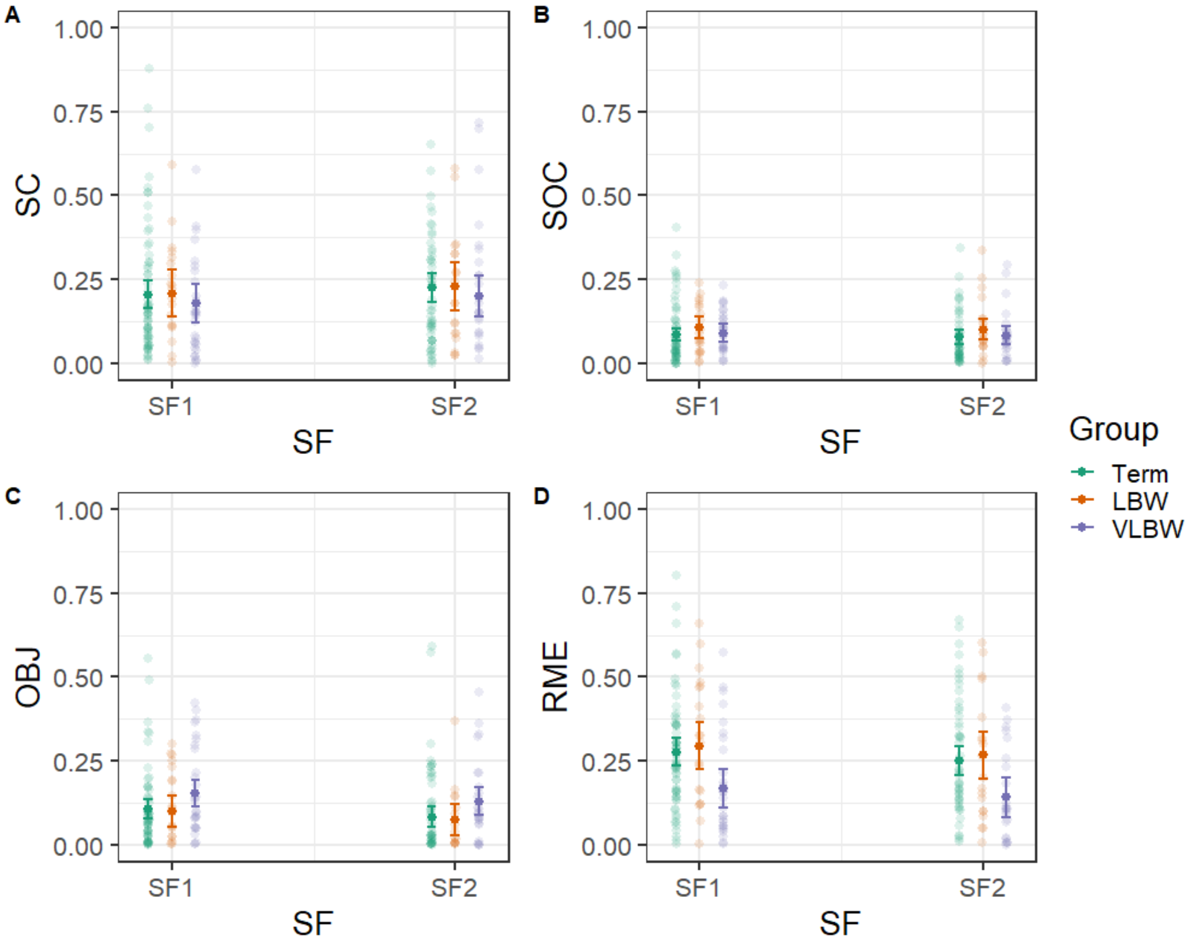
Table 5-9-b. Models B – joint effect of prematurity and birthweight on behavioural response

Models B	SC	SOC	OBJ	RME
Fixed effects	Beta (95% CI)	Beta (95% CI)	Beta (95% CI)	Beta (95% CI)
(Intercept)	0.21 *** (0.16 – 0.25)	0.09 *** (0.07 – 0.10)	0.11 *** (0.08 – 0.14)	0.28 *** (0.23 – 0.32)
Prematurity [Ref: Term]				
LBW	0.00 (-0.08 – 0.08)	0.02 (-0.01 – 0.06)	-0.01 (-0.06 – 0.05)	0.02 (-0.06 – 0.10)
VLBW	-0.03 (-0.10 – 0.04)	0.00 (-0.03 – 0.04)	0.05 * (0.00 – 0.09)	-0.11 ** (-0.18 – -0.04)
Still-face phase [Ref: SF1]				
SF2	0.02 (-0.01 – 0.05)	-0.01 (-0.02 – 0.01)	-0.02 (-0.05 – 0.00)	-0.03 (-0.05 – 0.00)
Random effects				
σ^2	0.01	0.00	0.01	0.01
τ_{00}	0.02 $_{ID}$	0.00 $_{ID}$	0.01 $_{ID}$	0.02 $_{ID}$
ICC	0.58	0.48	0.43	0.64
Marginal R^2 / Conditional R^2	0.008 / 0.581	0.013 / 0.491	0.041 / 0.458	0.083 / 0.674

N=111, Observations=206

$^{\#}$ *p<0.1* * *p<0.05* ** *p<0.01* *** *p<0.001*

Figure 5-6-b. Models B – predicted effect of joint preterm and birthweight factor on behavioural response



Model C – Specificity of effect of Prematurity on ER behavioural dynamics

Although dynamic measures were very strongly correlated with the overall behavioural response, the trend towards lower behavioural response in VLBW compared to Term infants was not significant at the 95% level (Effect: -0.07, 95% CI: -0.14 – 0.00, p=0.067). See Table 5-9-c and Figure 5-6-c.

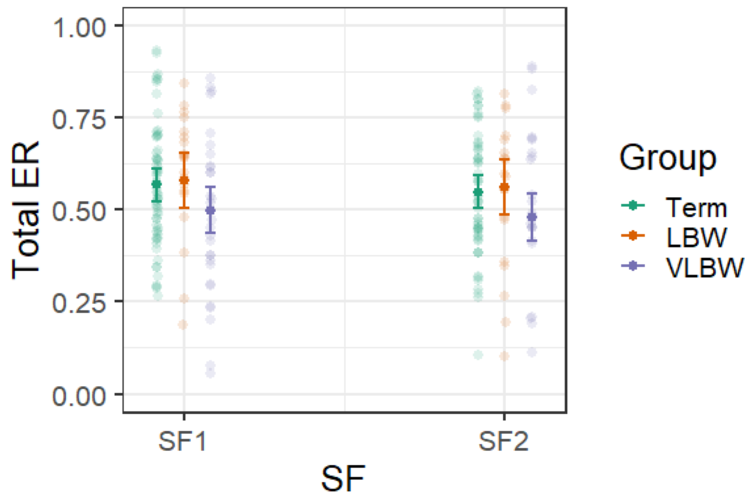
Figure 5-10. Models C – predicted effect of joint preterm and birthweight factor on Total behavioural response

	Total ER
Fixed effects	Beta (95% CI)
(Intercept)	0.57 *** (0.52 – 0.61)
Prematurity [Ref: Term]	
LBW	0.01 (-0.07 – 0.09)
VLBW	*-0.07# (-0.14 – 0.00)*
Still-face phase [Ref: SF1]	
SF2	-0.02 (-0.05 – 0.01)
Random effects	
σ^2	0.01
τ_{00}	0.02
ICC	0.58
Marginal R^2 / Conditional R^2	0.031 / 0.597

N=111, Observations=206

*# p<0.1 * p<0.05 ** p<0.01 *** p<0.001*

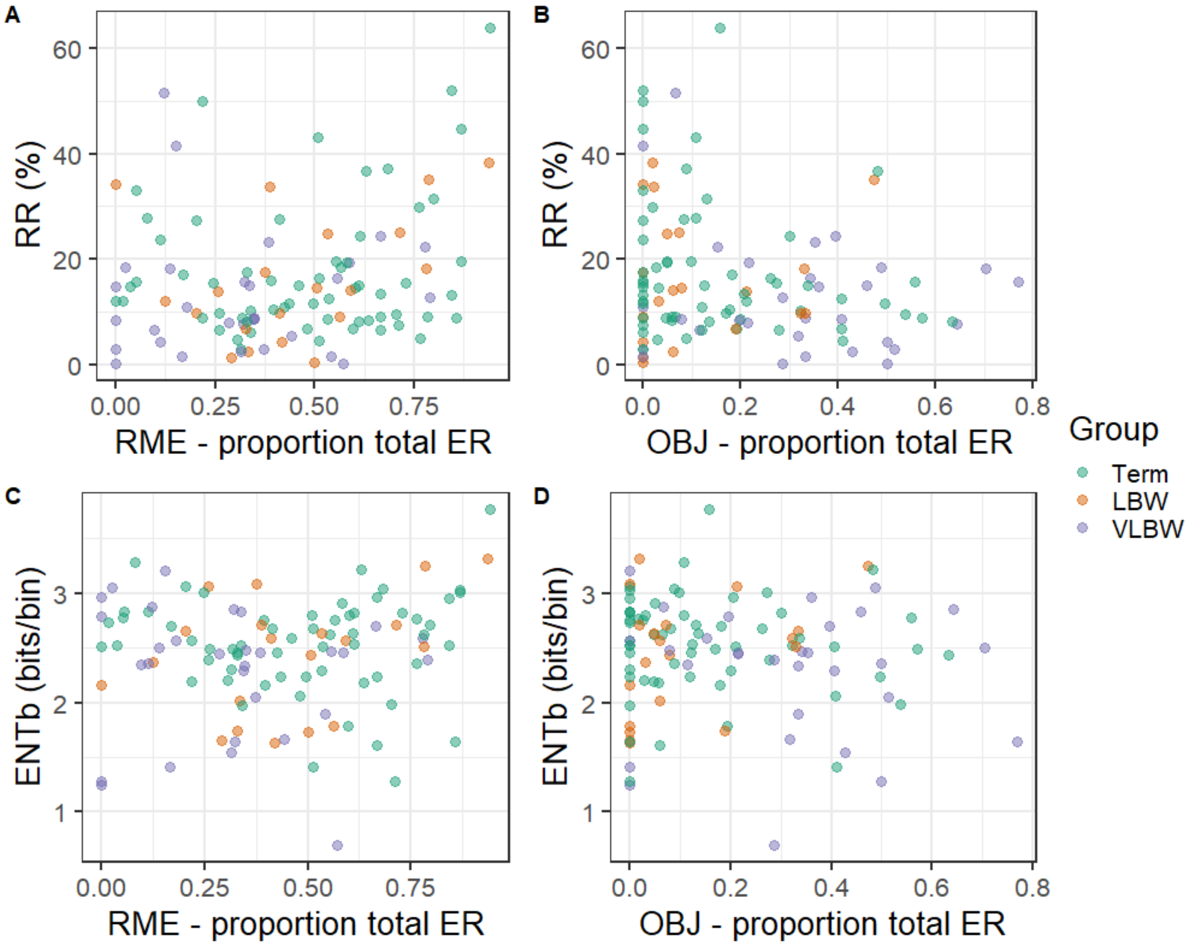
Figure 5-7. Models B – predicted effect of joint preterm and birthweight factor on total behavioural response



Correlation between relative proportion of RME and OBJ with ER behavioural dynamics

The proportion of RME behaviours contributing to the total ER behavioural response was correlated with RR (rho = 0.19, p=0.035), but not ENTb (rho=0.07, p=0.43). The proportion of OBJ behaviours contributing to the total ER behavioural response was not correlated with either RR (rho=-0.14, p=0.12) or ENTb (rho=-0.05, p=0.63). Figure 5-8 shows scatterplots depicting the relationship between ER dynamics and the proportion of RME or OBJ behavioural response.

Figure 5-8. Scatterplot of behavioural dynamics (RR and ENTb) with behavioural response (RME and OBJ)



Surrogate analysis

The null hypothesis that the value of TT and LAM came from a Gaussian process was rejected in 100% of infants, for both SF1 and SF2. For ENTb, this was 97.5% for SF1, and 97.1% for SF2.

5.4. Discussion

This study provides strong evidence that partially supports both hypotheses. Reductions in birthweight led to lower complexity, but no changes in dynamic stability. Lower birthweight was also correlated with greater OBJ behaviours and lower RME behaviours. When birthweight information was considered, group differences between term and preterm infants in line with these trends with birthweight were found. However, only preterm infants with VLBW, and not preterm infants with LBW, showed a different behavioural response and behavioural dynamics compared to term infants.

Findings related to behavioural response

Self-comforting behaviours. Consistent with other studies on infants between 6-9 months (Atkinson et al., 2021; Jean & Stack, 2012; Montirosso, Borgatti, et al., 2010), this study also did not find differences in self-comforting behaviours during the still-face paradigm. In line with this, self-comforting behaviours were the most-preferred regulatory strategy in both 5- and 10-month-old infants in similarly stressful social situation even as 10-month-old infants learn other behaviours in the motor, attentional and communicative domain (Stifter & Braungart, 1995). However, self-comforting behaviours were more likely to be related to reduction in negative affect at 10-months than at 5-months. This shows that self-comforting behaviours are not simply replaced by other self-regulatory behaviours when those develop, and suggests that it is potentially because infant's have learnt that they are effective for emotional self-regulation, when hand-to-mouth behaviours, fetal reflexes and present at birth, may be accidental (Piaget, 1952) or serve non-emotional oral and haptic self-stimulatory purposes linked to the feeding system (Rochat, 1993). While this study shows that preterm-born infants successfully learn and use effective emotional self-regulatory strategies by 9-months-old, the effect of prematurity on self-comforting behaviours, the earliest developing self-regulatory strategy, needs to be further investigated due to conflicting reports in younger 3 to 4-month-old infants (Chiodelli et al., 2021; Provenzi et al., 2017; Yaari et al., 2018). This may have implications on whether younger preterm infants may require more externally-mediated regulation before internal resources become well-developed.

Object exploration/distraction. Unlike Jean & Stack (2012) and Atkinson (2021), the present study found differences in object exploration/distraction behaviours due to prematurity. Similar to this study, both studies coded behaviours where infants were actively manipulating the object for it as well as gazing at it. However, Jean & Stack (2012) analysed these behaviours along with touch targeted at self (together defined as self-comfort exploratory behaviours) and Atkinson (2018) considered these behaviours under environment-reliant behaviours alongside escape behaviours and gaze aversion (for still-face only). Another difference was the earlier time-point examined by these studies, at 5.5 months. No difference was found at 12 or 18-months (Atkinson, 2021). Although Atkinson (2021) specifically compared very low birthweight infants with term-born infants and achieved a larger group size of very low birthweight infants, the heterogeneity in how object exploration/distraction was defined likely explain the contrasting findings.

Social interactive/monitor. Lack of differences between prematurity group status in social interactive/monitor behaviours may be because these develop later and differences may manifest only later. Atkinson highlights that infants increasingly seek dyadic modes of emotion regulation by 12 and 18 months, while this was unsubstantial at 5.5 months (only 2% of the time compared to 20% by 18-months). Infants born preterm used fewer mother-directed attention seeking behaviours at 18-months, but not at 12-months (Atkinson, 2021). Gazing at caregiver and social bidding was found to decrease with time within a SF episode (Ekas et al., 2013), but did not appear to decrease between the first and second SF episode in this study.

Repetitive movement episodes. Repetitive movement is often analysed as a measure of motor activity. Only one other study has compared the effect of prematurity on motor activity during the still-face paradigm, finding no differences (Chiodelli et al., 2021). However, the authors included only motor activity when infant was also expressing negative affect. In this study, the motor activity primarily of interest was those of rhythmic, stereotyped, nature that is highly common in development (Thelen, 1979). The rhythmic motor activity identified in this study included rocking or bouncing in chair, banging chair and leg kicking. These were extremely common in infants, and may or may not be accompanied by negative affect.

Effect of lower birthweight. In contrast to studies that considered the severity of prematurity, I did not find differences in self-comforting behaviours or social-regulatory behaviours in preterm infants with lower birthweight compared to low birthweight or term infants. One reason might be those studies used gestational age instead of birthweight and the effect of gestational age may be stronger than birthweight. Another reason might be the difference in coding self-comforting behaviours. In previous studies, self-comforting typically includes only mid-line hand clasping behaviours, and not foot-bracing behaviours although these are also towards the midline; and oral self-comforting but not tactile self-comforting behaviours. If prematurity affects the developmental timing and trends in which behaviours rise and fall, differences in self-comforting may be identified if one type of self-comforting behaviour is considered but not the other, more recently developed self-comforting behaviour. Self-comforting behaviours that involve behaviours crossing the mid-line is developmentally important and may be an early indicator of ADHD risk (Begum Ali et al., 2020).

Findings related to behavioural dynamics

This study further examined the possibility that the novel findings related to behavioural dynamics are important and adds to our existing understanding of emotion regulation. First, surrogate analyses provided support that the group differences in behavioural dynamics found are due to differences in underlying, complex, biological processes – processes producing temporal organisation that is far from that generated by a random Gaussian process. Second, correlation analyses addressed whether differences in behavioural dynamics could simply be attributed to differences in the dynamics of the type of emotional regulation behaviours used. Differences in behavioural complexity, measured by ENTb, are unlikely to be the result of specifically to more or less RME or OBJ behaviours contributing to the overall ER behavioural response as the two measures were not correlated. However, RME appears correlated with RR and the present study is unable to tease apart what underlies this correlation; for example, whether lower RR in VLBW infants may be because VLBW show fewer RME behaviours which tend to be more recurrent, or if lower RR and lower RME behaviours might be explained by a common factor, such as delayed development of the ER and motor system.

Dynamic measures were calculated directly from the behavioural states identified and, unsurprisingly, were strongly correlated with the overall behavioural response. Although this was so, the effect of prematurity appeared more strongly related and detectable in statistically analyses for ENTb and RR, than the overall behavioural response where models returned non-significant effects. The strong correlations between these measures of emotion regulation are in line with previous work identifying through Principal Component Analysis that dynamic measures of affect, also derived in the still-face paradigm albeit in the caregiver-present phases, map onto a single factor (Sravish et al., 2013). Taken together, dynamic measures are likely to be derived from the same (emotion regulation) process – and as a result also related to the overall behavioural response - but may characterise different aspects of it. Differences due to prematurity appear to implicate some but not all aspects of emotion regulation dynamics: behavioural complexity and recurrence rate but not dynamic stability.

Possible mechanisms and implications

Behavioural differences may be explained by group differences in susceptibility to distress in the still-face paradigm. Findings related to birthweight after applying the data reduction strategy can help us interpret the extent this was so. For infants who did not show negative affect in SF1, data from SF2 was examined if they later showed negative affect, and otherwise the mean of the two phases was used. This was a conservative approach to analyse emotion regulation behaviours mainly from the phase where infants were first expressing distress. When this strategy was applied, correlations between birthweight and RR, ENTb, RME and OBJ were still detected, albeit only a correlation trending towards statistical significance for OBJ. This shows that the difference in VLBW compared to term or LBW groups were not simply because VLBW infants were less distressed during the still-face paradigm.

Differences in OBJ. Additionally, OBJ was the most strongly negatively correlated with negative affect, in both SF phases. This might suggest that OBJ was indeed the most effective strategy, such that infants were actively distracting themselves from the social stressor using objects, to successfully reduce the negative affect triggered during the still-face paradigm. Alternatively, it might indicate that infants who spent more time manipulating objects were not affected by the disruption of social expectations in the still-face procedure, and continued interacting with the physical environment as they would normally when their caregiver was absent. Research on sustained attention supports the first mechanistic explanation, as attention plays a role in self-regulation and its development has roots in manual exploratory behaviours to actively gather perceptual information (Yuan et al., 2019). For example, when infants develop the ability to reach, they not just reach for, but manipulate the objects while sustaining attention – doing so for a longer duration when objects were novel (Ruff, 1986). Therefore, greater OBJ behaviours is likely to indicate use of objects to sustain attention, during a situation demanding emotional self-regulation. In data obtained when most infants were showing negative affect, the trend of lower birthweight and greater OBJ was not significant. A combination of the two mechanisms probably explains why infants in the VLBW group showed greater OBJ than LBW or term groups. VLBW infants may be paying more attention to objects than the social stressor initially and as a result are less distressed, and when distressed show more object-oriented attentional distraction strategies than the other two groups.

In infant-siblings of children with autism spectrum disorder, Miller and colleagues (2021) found that those who later developed ASD showed greater prolonged visual examination of objects in a non-social context. High levels of prolonged visual examination remained stable from 9-months in this group, in contrast to a reducing trend in other high-risk infant-siblings who did not later develop ASD. Further, this measure at 9-months longitudinally predicted lower social engagement at 12-months in all groups. The present study did not specify that object manipulation be for a prolonged duration and there was no difference in TT of emotional self-regulatory behaviours. Therefore, the present findings do not suggest that the greater OBJ behaviours in VLBW infants is itself an indicator of greater ASD risk in preterm infants born of lower birthweight. On the contrary, research suggests that ability to sustain attention precedes and predicts the development of higher-order self-regulatory processes (Johansson et al., 2015; Papageorgiou et al., 2015) including emotional self-regulation (Brandes-Aitken et al., 2019; Kochanska et al., 2000; S. G. Reck & Hund, 2011), as well as executive functioning abilities (Fisher, 2019). Greater persistence on tasks which relies on attentional effortful control processes (Rothbart et al., 2006), is also correlated with lower inattention, hyperactivity and impulsivity (Frick et al., 2019).

Differences in RME. Differences in RME might reflect differences in expression of negative affect, due to arousal. Motor activity, usually accompanying negative affect or thought to be indicative of agitation and physiological distress (Chiodelli et al., 2021; Feldman, 2009), tends to increase during the still-face phase (Mesman et al., 2009). In this study, the motor activity studied was those of rhythmic, stereotyped, nature, and the present findings suggest that they cannot simply be equated with negative arousal: contrary to what previous research identifying motor activity with negative affect would suggest, infants who showed lower negative affect engaged in more repetitive movement episodes.

Highly common in autistic children and children with intellectual disability (McCarty & Brumback, 2021), repetitive and stereotyped motor behaviours have been purported to be an early risk factor for autism (Wolff et al., 2014). Motor stereotypies are known to play a role in stress regulation, reported to have a calming effect that appears to have a neurobiological basis (McCarty & Brumback, 2021), and occurs during anxiety (Melo et al., 2020). Motor stereotypies occur frequently in early development (Arnott et al., 2010; Leekam et al., 2007; Thelen, 1979). Although there may be a higher rate in 2-year-old children who develop autism (Morgan et al., 2008), motor stereotypies show a declining trend from 8 months to at least 36 - 77 months (Sifre et al., 2021; Uljarević & Evans, 2017), and it may be its persistence that is atypical (Sifre et al., 2021). The cross-sectional nature of the study and the normal developmental trajectory of motor stereotypies means it is not possible to tell whether these 9-month differences in motor stereotypies during emotional regulation indicates developmental risk. Furthermore, contrary to indicating greater risk, RME behaviours in LBW preterm infants appear to reflect development typical of term-born infants at 9-months. Therefore, this study might only point to the effect of prematurity on the timing of, or extent of development of motor stereotypies as part of the normal behavioural repertoire of emotional self-regulatory abilities at 9-months-old, particularly in very low birthweight infants. Future research is needed to examine the timing and contexts in which motor stereotypies may be indicative of socioemotional risk. Furthermore, the development of these behaviours is unlikely to depend only on neurobiological factors. Environmental effects are also highly likely to play a role – children in Romanian institutional care - exposed to deprived environments including gross neglect and understimulating social and cognitive environment - were found to show autism-like phenotypes which include the presence of motor stereotypies (Sonuga-Barke et al., 2017). Therefore, research on whether motor stereotypies can be an important early risk factor also need to address the reasons why motor stereotypies continue to be a preferred strategy in the behavioural repertoire of emotional self-regulation later in childhood.

Differences in ENTb.

In this study, entropy quantifies the information contained in infant's emotional self-regulatory behaviours. In Chapter 2, I discussed how we can conceptualise movement, and by extension behaviour, as a continuous output of brain processing and the information in the output is related to the interactions within the brain. Entropy, a measure of information, may be affected by multiple factors.

Firstly, entropy may be associated with greater biological connectivity as more connections increases the number of interactions available to the system. Findings that infants born preterm with very low birthweight show lower entropy may therefore indicate a less complex organisation of brain processing. This is supported by widespread evidence that preterm infants show diffuse white matter injury (WMI) at birth alongside reduced cortical volume, folding and surface area at later follow-up (J. M. Dean et al., 2014). Further, differences at the level of neural connectivity has been seen in preterm infants, related to lower brain volumes (Ball et al., 2012), in Dean et al., 2014), may more directly implicate functional differences (Pavlova & Krägeloh-Mann, 2013). Reduced structural and functional connectivity, as well as loss of microstructural integrity in white matter tracts, between brain regions such as the thalamus and cortex has been observed in preterm infants relative to term-born peers (J. M. Dean et al., 2014). White matter microstructure of the amygdala, a key neural structure involved in emotional processing, has also been found to be altered by birthweight and gestation age (Stoye et al., 2020). While diffuse WMI, in contrast to localised WMI, is the most common type of white matter injury in surviving preterm infants (Volpe, 2003), the effect of WMI on the development of specific neural systems involved in emotional self-regulation may relate to the present findings. WMI has been associated with alterations to the amygdala (Cismaru et al., 2016), specific alterations to connectivity of the uncinate fasciculus, a tract connecting key structures within the limbic system was found to be associated with socioemotional functioning (Kanel et al., 2021).

Secondly, entropy changes as developing systems go through phases of orderliness and disorderliness, reflecting changes in the dimensionality of the system. Developmental systems are high-dimensional systems that become coordinated in adaptive forms, for example behavioural forms of locomotion are produced by synchronised and coordinated patterns of neuronal and muscular activity to move the limbs and maintain balance; in this study, I have focused on the coordination of behaviours in an emotional self-regulatory context. These forms are called “soft-assemblies” in dynamic systems theory – forms made up of lower level components working in a coordinated manner. Work by Bernstein suggests that learning requires solving the paradox of dimensionality – ability to find a useful solution out of the infinitely possible ways of coordinating movement and at the same time, the ability to coordinate movement in infinitely many possible ways. This work has been built upon by Hadders-algra (2010), showing that infants achieve useful movement forms through motor trial-and-error during a phase of “primary variability”. After successfully achieving a motor form, they can then adapt these forms to task contexts using the underlying dimensionality available in altering these forms. Therefore, the differences observed in entropy in this study may also result from differences in how emotional self-regulatory behaviours are assembled and coordinated at 9-months old. The results may suggest that birthweight implicates the stage of development of the emotional self-regulation achieved by 9-months.

Finally, entropy may also be a result of more random and disorganised interactions, and may indicate greater emotional dysregulation (Berry et al., 2019). The finding that negative behavioural affect positively correlates with entropy supports this idea. However, going back to the first explanation, this positive correlation may also suggest that infants who show more negative affect are using more neural resources to cope with the emotion.

Overall, what this study shows is that prematurity affects the behavioural response to the still-face paradigm, both in the behavioural profile of emotional self-regulation and the temporal structure of these behaviours. This reflects differences in the systemic organisation of emotional self-regulatory behaviours at this point in development, around the time when a range of motor and attentional skills are developing rapidly. What the results might imply is VLBW preterm infants, may take a different developmental trajectory, one that is constrained by neural and biological differences at birth, as well as early experiences that shapes the progressive development of abilities. Findings of differences in complexity shows that the systems underlying emotional self-regulatory behaviours are already being shaped by biological and environmental factors within the first 9-months of life. This further emphasises the importance of acting early to reduce the effects of parental and environmental risk factors known to influence socioemotional risk, such as maternal depression, family environment, and socioeconomic deprivation.

Strengths, limitations and future directions

In hindsight, a limitation of the coding scheme was that attentional engagement without active manipulation of objects was not examined. In Chapter 3 (Methodology), the development of the video coding scheme was described, and the conservative decision was made to code attentional strategies only where there was active manipulation of objects. This meant it was not possible to tease out whether the differences found in this study might suggest that VLBW infants need to actively manipulate objects in order to sustain attention, while LBW and Term infants are able to separate attentional control from motor function. Nevertheless, a code combining both Object and Environment Engagement was coded using the ICEP and available in the wider Theirworld Edinburgh Birth Cohort Study (Ginnell et al.,

2021) and future work can address this question. Vocalisation, arguably also a motor behaviour, was not examined in the video coding scheme which focused on bodily movements.

By conceptualising emotion and its regulation as a dynamic system, the methods used in this study does not attempt to distinguish which processes are the result of emotionality or the expression of emotion and which are regulatory processes to alter the emotion; which are self-imposed or externally-driven. Instead the focus is on the activity of the behavioural system during a context that emotion is elicited, assuming that emotion and its regulation draws on the same processes (Campos et al., 2004), or that even if those processes are different, regulatory processes continuously interact with processes underlying emotionality to exert its effects. The dynamic nature of emotion and its regulation, which are the result of complex spatiotemporal processes, make this a reasonable assumption to make in examining the organisation of emotional self-regulation. Nevertheless, analysis of the factor structure of temperament have identified two distinct domains of emotional reactivity and regulation. The interaction of the two processes in time may make up the whole system, but the individual processes may have different implications on developmental outcomes, and the present dynamic systems analysis cannot address this.

The study's major strength is in deploying dynamic systems analysis to provide novel insights into infant's emotional self-regulation within an established developmental paradigm. By using an analytic method, RQA, that extracts temporal information, the study fills a major gap in research on emotion regulation to study its dynamic nature in a paradigm that is inherently well-suited for studying dynamics.

In doing so, however, a number of assumptions were made from drawing together evidence from multiple disciplines. Future research can address these assumptions. Firstly, integrating theories of emotional regulation and findings from the extensive research using the still-face paradigm led to the identification of five behavioural states with distinct functions as measures of infants' emotional self-regulation. I will address in the next chapter whether there is evidence that the behaviours examined in this study, elicited during the self-regulation of emotions, represent the product of emotionality and regulatory processes. Secondly, as described in Chapter 2 and in the introduction of this chapter, theoretical justification and indirect empirical evidence, from the study of dynamic physical systems in theoretical physics and from research on motor control, led to the assumption that entropy of a signal reflects to the organisation of the neurobiological system. With rich biological alongside behavioural data in the TEBC, the obvious next step for future research is to examine links between neonatal amygdala microstructural differences and 9-month behavioural complexity, to provide direct evidence to support this.

5.5. Conclusions

Relative to term-born infants, infants born preterm with very low birthweight show a different behavioural pattern during emotional self-regulation, including in the type of behaviours used as well as in the dynamics of behaviour. Differences were identified in behaviours related to object manipulation during a distressing situation, and may indicate that infants born with very low birthweight are capable of, and are actively using attention to regulate emotions at 9-months-old. Differences in repetitive movements were not simply an indicator of negative arousal; its occurrence is a part of the normal behavioural repertoire of infants during emotional self-regulation and at 9-months-old, and fewer repetitive movements, as seen in infants in the VLBW group relative to the term-group, may characterise greater socioemotional risk. The differences in behavioural complexity might indicate that within the first 9-months of life, the systems underlying emotional self-regulatory behaviours are already being shaped biological and early environmental factors, or may respond different to emotional demands.

6. Relationships between infant temperament and emotional self-regulation

6.1. Introduction

Emotional self-regulation in a temperamental systems framework

In Chapter 2, I showed that emotional self-regulation can be considered within a temperamental systems framework (Mary K. Rothbart & Sheese, 2007). Temperament is defined as relatively enduring individual differences in reactivity and self-regulation, including in emotional, motor and attentional domains (Mary K. Rothbart & Derryberry, 1981)). While reactivity refers to the temporal profile of emotional, motor and attentional reactions, self-regulation refers to the processes modulating reactivity (Mary K. Rothbart et al., 2004; Mary K. Rothbart & Derryberry, 1981). The Infant Behaviour Questionnaire was developed to capture parent-report of infant temperament across dimensions identified to capture the involvement of emotional and attentional systems when reacting to different stimuli and situations (Mary K. Rothbart et al., 2004), for example, rate of recovery from distress, excitement or general arousal; and attention to objects for extended periods of time. Factor analysis confirmed that the questionnaire indeed measures a combination of reactivity and regulation as it contains a three-factor structure comprising two factors related to reactivity - negative affectivity and surgency/extraversion – and a factor related to orienting/regulation (Gartstein & Rothbart, 2003). The orienting/regulation factor is thought to be related to later developing Effortful Control (Gartstein & Rothbart, 2003) – as described in the Chapter 2, a key process underlying infant's early self-regulatory abilities (Nancy Eisenberg et al., 2010; Mary K. Rothbart & Rueda, 2006). In the Infant Behaviour Questionnaire (Revised) (Gartstein & Rothbart, 2003), Negative affectivity contains the dimensions of Sadness, Distress to Limitations, Fear, and Falling Reactivity; Surgency/extraversion contains Approach, Vocal Reactivity, High Intensity Pleasure, Smiling and Laughter, Activity level and Perceptual sensitivity; and finally the Orienting/regulation factor contains Low intensity pleasure, Cuddliness, Duration of Orienting and Soothability.

Gap in the understanding of relationships between emotional self-regulation and temperament

Despite the close conceptual links between the structure of temperament with emotional self-regulation, surprisingly few studies have investigated the links between the two in the still-face paradigm (Mesman et al., 2009). In their review, Mesman and colleagues identified two studies, one which found that infants who were rated by parents as having high negative affectivity showed fewer self-comforting behaviours and object orientation, but there was no relationship with negative affect during the still-face phase (Braungart-Rieker et al., 1998). However, more recently, Yoo and Reep-Sutherland (2013) found the opposite pattern of results, that negative reactivity *was* associated with negative affect - albeit more so during the reunion phase – and negative reactivity was not associated with self-comforting and object-orientation behaviours. Another study identified in the review did not find that infant fussiness (being more fussy, more reactive to novelty and more difficult to soothe) predicted infant affect or self-soothing after adjusting for maternal behaviour (Tarabulsy et al., 2003), though Mesman and colleagues (2013) later found evidence that less fussy infants showed more positive affect at baseline and reunion, and gaze at parent in the still-face episode. The Effortful control and negative affect subscale of the Early Childhood Behaviour Questionnaire (Putnam et al., 2006) was found to be associated with an emotion regulation composite comprising negative affect, physical approach and gaze aversion in the still-face phase (Gago Galvagno et al., 2019).

Prematurity and temperament

Temperament is genetically and biologically-based and can be vulnerable to exposure to early life stress in preterm birth. In the reactivity domain, higher temperamental negative affectivity has been reported in infants born preterm (Caravale et al., 2017; Pesonen et al., 2006), although this finding is inconsistent (Cassiano et al., 2017; Langerock et al., 2013; Voigt et al., 2013). Altered negative affectivity in premature birth has been attributed to infants' response to painful and uncomfortable medical procedures in the NICU (Klein et al., 2009; Valeri et al., 2015; Voigt et al., 2013). Although negative emotional reactivity may be impacted by neonatal pain and distress, parental and environmental risk and protective factors may also contribute to the development of temperament later in life (Valeri et al., 2015; Voigt et al., 2013). In line with this, higher biobehavioural reactivity to pain and distress predicted higher maternal-rated temperamental negative emotionality, but this association is seen in the first but not second year of life (Valeri et al., 2015).

In the regulatory domain, preterm birth appears to be associated with altered effortful control, in particular difficulties with attentional focusing and attention span or persistence (cite?). Lower cuddliness, related to the enjoyment of closeness with caregivers, has also been reported (Cosentino-Rocha et al., 2014). This trait affects the involvement of caregivers in regulation of infants' emotional states, is potentially implicated by maternal separation immediately following preterm birth. Biological effects of preterm birth also appear to influence the regulatory domain of temperament, as suggested by findings that grey matter abnormalities are associated with lower Cuddliness at 3-months-old (Tamm et al., 2020).

Behavioural dysregulation can be seen as the interaction between emotionality and regulation of it (Keenan, 2000; Mary K. Rothbart et al., 2004). Low effortful control in the presence of high negative emotionality predicts behaviour problems (Nancy Eisenberg et al., 2000), and anxiety (Nigg, 2006).Further, there is evidence that the association between high negative affectivity with behavioural problems is stronger in preterm-born infants than their peers born at full-term, while lower effortful control predicted behavioural problems in both groups to the same extent (Martins et al., 2021). This suggests that preterm birth may be especially susceptible to altered emotional reactivity, and the development of effortful control is an important protective factor. Therefore, as a first step, it is important to understand how reactivity and regulatory processes shape behavioural output.

Current study

In the general methodology, I described the development of a new coding scheme, which identified behaviours occurring during the still-face paradigm as emotional self-regulatory behaviours, given they occurred in a distressing context. In in Chapter 5 (Study 2A), the effect of prematurity was then investigated on the behavioural measures at 9-months-old, based on the theoretical assumption that emotional reactivity and regulation continuously interact within a dynamic system and that the temporal dynamics reflect the interactions within this system. Measures of infant temperament characterise emotional reactivity and regulation in another context. Therefore, if it is possible to demonstrate associations between behaviours purported to result from interactions within an emotion regulation system, with other measures of the same underlying process, this would strengthen the interpretation of those findings and the validity of the video coding scheme. Furthermore, understanding how these early identifiable factors relate to behavioural patterns of emotion regulation will enable a better understanding of what shapes socioemotional risks, and can be applied to understanding the effects of preterm birth on emotion regulation.

This study will compare behavioural measures derived from the still-face paradigm with a previously validated questionnaire of the temperamental domains of emotional reactivity and regulation - the Infant Behaviour Questionnaire Revised (IBQ-R) (Bosquet Enlow et al., 2016; Gartstein & Rothbart, 2003). The former includes both new measures of emotional self-regulation, and a widely-used measure of negative affect from the ICEP Video Coding Scheme, in order to understand more comprehensively the relationship between behavioural expressions of affect, as well as behaviours related to emotional self-regulation. This study aims to explore the relationship between measures of infant temperament with (A) the range of behaviours and (B) the behavioural complexity, during emotional self-regulation in the still-face paradigm.

6.2. Methods

Participants and procedures

The same sample of infants included in the analytic sample in Chapter 5 (Study 2A) was included in this study. Exclusion criteria were infants who did not have data on the temperamental domains of interest.

Of 111 infants who participated in the still-face paradigm with analysable data on emotional self-regulation, 9 infants (2 term, 7 preterm) had missing data on the IBQ-R. Additionally, 1 term infant had missing data on all items in the Soothability scale. The median number of incomplete items on the IBQ-R short form was 5 items, with an interquartile range between 2 and 10 items.

Temperamental domains. Infant temperament was measured using parent-report of 91 items on the Infant Behaviour Questionnaire Revised, short form (Putnam et al., 2013). The IBQ-R measures temperament along 3 domains, across 14 subdomains (Table 6-1). Temperamental Negative reactivity (the mean of scores on the Sadness, Distress to Limitations, Fear, and Falling Reactivity) and Orienting/Regulation (the mean of Low intensity pleasure, Cuddliness, Duration of Orienting and Soothability) was used in this study.

Temperamental subdomains. Yoo & Reeb-Sutherland (2013) found associations between SF affect and negative reactivity defined as Distress to Limitations and Fear. In contrast to the original factor structure proposed by Gartstein & Rothbart (2003), Cuddliness (Bosquet Enlow et al., 2016; Gartstein et al., 2005) and Soothability (Bosquet Enlow et al., 2016) had low factor loadings on the Orienting/Regulation domain. Gartstein & Rothbart (2003) suggests that these two factors likely reflect caregiver involvement in infants' early regulatory abilities, before infant's self-regulatory abilities via attentional and inhibitory control become more developed. Greater Soothability was also found to be related to greater efficiency of attention disengagement, a relationship that appeared to be indirectly attributed to serotonin signalling (Leppänen et al., 2011). Therefore, the scales of Distress to Limitations, Fear, Cuddliness and Soothability were also individually examined as these may be more pertinent to emotion regulation during the still-face paradigm. All domains and subdomains scores were calculated after excluding missing data on any item or scale.

Table 6-1 – Summary of IBQ-R factor structure (adapted from Gartstein & Rothbart, 2003)

Domain	Subdomain	Description
Surgency/ extraversion	Approach	Rapid approach, excitement and positive anticipation of pleasurable activities
	Vocal reactivity	Amount of vocalisation exhibited in daily activities
	High intensity pleasure	Amount of pleasure or enjoyment related to high stimulus intensity, rate, complexity, novelty and incongruity
	Smiling and laughter	Smiling or laughter in general caregiving and play situations
	Activity level	Baby's gross motor activity, including movement of arms and legs, squirming and locomotor activity
	Perceptual sensitivity	Amount of detection of slight, low intensity stimuli from external environment

Negative affectivity	Sadness	General low mood, lowered mood and activity related to personal suffering, physical state object loss, or inability to perform a desired action
	Distress to Limitations	Fussing, crying or showing distress when (a) in a confining place or position, (b) involved in caregiving activities, (c) or unable to perform a desired action
	Fear	Startle or distress to sudden changes in stimulation or novel physical objects or social stimuli; inhibited approach to novelty
	Falling reactivity	Rate of recovery from peak distress, excitement, or general arousal; ease falling asleep
Orienting/ regulation	Low intensity pleasure	Amount of pleasure or enjoyment related to low stimulus intensity, rate, complexity, novelty and incongruity
	Cuddliness	Expression of enjoyment and moulding of body to being held by caregiver
	Duration of Orienting	Attention to and/or interaction with a single object for extended periods of time
	Soothability	Reduction of fussing, crying or distress when caregiver uses soothing techniques

Behavioural measures from the still-face paradigm

Behavioural indicators of negative affect

Data on infant negative affect was available from another doctoral study within TEBC (Ginnell et al., 2021), obtained using video coding with the Infant and Caregiver Engagement Phases (ICEP) video coding scheme (C. Reck et al., 2009). Negative affect was defined as negative engagement, during which the infant is showing negative facial expressions, is protesting or withdrawn, and was expressed as proportion of the total phase time.

Emotional self-regulation – behavioural response and dynamics

Five types of behaviours thought to reflect emotional self-regulation during the still-face phase were micro-analytically coded. These included Self-comforting (SC), Social interaction/monitor (SOC), Object distraction/exploration (OBJ) and Repetitive Movement Episodes (RME), and distancing. However, distancing behaviours were not examined as a unique category this study, because very few infants showed these behaviours in the still-face phases. These were calculated as the proportion of time when these behaviours occurred in each phase. An ER composite score was also calculated, representing the total proportion of time spent in any of the five behavioural states.

The dynamics of infant's behavioural response during the still-face phase was derived from Recurrence Quantification Analysis of the behavioural timeseries. Information entropy of the behavioural response was used as a measure of behavioural complexity. This was selected as it was found to be different in infants of VLBW and has the strongest theoretical justification that it is related to the systemic organisation of infant's emotional self-regulatory system.

The data-reduction strategy described in Study 2A was employed, where behavioural data from the SF phase where infants first showed negative affect was used. Where infants did not show negative affect in either SF1 or SF2, or if no data on negative affect was available, the mean of the two phases was used.

Statistical analyses

Descriptive statistics of IBQ domain and subdomain scores was calculated separately for term and preterm groups, and for the overall sample. Means with standard deviations are provided for normally distributed variables, and Medians with Interquartile Range for non-normally distributed variables.

Due to non-normality of IBQ domain-level and subdomain measures, measures of ER and negative affect, a non-parametric method was selected to examine correlations. Spearman's rank correlation coefficients were calculated for bivariate comparisons between each IBQ domain or subdomain, with each still-face behavioural measures. Spearman rank correlation coefficients was also calculated for bivariate comparisons between negative affect with each measure of ER. The statistical significance of correlation coefficients was assessed at the 95% confidence level. Correlation analysis was examined the relationship in the entire sample. As this was an exploratory study, Bonferroni correction for multiple comparisons was not applied (Armstrong, 2014). Statistical analyses were conducted in R (version 4.02), on Rstudio (version 1.1).

6.3. Results

Descriptive statistics

Table 6-2 shows the descriptive statistics of IBQ domain and subdomain scores.

Table 6-2. Descriptive statistics of IBQ domain and subdomain scores

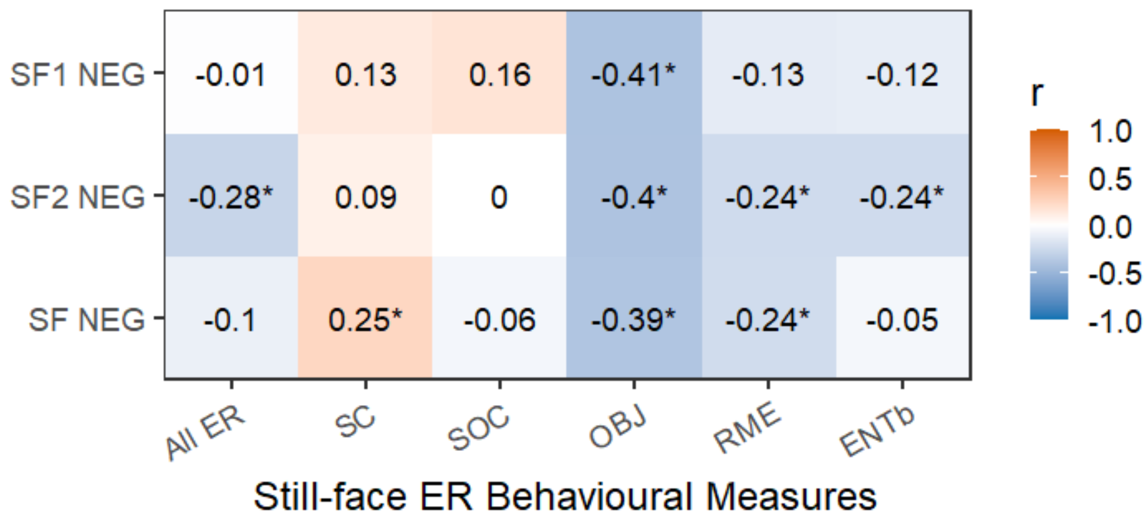
Characteristic	Overall, N = 111[1]	Term, N = 61[1]	Preterm, N = 50[1]
IBQ domain			
Negative reactivity	3.44 (0.71)	3.51 (0.75)	3.34 (0.64)
Regulation	4.61 (0.77)	4.54 (0.77)	4.71 (0.76)
IBQ subdomain			
Distress to limitations	4.00 (0.94)	4.07 (0.89)	3.91 (1.01)
Fear	2.63 (1.81, 3.79)	2.50 (1.80, 3.83)	2.67 (1.92, 3.55)
Cuddliness	4.33 (3.50, 5.33)	4.33 (3.58, 5.17)	4.80 (3.50, 5.58)
Soothability	4.00 (3.50, 5.86)	4.00 (3.45, 5.80)	5.29 (3.69, 6.14)

[1]Mean (SD); Median (IQR)

Correlations between negative emotionality and ER during the SF paradigm

Figure 6-1 presents the results of correlation analysis between negative affect and ER behaviours from data in the reduced dataset, as well as from data specifically from SF1 and SF2. Negative affect was negatively correlated with OBJ in SF1, SF2 as well as in the reduced dataset (p<0.001); negatively correlated with RME in SF2 and in the reduced dataset; positively correlated with SC (rho=0.25, p=0.014) only in the reduced dataset; and negatively correlated with ENTb (rho=-0.24, p=0.025) and the composite ER measure (rho=-0.28, p=0.007) only in SF2.

Figure 6-1. Correlation between still-face negative affect and still-face behavioural response and dynamics



Correlations between SF measures and IBQ domains

Figure 6-2 shows the Spearman rank correlation coefficients for each comparison. Negative affect during the still-face phase (SF NEG) was positive correlated with the negative reactivity domain of the IBQ (rho=0.16, p=0.107) and negatively correlated with the regulatory domain (rho=-0.14, 0.161). RME was negatively correlated with negative reactivity (rho=-0.15, p=0.123), and SC was positively correlated with orienting/regulation (rho=0.11, p=0.253). However, these were weak correlations and none of them reached statistical significance.

Correlations between SF measures and IBQ subdomains

When examining correlation with individual IBQ subdomains, moderate positive correlations between ER composite (rho=0.25, p=0.011) and SC (rho=0.22, p=0.029) with Cuddliness domain of orienting/regulation, and a moderate negative correlation between SF NEG and Cuddliness (rho=-0.21, p=0.036) reached significance. There was also a statistically significant moderate negative correlation between RME and the Fear subdomain of negative reactivity (rho=-0.21, p=0.030), and a non-significant weak negative correlation between with the Soothability subdomain of orienting/regulation (rho=-0.14, p=0.158)

Figure 6-2. Correlation between IBQ domain and subdomains with still-face measures

6.4. Discussion

This exploratory study reveals interesting patterns of correlations between behavioural indicators of affect and emotion regulation with parental report of temperament. Although I did not find significant correlations with domain level constructs of temperamental negativity and regulation, this is not unexpected as the temperamental domains measure reactivity and regulation in both emotional and non-emotional contexts, and is inherently a multilevel construct comprising aspects of behaviour (such as inhibition to novelty), psychological experience (such as of fear), and physiological arousal (such as sensitivity intensity of stimulation) - responses that depend on different types of neural activity (such as of reactivity and modulation of limbic networks related to emotion) (Nigg, 2006). As I shall discuss, evidence on the correlations with subdomains of temperament support the construct validity of behavioural measures of emotion self-regulation used in Chapter 5 (Study 2A). The pattern of correlation with CUDD provides the strongest direct evidence for the construct validity of self-comforting behaviours. Interpreting correlations with behavioural measures of affect enable support for the validity of RME, OBJ and ENTb, although results remain inconclusive for SOC. Notably, the relationship between temperament and emotion regulation have implications on how we understand the effect of preterm birth on the emergence of behavioural difficulties.

Comparison with other studies

There have been contradictory reports of how infant behaviours during the still-face paradigm relates to parent-report of infant temperament. The lack of a correlation between the IBQ reactivity domain or subdomains with negative affect during the still-face phase is in line with Braungart-Rieker (1998), a study of comparable sample size to mine. This suggests that the corresponding correlation identified by Yoo & Reeb-Sutherland (2013) might be a false positive result, due to their smaller sample size (n=60). The lack of correlations between temperamental negative affectivity and SC and OBJ behaviours, however, is in contrast with Braungart-Rieker (1998). The differences in these findings may be due to the way SC and OBJ were defined, as Braungart-Rieker (1998) and Yoo & Reeb-Sutherland (2013) both used the ICEP definition, where self-comforting included only oral self-comforting and self-clasping, and object engagement included gaze at objects without the requirement of manual manipulation. Similar to Tarabulsy and colleagues (2003), we did not find that infant's ease of soothing correlated significantly with any SF behavioural measure, a finding that contrasted with what Mesman and colleagues (2013) reported. However, it has to be noted that those studies used a different questionnaire (the Infant Characteristics Questionnaire (J. E. Bates et al., 1979) to measure overall difficult temperament as a global composite including measures on infant fussiness and difficulty to soothe.

Evidence of construct validity

The findings demonstrate the convergent validity of self-comforting behaviours as measures of regulation. Self-comforting was correlated with temperamental regulation, specifically the subdomain of cuddliness. Total ER composite also correlated with Cuddliness but this appears to be driven predominantly by self-comforting behaviours. These two behavioural measures were not related to reactivity, showing discriminant validity as measures of emotion self-regulation.

In line with the idea that indicators of affect expression are the result of emotionality and regulation, negative affect during the SF paradigm was positively correlated with temperamental reactivity, and negatively correlated with temperamental regulation. Infants who were more upset showed more self-comforting behaviours, corresponding to how emotionality triggers regulation and the two interact dynamically. Importantly, the temperamental trait of cuddliness showed opposite patterns of correlation with negative emotionality and self-comforting. This suggests that higher temperamental regulation was not just related to more regulatory behaviours, but potentially also successful reduction of negative emotions. By 9-months, the influence of regulation on reactivity may be more important in explaining infant's emotional expression.

Although no correlation between ENTb and temperamental regulation or reactivity was found, there is evidence of discriminant validity of ENTb as a measure of the emotion regulation system. In Chapter 6 (Study 2B), I showed that ENTb was strongly correlated with ER composite - expectedly so, as it was derived from behaviours indicative of ER. Despite this, ER composite was correlated with temperamental regulation but ENTb was not. This suggests that ENTb characterises an aspect of the ER system that is distinct from what aggregate measures of ER behaviours characterise. However, further research is needed to confirm the idea that ENTb is linked to biological neural activity.

The finding that ENTb was correlated to expression of negative affect also indicates convergent validity. Interestingly, there appears to be a difference in patterns of correlation when infants first expressed negative affect, and in SF2 where some infants may be extremely distressed. When infants first became upset, they used more self-comforting behaviours, and fewer object and repetitive motor behaviours. However, the total ER composite was unrelated to negative affect, even though it appears to be related to temperamental regulation in a similarly to self-comforting behaviours. In SF2, expression of negative affect correlated with a lower ER composite as well as lower ENTb. Taken together, these patterns suggest that, initially, self-comforting behaviours, over and above other ER behaviours, may be more effective for regulating negative emotions. However, when stressful situations become prolonged or extended, in the absence of the caregiver, the ability to continue engaging the neural systems to self-regulate emotions becomes crucial.

At first brush, the finding of a correlation between RME and the FEAR subscale of temperamental negativity suggests that RME is related to reactivity. However, contrary to what would be expected if motor activity simply reflected the level of physiological arousal (Chiodelli et al., 2021; Feldman, 2009), infants who were rated as more reactive in fact showed fewer repetitive motor behaviours. One plausible explanation could be that fearful responses in the still-face paradigm are characterised by an inhibited motor activity, linked greater inhibited approach to novel stimuli measured by the FEAR subscale of the temperament questionnaire. Fear reactivity is the arousable, responsiveness and excitability of behavioural, and neurophysiological systems, but within the first year of life, infants develop increased control over reactive behaviours (Mary K. Rothbart et al., 2004). Infants rated by their mothers as more reactive to fear show inhibited motor activity and emotional expressions to fear in a novel social situation (Diaz & Bell, 2012). Infants with more fearful temperaments may show high negative affect and motor activity early on, but later develop more inhibited behaviour in similar social situations inducing fear (S. D. Calkins et al., 1996; Degnan & Fox, 2007; N. A. Fox et al., 2001; Hane et al., 2008; Kagan & Snidman, 1991). This suggests that reactivity and regulation likely influence each other (Witt et al., 2014). Indeed, infants who show less regulation develop greater fear reactivity over time (Braungart-Rieker et al., 2010)). Inhibited fear expression and motor activity (Diaz & Bell, 2012), as well as avoidance or inhibited approach behaviours in novel situations (S. D. Calkins et al., 1996; N. A. Fox et al., 2001; Hane et al., 2008; Kagan & Snidman, 1991), were predicted by greater right frontal 4-6 Hz EEG neural activity and concomitantly, asymmetric frontal activity. This likely contributes to the inhibition of subcortical limbic activity. In support, asymmetric right frontal activation has been observed in the still-face paradigm, and is moderated by the initial intensity of play interactions, which contributes to greater unpredictability when the caregiver becomes absent in the still-face phase; and right frontal activation was only marginally significantly correlated with negative emotionality (Gartstein, 2019). Taken together, RME might not simply reflect reactivity but also developing regulatory mechanisms that lead to patterns of withdrawn, inhibited motor activity to fear in the still-face paradigm. Another piece of evidence that supports this is the present finding that the amount of negative affect expressed was related to regulatory temperamental traits, but not reactivity traits – suggesting that voluntary processes start to play a crucial role to control emotional expression by 9-months-old.

Surprisingly, OBJ was not correlated with any of the IBQ measures examined. Using objects to provide attentional distraction may be more related to effortful and inhibitory control, which was not measured in the IBQ regulation domain, and only included later in 2-year temperamental questionnaires (Mary K. Rothbart et al., 2001). Nevertheless, OBJ was the most strongly negatively correlated with negative affect during both still-face phases. This effect remained the same even after data reduction to include the phase where infants did show negative affect, a conservative strategy to infer that infants were regulating emotion. This is in line with findings that infants who gazed at objects were less distressed when approached by a stranger which normally elicits fearful reactions (Braungart-Rieker et al., 2010).

SOC was also not correlated with any of the IBQ measures examined. SOC includes both social interaction and monitoring. Therefore, low variability of SOC (which has an interquartile range of X) because infants consistently turn away from the caregiver, may explain the lack of a correlation. Additionally, not all infants have started to use mother-directed interactive behaviours consistently as an emotion regulation strategy, as this strategy emerges within the first year of life but continues to increase from 12-18 months (Atkinson et al., 2021). Socially-oriented emotion regulation strategies were more common in 18-month-old infants than 6 or 12-month old infants (Mangelsdorf et al., 1995).

Implications of findings on premature birth

Not all temperamental domains are related to infants' emotion regulation abilities in the still-face paradigm. The results emphasise the role of caregivers in scaffolding the development of emotional self-regulation (Kopp, 1982). Instead of relying more on caregivers to regulate emotions, infants who were rated as enjoying closeness with caregivers were more successful in independently regulating emotions when their caregiver was absent. Cuddliness may also be related to the crucial importance of close body contact with the caregiver both as part of attachment formation and in the regulation of distress (Ainsworth, 1979; Bowlby, 1969). As the formation of an attachment relationship can be disrupted by separation from mother following preterm birth, improving this will likely have long-term effects on infants' abilities to self-regulate emotions and protect against later difficulties.

While significant, the correlations between ER with temperament in this study were weak. Temperament, biologically or genetically-based traits that are relatively stable (Bornstein et al., 2019), influences infants' capability to self-regulate emotions, but do not entirely determine it. Environmental risk factors such as low socioeconomic status, alongside low effortful control and high negative affectivity, predicted behavioural problems in preterm children (Burnson et al., 2013; Cassiano et al., 2017), and in infants from low-income backgrounds (Northerner et al., 2015). As discussed in the introduction, there are also modifiable environmental factors, such as parenting stress, that affect whether exposure to pain in the NICU leads to elevated negative affectivity. This highlights the importance of supporting families, particularly those with identified risk-factors, to create conducive environments for preterm infants' emotional development.

Strengths, limitations and future directions

This study focused on exploring subdomains of temperamental regulation and reactivity which had evidence of a specific association to emotional self-regulation in the still-face paradigm. I did not examine Duration of Orienting, a subdomain of temperamental regulation defined in a similar way to OBJ behaviours in the still-face phase. However, the correlation between OBJ and the domain-level temperamental regulation measure was very close to 0, suggesting that it is unlikely that I missed an important correlation between OBJ and Duration of Orienting.

Distinct neural networks appear to underlie approach and withdrawal/avoidance behaviour, driven by asymmetric left or right frontal activity respectively, to modulate amygdala activity (Hane et al., 2008). Higher levels of temperamental Surgency, related to Approach and Activity level, was associated with left frontal EEG activity in the still-face phase. Further positive emotionality appears to reduce infants' susceptibility to fear-related neural responses in the still-face phase (Gartstein, 2019). While I focused on temperamental negative emotionality as the still-face paradigm was designed to induce negative affect, future research should also consider how surgency might moderate infants' behavioural response in the still-face paradigm. This may be another piece of the puzzle in understanding preterm infants' emotion and behavioural regulation, as research on temperamental differences between preterm and term children consistently point to higher Activity Level (in the surgency domain) alongside lower Attentional Focusing and Attention span/persistence (in the effortful control domain) (Cassiano et al., 2020). Some studies have also reported an under-reactive pattern, of lower reactivity to high intensity positive stimuli that was related to both brain abnormalities (Tamm et al., 2020) and painful clinical procedures (Klein et al., 2009), or may show the opposite pattern, a preference for high intensity stimuli related to having a higher threshold for stimulation following exposure to the highly stimulating sensory environment in the NICU (Montirroso et al., 2016).

Gray matter abnormalities have been found to be associated with less cuddliness and under-reactive temperament (Tamm et al., 2020). Preterm infants have also been reported to show more fear (Witt et al., 2014) or less fear (Langerock et al., 2013). Future studies can consider whether preterm birth moderates associations between temperament and emotional self-regulation, and in particular focus on how fearfulness and cuddliness may impact the development of emotion self-regulation in preterm infants.

6.5. Conclusions

To conclude, there is evidence that behavioural measures obtained from the still-face paradigm provide valid indicators of infants' emotional self-regulatory abilities. Self-comforting behaviours appear to be uniquely related to regulation, but repetitive behaviours may be the result of regulatory process altering emotional reactivity. Entropy, proposed to represent ad-hoc neural activity related to emotion regulation during the still-face paradigm, was not related to enduring temperamental trait, but was related to negative affect expression. These results fit within neuropsychological models of emotion regulation recognising the dynamic process of emotion and its regulation, and provide integrative evidence that these are similar to the processes of reactivity and regulation set in a temperamental framework of emotion regulation. There appears to be a link between temperamental traits and behavioural responses to emotionally stressful situations, but this is far from deterministic. Modifiable factors, especially the development of secure attachment, can afford resilience to the effects of early life adversity on the development of emotional self-regulation.

7. The influence of motor development on behaviours during emotional self-regulation

7.1. Introduction

In Chapter 1, I showed that preterm infants are at risk of socioemotional behavioural difficulties and that motor developmental delays are widely documented in preterm populations and tend to precede behavioural difficulties. In Chapter 1, I also reviewed theoretical arguments that higher-level mental capacities involve motor skills, and motor skills can influence their development.

In Chapter 2 I highlighted the importance of understanding emotional self-regulation, and I then characterised differences in the behaviour of term and preterm infants during a paradigm to elicit emotional self-regulation. I employed a dynamic systems approach to do so. As discussed in Chapter 2, entropy potentially reflect the micro-level processes involved in emotional self-regulatory behaviours. In this section, I outline further evidence on why motor development may be important for understanding the development of emotional self-regulation and the existing gap in understanding and should be considered in understanding prematurity-related differences in emotion regulation.

Motor skills and socioemotional development

Infants socioemotional abilities are grounded in their motor skills. Hand-to-mouth behaviours are present from birth, and are related to an early motivation to seek oral stimulation (Adolph & Franchak, 2017; Needham & Libertus, 2011; Thelen, 2005). These movements are also used to self-soothe in the presence of negative emotions (Kopp, 1982).

Early motor experiences shape the development of cognitive and socioemotional abilities (Campos et al., 1989, 2000; Skranes, 2019). Reaching and manual exploration has been thought to facilitate the development of effortful control self-regulatory abilities, in particular by facilitating voluntary attentional control. When infants learn to reach (Lobo & Galloway,

2013) or have more active reaching experience (Libertus & Needham, 2010), they start to show greater interest in object, and explore objects more when allowed to. Reaching also leads to greater manual and oral exploration (Needham et al., 2002) which generates perceptual feedback, and infants who grasped objects more and held them for longer duration were better able to identify perceptual changes in object appearances in a habituation paradigm (Baumgartner & Oakes, 2013; Perone et al., 2008), as well as were better able to integrate multisensory information (Eppler, 1995). Ruff (1986) considered that when infants manipulate objects, they are sustaining attention to actively seek perceptual information, and demonstrated evidence for in showing that duration of looking and manual exploration of objects decreased over time, when the object was no longer novel. Yuan and colleagues (2019) further showed that object manipulation is coupled with directing gaze towards the object, by manipulating the weight of objects to make it more or less accessible to hold and manipulate objects. They demonstrated that infants reaching to heavy or light toys only made the same number of reaches, however the duration of manual exploration, and duration of visual attention to the object were shorter in the heavy than light object condition. Compared to the heavy object condition, infants in the light object condition also showed greater proportions of interactions with the toy requiring sustained attention coupled with manual explorations, in contrast to brief interactions.

There is also evidence that sustained attention with objects develops alongside the attentional network, which affects the development of effortful control, the ability to inhibit a dominant response and engage in a subdominant one. Sustained attention during free play with objects during the time when attention network is developing predicted effortful control at around 2-years (Johansson et al., 2015; Kochanska et al., 2000), assessed comprehensively across different domains of attentional, motor and behavioural tasks (Kochanska et al., 2000) or using parental ratings (Johansson et al., 2015).Sustained attention assessed using attention to images of objects, rather than during manual play, also predicted later effortful control (Brandes-Aitken et al., 2019; Papageorgiou et al., 2014) as well as emotion regulation and executive functioning (Brandes-Aitken et al., 2019; S. G. Reck & Hund, 2011). Sustained attention in 8-month infants during interactions with objects were associated with better overall cognitive development at 2-years, even after adjusting for a number of demographic variables that may impact experience with objects and developmental outcomes (Kopp & Vaughn, 1982). Kochanska and colleagues (2000) further showed that better effortful control led to more successful modulation of the intensity of emotions and better behavioural restraint. Greater sustained attention in infancy also predicted better performance on the A-not-B task at 2-eyars (Johansson et al., 2015) Furthermore, sustained attention assessed at 7-month in over 1000 infants was also found to mediate the association between poverty with development of effortful control, emotion regulation and executive functions (Brandes-Aitken et al., 2019).

Gap in existing research on motor development and emotional self-regulation

Existing work have suggested that age affects the development of emotional self-regulatory behaviours (de Weerth et al., 1999). Age-related changes have been attributed to the development of attention and orienting network. For example, as I reviewed in the introduction of Chapter 5 (Study 2A), infants are initially able to use oral and tactile self-soothing strategies, but this decreases over the first year of life, alongside increases in gaze aversion strategies (G. A. Moore et al., 2001; M.K. Rothbart et al., 1992; B. Shapiro et al., 1998). Some studies have also attributed age-related changes to infants' new motor skills, as during emotional contexts, infants show greater stimulation-seeking repetitive motor behaviours from 3 to 6-months (Rothbart et al., 1992). Rothbart et al (1992) also found that repetitive motor behaviours, mainly banging and kicking, reduced in contexts requiring self-regulation after 10-13 months. Ekas et al (2013) further suggested that infants use fewer motor behaviours for emotion regulation as they learn that this is less adaptive for reducing distress. Infants increasingly use more dyadic emotion regulatory strategies from 12-months, such as seeking social interaction with mothers (Atkinson et al., 2021), linked to the development of intentional communicative behaviours around 9-months-old (Kopp, 1982; Thompson & Malatesta, 1990). Despite evidence that changes in motor skills with age can affect emotion regulatory behaviours, no one has looked at how emotion regulation behaviours are related to motor development.

Current study

To summarise, extensive evidence show that motor development is altered in preterm birth and can influence socioemotional outcomes. Motor skills delays has been proposed to have cascading effects on higher level abilities. There are also strong theoretical arguments for the idea that motor skills, and evidence from prior research demonstrating that, motor skills shape the development of processes crucial for emotional self-regulation. Although there is evidence that age influences infants' behavioural profile related to emotional self-regulation, in line with the acquisition of motor and attentional skill, no study has specifically considered the association between motor skills and emotional self-regulation. This study will address this gap, by examining first, does motor development affect the behaviours used for emotional self-regulation and the behavioural complexity during emotional self-regulation? Secondly, for those outcome measures found to be associated with motor development, do motor development and prematurity independently affect emotional self-regulation behaviours or behavioural complexity during emotional self-regulation? I hypothesise that motor development affects both the behaviours used and the behavioural complexity and would do so independently of prematurity.

7.2. Methods

Participants

This study draws on the same sample of infants in Chapter 5 from Theirworld Edinburgh Birth Cohort Study (TEBC), who participated in the still-face paradigm at their 9-months appointment. In addition, only infants who had data on motor development measured using the Vineland Adaptive Behaviour Scale were included. As in Study 2A and Study 2B, Infants were grouped by preterm birth status, and further categorised by birthweight status. This resulted in three groups: Term, Preterm Low Birthweight (LBW), and Preterm Very Low Birthweight (VLBW).

103 infants analysed in Chapter 5 (Study 2A), who had data on VABS motor development, met inclusion criteria for this analysis. A total of 8 infants (6 Term infants and 2 Preterm VLBW infants) did not have data on VABS gross and fine motor scales, and an additional VLBW infant did not have data on VABS DLS. A one-way ANOVA showed that the age at 9-month assessment differed between groups ($F(2, 108)$, $p=0.023$). The LBW group was assessed at a lower mean corrected age ($M = 8.74$ months; $SD=0.52$), compared to the Term ($M = 9.03$ months; $SD = 0.52$) months) and Preterm VLBW ($M = 9.11$ months; $SD=0.55$) groups.

Measures

Motor development

Motor development was obtained from caregiver report of infant development in the Motor domain, measured on the Vineland Adaptive Behaviour Scale Version 2 (VABS) Comprehensive Parent Interview Form. A researcher from the TEBC follow-up team administered the interview with the infants' caregiver – someone who is able to report on their day to day behaviours - either face-to-face at the follow-up appointment, or through a video call. The researcher completed a paper form or completed the form available on the Q-Global platform. Raw scores from the Motor (MOT) domain comprising the Gross and Fine Motor subscale were used.

VABS raw scores were used based on Farmer et al (2020) recommendation to use raw scores when ability is of interest, in contrast to standard scores which measure ability relative to others. Furthermore, raw scores have more variability than standard scores where most values fall around the mean (as they have been transformed to reflect a normal distribution) and is suitable for investigating for associations. V-scale scores, representing standardised scores for the subdomains were also available.

Emotional self-regulation - behavioural response

Behavioural response related to emotional self-regulation was measured by video coding of four different behaviours during the still-face paradigm, namely self-comforting (SC), object exploration/distraction (OBJ), social interactive/monitor (SOC), and repetitive movement episodes (RME). As described in Chapter 3 (Methodology), the TEBC used an extended version of the still-face paradigm, where infants participated in a 10-minute interaction with an A-B-A-B-A structure where the caregiver was absent in the "B" still-face phases. Only behaviour during the still-face phase was considered emotional self-regulation. Further, a data-reduction strategy was employed to select the phase where infant first showed negative affect, indicating that they were distressed. Proportion of time using each behaviour was calculated from the selected still-face phase. If the infant did not show negative affect in either of the still-face phase, or if data on negative affect was not available, the average proportion of time from the two phases was obtained.

Negative affect was obtained from another study which coded infant's behavioural states using the Infant and Caregiver Engagement Phases (ICEP) coding scheme. Negative affect was defined as the proportion of time out of the still-face phase where infant was showing negative facial expressions, is protesting or withdrawn.

Emotional self-regulatory - behavioural dynamics

Behavioural dynamics quantifies the temporal aspects of infants' emotional self-regulatory behavioural response. Entropy, a measure of behavioural complexity, was obtained from Recurrence Quantification Analysis (RQA) of the timeseries of infants' behavioural response. RQA involves plotting recurrences on a two-dimensional "recurrence plot". In auto-recurrence, the timeseries is plotted against itself on the x and y-axes. The value of the timeseries at each timepoint is compared against the values at every timepoint. If one value matches with another value at another time, this is plotted accordingly as a recurrence. Timeseries containing categorical behavioural states tend to produce rectangular structures in the recurrence plot. Entropy of block structures, referring to average amount of information contained in the block structures in the recurrence plot, was used as a measure of behavioural complexity. As it is calculated from the histograms representing the distribution of the block sizes, entropy of block structures is measured in units bits/bin.

Statistical analyses

All statistical analyses were conducted in R (version 4.02), on Rstudio (version 1.1).

Descriptive statistics

Means with SD of the MOT domain and subdomains were obtained and. group differences compared using One-Way ANOVAs. Group differences in the still-face phase included for analysis in the reduced dataset were compared using Fisher's exact test. Medians with IQR of the total behavioural emotional self-regulatory response and negative affective response in SF1, SF2, and in the reduced dataset were obtained, and group differences compared using non-parametric Kruskal-Wallis rank sum test. A scatterplot between MOT and ENTb were visualised to determine if a nonlinear trend was appropriate.

Univariate analyses

Least-square regression models were run with MOT as a predictor of self-comforting, social, object-oriented and repetitive movement episodes (Models A) and Entropy (Models B). Linear trends with MOT was considered for SOC, OBJ, RME, SC, and nonlinear polynomial trends up to the third order were considered for ENTb.

Sensitivity analyses – cook's distance, robust regression

For the third-order polynomial trend identified between MOT and entropy, Cook's distance was inspected to determine the influence of outliers on the predicted trend identified in univariate analyses. 3 data points was identified as having high cook's distance (outside the confidence intervals). For sensitivity analyses, two models were run: first, the same least-squares regression, after excluding a deviant data point which had high Cook's distance and was also an outlier of motor scores, as examined on a boxplot; second, a robust regression model using the original dataset using the *lmrob* command from the *robustbase* package (Maechler et al., 2021).

Multivariate

Multivariate regression models were run with MOT and Prematurity as predictors. The model was built in a stepwise procedure, first including Prematurity as a predictor and then adding variables representing a linear or nonlinear MOT trend. The amount and significance of R^2 change was obtained to examine if motor development explained additional variance in entropy after accounting for prematurity.

Exploratory analyses

Surprisingly, in univariate analyses, there were no associations between MOT with any emotional self-regulatory behaviours. As post-hoc exploratory analyses, motor development was considered as adaptive behaviour in the Daily Living Skills (DLS) domain comprising the personal subscale, as items in the subscale measured performance of motor skills under functional contexts, such as using a spoon independently and dressing (You et al., 2019). Researchers have argued that daily living skills, self-care depend on motor abilities, motor skills within the natural environment (Jasmin et al., 2009; Øberg et al., 2012; Snider et al., 2009) and motor performance has been found to be associated with adaptive self-care behaviour (Jasmin et al., 2009; Snider et al., 2009), including in preterm infants (Hemgren & Persson, 2007). Raw scores of DLS were used and descriptive statistics were obtained, including one-way ANOVAs to compare differences between prematurity groups. Associations between DLS and each type of emotional self-regulatory behaviour were examined using least-squares regression. Only linear trends were considered, and multivariate associations with prematurity were not examined.

7.3. Results

Sample characteristics

Motor development. Table 7-1 shows the motor developmental characteristics by prematurity groups. Differences in the MOT scale ($F_{2,100}$ = 6.47, p=0.002) were reflected in gross ($F_{2,100}$ = 6.28, p=0.03) and fine motor subscales ($F_{2,100}$=2.92, p=0.058). However, group differences in fine motor skills were weakened when age or corrected age at assessment was accounted for in v-scale scores ($F_{2,105}$=2.71, p=0.071). At 9-months, DLS comprised the Personal subscale only and although there were differences in raw scores ($F_{2,99}$= 4.89, p=0.009) there were no group difference in Personal v-scale scores ($F_{2,104}$=1.59, p=0.20).

Table 7-1. Descriptive statistics of VABS motor development and daily living skills

Characteristic	Term, N = 61[1]	LBW, N = 20[1]	VLBW, N = 30[1]	p-value[2]
Age at 9-months	9.03 (0.40)	8.74 (0.52)	9.11 (0.55)	0.023
VABS domain raw scores				
MOT	27 (6)	22 (8)	23 (6)	0.002
DLS	12 (3)	11 (3)	10 (3)	0.009
VABS subdomain scores				

Characteristic	Term, N = 61[1]	LBW, N = 20[1]	VLBW, N = 30[1]	p-value[2]
Gross Motor – raw score	13 (4)	11 (5)	10 (4)	0.003
Gross Motor – v-scale score	14 (3)	12 (3)	12 (3)	0.019
Fine Motor – raw score	14 (4)	12 (4)	13 (3)	0.058
Fine Motor – v-scale score	15 (3)	14 (3)	15 (2)	0.071
Personal - v-scale score	17 (2)	17 (2)	17 (2)	0.200

[1]Mean (SD)

[2]One-way ANOVA

Still-face response. Table 7-2 shows the medians and IQR behavioural response by prematurity groups. Kruskal-Wallis rank sum test identified differences in negative affective response in SF1 between groups ($H(2)=7.40$, $p=0.025$), where the term group expressed greater negative affect. In SF2, the LBW and VLBW group showed a lower median negative behavioural response, but this was not statistically different between all three groups ($H(2) = 0.43$, $p=0.80$). There was a trend towards a difference in the total emotional self-regulatory behaviours in SF1 ($H(2) = 5.43$, $p=0.066$), but no difference in this measure in SF2 ($H(2) = 0.19$, $p=0.910$). Fisher's exact test showed that proportionately more infants in the LBW group showed negative affect in SF2 but not SF1 (50% compared to 21-23% in the other two groups). Following data reduction, there was no evidence of a difference in negative affect between groups for the phase included in analysis ($H(2)=3.79$, $p=0.15$).

Table 7-2. Descriptive statistics of still-face behavioural response by group

Characteristic	Term, N = 61[1]	LBW, N = 20[1]	VLBW, N = 30[1]	p-value[2]
SF1				
Negative affect	0.16 (0.00, 0.39)	0.00 (0.00, 0.09)	0.02 (0.00, 0.21)	0.025
Total ER	65 (53, 79)	77 (66, 84)	58 (43, 74)	0.066
SF2				
Negative affect	0.58 (0.11, 0.75)	0.37 (0.08, 0.72)	0.33 (0.05, 0.79)	0.808
Total ER	62 (51, 80)	71 (50, 80)	58 (53, 79)	0.910
Reduced dataset				
Include				0.027
Mean	6 (9.8%)	4 (20%)	6 (20%)	
SF1	42 (69%)	6 (30%)	17 (57%)	
SF2	13 (21%)	10 (50%)	7 (23%)	
Negative affect	0.28 (0.12, 0.58)	0.20 (0.08, 0.64)	0.13 (0.02, 0.40)	0.150
Total ER	0.55 (0.45, 0.64)	0.57 (0.48, 0.66)	0.52 (0.37, 0.64)	0.284

[1]Median (IQR); n (%)

[2]Kruskal-Wallis rank sum test; Fisher's exact test

Univariate models

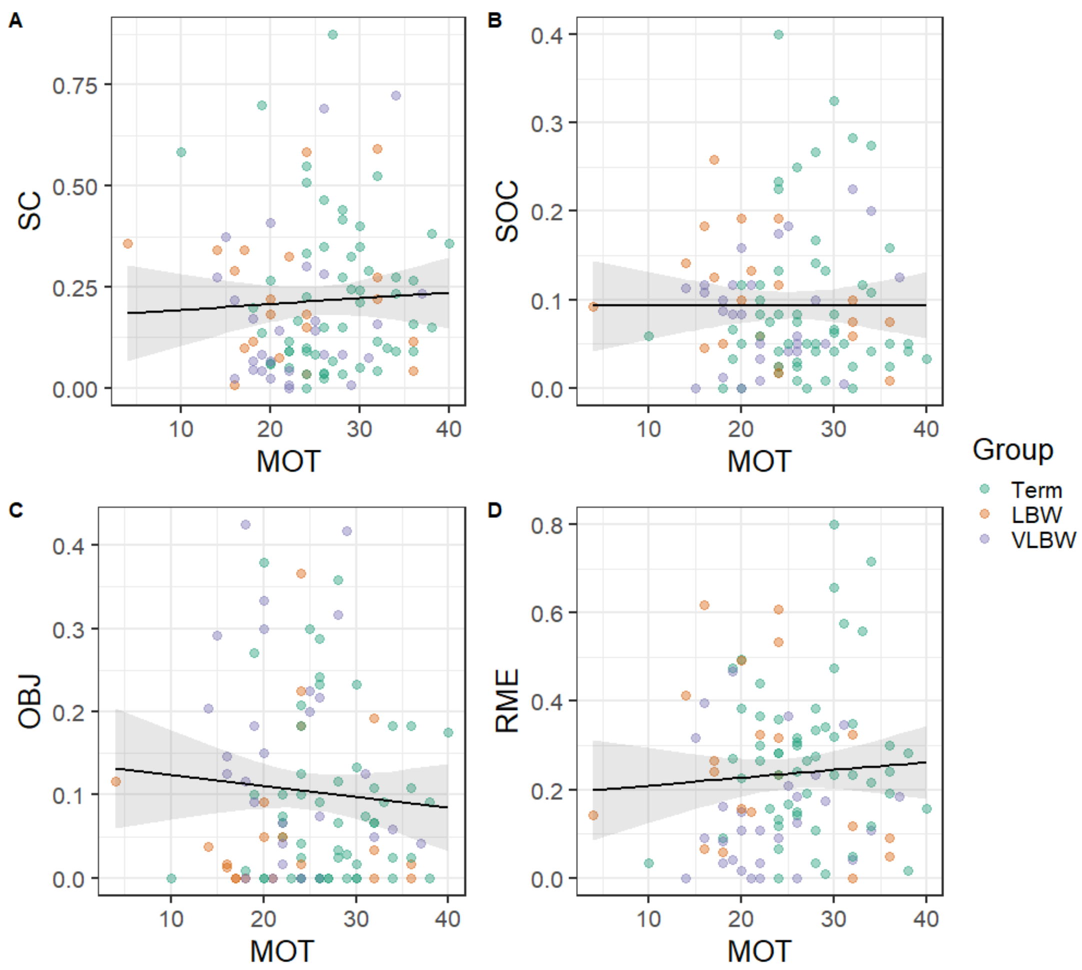
As shown in Table 7-3, there was no evidence of linear associations between MOT and the proportion of time using each type of emotion regulation behaviour in the still-face paradigm (p>0.001).

Table 7-3. Models A – effect of motor development on still-face behavioural response

	SC	SOC	RME	OBJ
Predictor	Beta (95% CI)	Beta (95% CI)	Beta (95% CI)	Beta (95% CI)
MOT	0.001	0.000	0.002	-0.001
	(-0.004 – 0.007)	(-0.002 – 0.002)	(-0.003 – 0.007)	(-0.005 – 0.002)
R/R^2 adjusted	0.003 / -0.007	0.000 / -0.010	0.004 / -0.005	0.006 / -0.004
F(1, 101)	0.27	0.000084	0.45	0.61

*N=103; # p<0.1 * p<0.05 ** p<0.01 *** p<0.001*

Figure 7-1. Predicted effect of motor development on still-face behavioural response



As shown in Table 7-4, a third-order polynomial trend was identified between MOT and ENTb. Although there was evidence that the linear and third-order MOT term was greater than 0, there was no evidence that the polynomial trend explained a significant amount of the total variance in ENTb (R^2=5.6%, $F_{3, 99}$ = 1.96, p=0.125). Table X presents the results of sensitivity analyses, showing that removing an outlier of motor score from analyses (Model C1), or using robust regression for the whole dataset (Model C2) only slightly altered the coefficients.

Table 7-4. Models B – effect of motor development on entropy of still-face behavioural response

	ENTb		
Predictors	Beta (95% CI)	Beta (95% CI)	Beta (95% CI)
MOT	0.005	0.006	0.026 *
	(-0.010 – 0.021)	(-0.010 – 0.021)	(0.001 – 0.050)
MOT^2		0.00087	-0.00019
		(-0.00078 – 0.0025)	(-0.0021 – 0.0017)
MOT^3			-0.00016*
			(-0.00031 – -0.00001)
R/R^2 adjusted	0.004 / -0.006	0.015 / -0.005	0.056 / 0.027
F	0.41	0.75	1.96

*N=103; # p<0.1 * p<0.05 ** p<0.01 *** p<0.001*

Table 7-5. Models C – sensitivity analyses after removing outliers (C1) and using robust regression (C2)

	ENTb	
	Model C1	Model C2
Predictors	Beta (95% CI)	Beta (95% CI)
MOT	0.036 *	0.022
	(0.006 – 0.066)	(-0.004 – 0.048)
MOT^2	0.00042	-0.00053
	(-0.0017 – 0.0026)	(-0.00284– 0.00178)
MOT^3	-0.00029 *	-0.00015 #
	(-0.00055 – -0.00002)	(-0.00031 – 0.00001)
R/R^2 adjusted	0.057 / 0.028	0.051 / 0.023
F or χ^2	1.97	11.68 **
N	102	103

*# p<0.1 * p<0.05 ** p<0.01 *** p<0.001*

Multivariate models

As in Study 2A (Chapter 5), in Model D1 fitted in Step 1, prematurity led to lower entropy for VLBW infants (Beta= -0.298, 95% CI -0.534 to -0.062, p=0.014). In Model D2 in Step 2, including MOT as a third-order polynomial predictor alongside prematurity weakened both the Beta coefficients slightly for both VLBW (Beta= -0.261, 95% CI -0.509 to -0.014, p=0.039). After including Prematurity, there was only weak evidence that the coefficients for MOT and MOT^3 were different from 0. Both models explained a small amount of variance in ENTb (R^2=6.1%, $F_{2, 99}$ = 3.23, p=0.043 and R^2 = 9.8%, $F_{5, 96}$=2.10, p=0.073, respectively). Although MOT explained an additional 3.7% variance in entropy, there was no evidence suggesting that this was not by chance ($F_{3, 96}$ =1.13, p=0.275).

Table 7-6. Models D – Multivariate analyses. Effect of prematurity and motor development

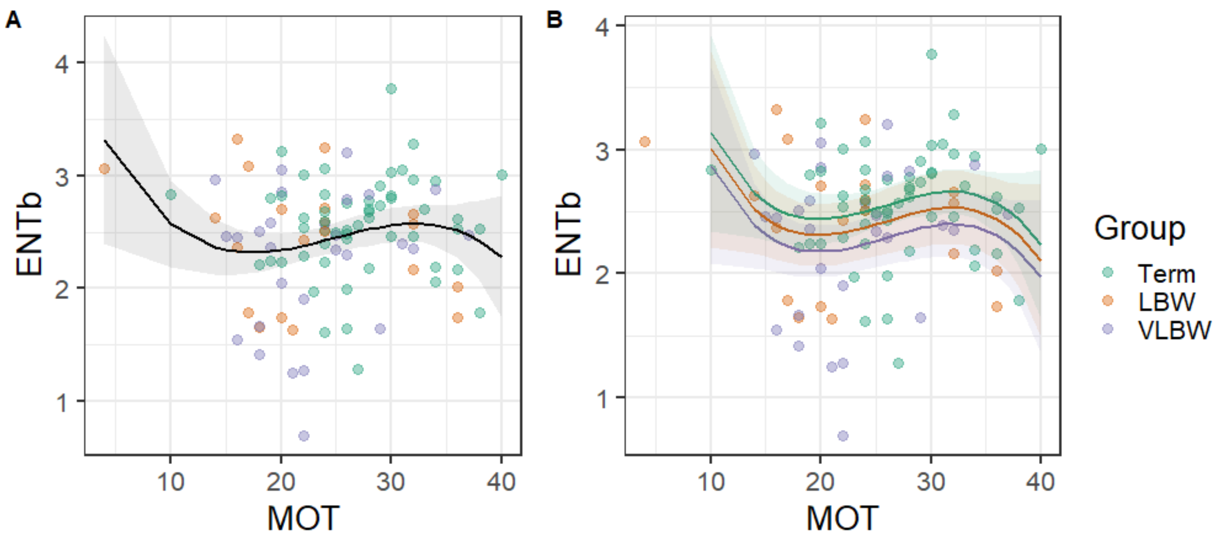
	ENTb	
	Model D1	Model D2
Predictors	*Beta (95% CI)*	*Beta (95% CI)*
Step 1: Prematurity		
Term [Ref]	Ref	Ref
Low Birthweight	-0.159	-0.129
	(-0.430 – 0.111)	(-0.410 – 0.152)
Very Low Birthweight	-0.298 *	-0.261 *
	(-0.534 – -0.062)	(-0.509 – -0.014)
Step 2: 9-month motor development		
MOT		0.027 #
		(-0.004 – 0.058)
MOT^2		0.00058
		(-0.0016 – 0.0027)
MOT^3		-0.00025 #
		(-0.00051 – 0.00001)
R^2 / R^2 adjusted	0.061 / 0.043	0.098 / 0.051
F	3.23 *	2.10 #

R^2 change	0.037/0.008
F	1.13

*N=102; # p<0.1   * p<0.05   ** p<0.01   *** p<0.001*

Figure 7-2 depicts the fitted polynomial relationship in univariate analyses (Model B3), and multivariate analyses (Model D2). Increase in MOT skills led to a reduction in behavioural complexity until around a raw score of 15. A further increase in motor skills then led to increase in ENT peaking around a raw score of 32 and then decreasing thereafter (Figure). However, this polynomial relationship appears to have little predictive value as they contributed little in explaining the variability in entropy between individuals, as can be seen in the large spread of values around the predicted trend.

Figure 7-2. Predicted effect of motor development on entropy. A: univariate model (Model B3); B: multivariate model (Model D2)



Exploratory analyses

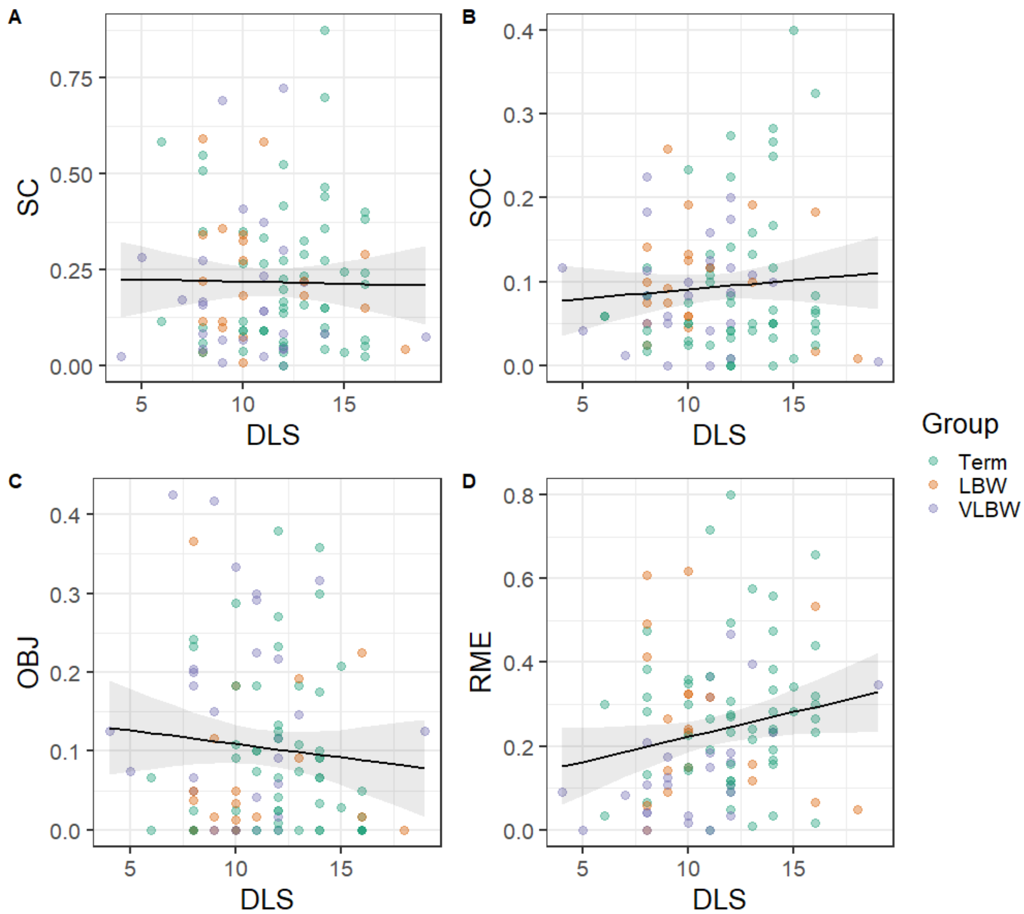
RME was found to be positively associated with DLS (Beta=0.012, 95% CI 0.000 – 0.024, p=0.048). No other emotional self-regulatory behaviours were associated with DLS. (see Table 7-7)

Table 7-7. Exploratory analyses. Effect of VABS Daily Living Skills domain on still-face behavioural response

	SC	SOC	RME	OBJ
Predictor	Beta (95% CI)	Beta (95% CI)	Beta (95% CI)	Beta (95% CI)
DLS	-0.001	0.002	0.012 *	-0.003
	(-0.014 – 0.012)	(-0.003 – 0.008)	(0.000 – 0.024)	(-0.011 – 0.004)
R/R^2 adjusted	0.000 / -0.010	0.007 / -0.003	0.039 / 0.029	0.008 / -0.002
F(1, 100)	0.028	0.66	4.02	0.80

*N=102; # p<0.1   * p<0.05   ** p<0.01   *** p<0.001*

Figure 7-3. Predicted effects of daily living skills on still-face behavioural response



7.4. Discussion

Summary of findings

Overall my hypothesis that motor skills related to changes in behaviours during emotion regulation was not supported, but requires further investigation as motor skills in daily contexts were associated with greater repetitive movements. I found a weak non-linear relationship between motor development with behavioural complexity during emotional self-regulation, alongside weak evidence that this is independent of the effect of prematurity. However, this finding still needs to be considered with caution.

Robustness of findings

The nonlinear third-order polynomial association between VABS MOT scores and complexity of emotional self-regulatory behaviours shows a U-shape trend with a minimum at around a raw score of 20 and transits into an inverted U-shape trend with a maximum at around 32. This association was strengthened after removing an outlying point which had a strong influence on the parameters of the curve. Robust regression, which reduces the weights of outlying points, and thereby their influence on the estimated regression curve, did not drastically alter the Beta effect estimates for the linear and cubic term. However, the polynomial trend explains only 5.6% of the variation in ENTb, an amount that was not significantly different from zero. It is likely because this was a group-level association, identified from a sample of infants at a range of motor developmental stages. As such, there could be high amounts of individual variability around the minima and maxima of the U and inverted U-shaped trend respectively. This is potentially due to the fact that infants show slight variations in when developmental “peaks” and “troughs” occur during the course of motor and socioemotional development. Overall the third-order polynomial association observed here are robust to sensitivity analyses, and the evidence would be strengthened if it can be replicated in a within-subject design where infants are followed up during various points in their motor development.

Similarly, the lack of an effect between measures related to motor milestone achievement may be because I assessed between-individual trends, rather than within-individual trends. Motor development is not a linear process and infants achieve crucial milestones at different ages. Therefore, motor milestones may contribute to behaviour changes at different ages for different infants, contributing to variability as raw MOT scores capture overall motor development, but may capture different skills achieved. It is also possible that motor development acts on a longer timescale to have an effect on emotion regulation behaviours, and capturing motor development in a snapshot in time may not be able to capture the associations that have previously been identified, between infant age and emotion regulation behaviours measured over several months (Ekas et al., 2013; M.K. Rothbart et al., 1992).

This study only provided weak evidence that motor development predicted entropy independently of prematurity. This weaker evidence is likely attributed to lower power when extra terms are added to the regression model as well as resulting from a smaller effects of motor development when controlling for the effect of prematurity.

Interpretation of findings

The finding of a non-linear association between motor development and behavioural complexity contrasts with ideas of movement complexity always increasing, reaching a maximum in adulthood (Bisi & Stagni, 2018). The U-shaped and inverted U-shaped trend agrees with other studies which have identified such changes in complexity with development (Deffeyes, Harbourne, Dejong, et al., 2009; Harbourne & Stergiou, 2003). As a motor skill develops, motor complexity changes as infants learn to control movement in more organised, or variable ways (Hadders-Algra, 2010). This study might indicate that the progressive development of motor skills also impacts the organisation of behaviour. Behavioural complexity around 9-months where there is rapid motor development, might go through periods of stabilisation and destabilisation with the acquisition of motor skills.

The lack of associations between motor development and self-comforting or object distraction behaviours are in contrast to Ekas et al (2013) which found that self-comforting, attention at parent decreased from 3-7months and distraction strategies increased from 3-7 months. This may be because by 9-months, the developmental trends in these behaviours have stabilised and are no longer increasing or decreasing. Socially-oriented behaviours appear to develop more rapidly in the first year of life and may be why no associations were identified in this study.

At 9-months, the “personal” domain of DLS measures the extent infants assists caregiver in contexts involving daily care activities such as dressing, eating, and washing and can be seen as the ability to independently use motor abilities in these situations (Cameron et al., 2021). Increases in adaptive behaviour related to daily living contexts increases repetitive movements during emotional self-regulation, but does not affect other behaviours. This also suggests that motor development does not simply replace present abilities to self-regulate emotions with the newly acquired ability.

Repetitive movements may play a role in enabling motor experience, and then become recruited for use in emotional contexts. Motor experience and movement with a stereotyped pattern are known to be related, rhythmic body movement enables practice and leads to more controlled use of the body part, and may serve development of more complex abilities, for example banging with hammering (Kahrs et al., 2012) and kicking with onset of locomotion; and the onset of rhythmic movement increase in frequency with motor development, particularly with acquisition of new postures (Piek & Carman, 1994; Thelen, 1979). Nevertheless, the onset and occurrence of motor stereotypies in development does not directly translate to greater RME during emotional contexts. Motor skills can be seen as enabling participation in daily lives, impacting the amount of physical activity throughout the day; however, physical activity and motor skills are unique outcomes and one can have typical motor skills and yet have lower physical activity (Cameron et al., 2021). Therefore, my findings might indicate that those infants who have greater participation in everyday socioemotional interactions, learn to instrumentally apply newly acquired repetitive behaviours in responding to a stressor.

Strengths, limitations and future directions

The strength of this work was in using a validated measure of motor development and comparing a range of behaviours elicited during distress in an established developmental paradigm. However, this has revealed important considerations for future work on motor development and emotion regulation – which also reflect the limitations of the present study. Using within-subject designs may be more suitable due to individual differences in developmental trajectories – motor development may not impact behaviours during emotional self-regulation in the same way for individual infants. Examining motor development over a longer period in relation to the gradual emergence of emotional self-regulatory skills may be important.

In addition, not all motor skills may affect emotion regulation and there may be key transitional skills such as the acquisition of reaching skills, that may have cascading effects on socioemotional development. Future work, using both within- and between-subject designs can also consider these key transitions in motor skill acquisition. It may also be possible to measure the amount of experience using motor skills, for example, sitting ability can be characterised different stages of sitting skill acquisition – non-sitters; early, unstable sitters and learned, stabled sitters (Harbourne & Stergiou, 2003). If there are indeed specific motor skills which affect emotional self-regulation, this may provide a more sensitive analysis in contrast to a measure on a range of motor skills.

The novel finding that motor development may affect behavioural organisation during emotional self-regulation requires confirmation, and may also benefit from a more sensitive analysis focusing on specific motor skills. Doing so may have implications on understanding if there are critical periods during the motor skill development which influence emotional self-regulatory abilities, and which may serve as important points for early intervention, paralleling Lichtwarck-Aschoff and colleagues (2012) finding that peaks in entropy represent periods of destabilisation and is associated with more effective intervention for childhood behaviour.

Although daily living skills was found to influence repetitive movements, this requires further investigation, and confirmation, as this was a post-hoc exploration. How daily living skills on socioemotional development, in particular by affecting opportunities for active involvement in richer social interactions may require further investigation as it can have implications on preterm-born infants' development. Preterm-born infants, relative to term-peers, not just show motor impairments but also lower physical activity (Cameron et al., 2021). In 2-year-old infants born with low birthweight, using the Bayley III, social-emotional skills including emotional self-regulation and other emotional skills, appears to correlate more strongly with objective motor, cognitive and language measures, than measures adaptive behaviour in various contexts (Nagy & Kenyhercz, 2021). However, in a group of both preterm and full-term infants, neither gross motor skills and fine motor skills, nor measures of adaptive behaviour were associated with self-regulation skills (You et al., 2019). Therefore, future research can clarify associations between DLS and the lack of an association between MOT with repetitive movements during emotion regulation, as well as understanding of whether these associations might vary by preterm-birth status.

7.5. Conclusions

Despite evidence that motor development might influence emotional self-regulation, few studies have provided direct evidence. This study attempted to do so, but has a number of limitations, primarily limited by the present study design capturing motor development and emotional self-regulation in a snapshot in time. The influence of motor development on emotional self-regulation still needs to be understood better, including on how it impacts active participation in everyday social interactions, and has the potential to impact early identification and intervention as motor delays occur early and impact early social interactions. This study provides a number of recommendations for future research, including focusing on critical motor skills instead of a general picture of motor development.

8. Prospective association of 9-month emotional self-regulation and 2-year autistic traits

8.1. Introduction

The social and behavioural development of preterm-born can have a long-term impact on adaptive functioning in the family and school environment, satisfactory friendships (Ritchie et al., 2015) and academic and occupational achievement (Leon Hernandez, 2018; Linsell et al., 2019). In Chapter 1, I highlighted that in preterm birth, children are at risk of, predominantly, a triad of socioemotional difficulties related to autism, ADHD and anxiety. In relation to autism, preterm-born children relative to their term peers show greater social-interactive and communicative difficulties and repetitive or stereotyped behaviours, traits indicative of risk for developing autism (S. Johnson et al., 2010a; Wong et al., 2011, 2014). An estimated 8% of infants would meet criteria for autism (Agrawal et al., 2018; S. Johnson et al., 2010a), a prevalence rate much higher than in the general population. Therefore, understanding how preterm birth affects the development of social-communicative and social interactional difficulties is one important aspect of research towards improving preterm socioemotional outcomes.

In Chapter 1, I also introduced how socioemotional development can be understood through the framework of social-emotional competence. Social-emotional competence is the ability to form successful relationships with others (J. S. Calkins & Mackler, 2011; Ritchie et al., 2015), a skill that is implicated by many functions operating during social interactions and for coping with emotional stressors (Happé & Frith, 2014). To capture this complex ability, social-emotional competence has been conceptualised as an ability made up of lower-level components in three hierarchically-ordered domains (Taylor, 2020; Yeates et al., 2007): social cognition, social interaction and social adjustment. Firstly, social cognition involves a suite of mental processes underlying behaviour in social context. This involves socio-cognitive processes such as theory of mind, joint attention and intentional understanding; socio-affective processes such as affect perception, empathy, emotion regulation and motivational decision making. Secondly, social interaction or performance is the ability to evoke social cognitive skills in daily social situations to engage with others appropriately -

for example, prosocial behaviour such as peer-play, cooperation, turn-taking, expressing concern for others. Thirdly, at the highest level, social adjustment refers to the child's desired social outcomes that implicates the individual's quality of life, such as having friends, social withdrawal or experience of peer problems (Taylor, 2020). This model highlights how, at the most basic level, the early development of social cognition can have cascading effects on an individual's social interactions and achievement. Within this framework, Emotion regulation is one of these basic functions which affects the individual's ability to deal with emotional situations occurring regularly in daily social interactions (Eisenberg et al., 2010) and is thought to be associated with better social performance and social adjustment (Reeck et al., 2016).

In Chapter 1 and 2 I highlighted differences in the early development of emotional self-regulation could be important to understand in preterm birth as it is highly prevalent in this population and can contribute to a range of difficulties. Emotion regulation, by definition, works by integrating a range of cognitive and behavioural processes, such as recognising emotional and social cues, and in response, inhibiting or selecting appropriate behaviour, and directing attention selectively. Accordingly, it has been proposed to be a sixth RDoC domain, achieved by the functional interaction of the five RDoC domains, namely, positive and negative valence systems, arousal and regulatory systems, social process and cognitive systems (Fernandez et al., 2016). Alterations in emotion regulation have also been identified to be a transdiagnostic factor, one which underlies difficulties seen across different psychiatric diagnoses (Cludius et al., 2020; Fernandez et al., 2016; Sun et al., 2017), including autism (Cai et al., 2018; Mazefsky et al., 2013) and anxiety (Cisler & Olatunji, 2012). Disruption to emotion regulation has also been proposed to contribute, either, to the mechanism affecting the range of difficulties characteristic of autism and its common psychiatric comorbidities, or it may have shared risk factors with autistic social-communicative and interactional difficulties (Mazefsky et al., 2013).

Taken together, emotion regulation can, on one hand, directly affect social functioning as it is an integral part of social interactions. On the other hand, its transdiagnostic, integrative nature suggests it can be implicated by similar mechanisms that give rise to social and behavioural difficulties. These two perspectives converge on the importance of seeing social cognitive functions not as disparate modules working independently, but each ability can that influence the development of the other.

Gap in existing research

Preterm infants show delays in social-emotional development and are rated by caregivers and parents as having poorer social-emotional competence in home and school context, across self-regulation, non-verbal social communication, interaction and emotional behaviour in social contexts, as well as problematic internalising and externalising behaviours. Early socioemotional difficulties may be indicative of autism and later autism-related difficulties. 13% of infants screen positive for autism in toddlerhood (Pritchard et al., 2016). Additionally, in childhood and adulthood, 30-40% of individuals born preterm are characterised as having a "broader autism phenotype", which includes subclinical difficulties (O'Reilly et al., 2021; Vermeirsch et al., 2021).

Although evidence on the range of social and behavioural difficulties in preterm infants has been organised within a framework of social-emotional competence (Ritchie et al., 2015), few studies address how the components of social-emotional competence influence each other. This can have important implications on mechanistic understanding of how social and behavioural difficulties develop. For example, such a hierarchical framework can help to understand the emergence of higher level social interactional and social adjustment difficulties. Lower level social cognitive skills have been found to predict prosocial behaviour and later peer problems at the higher levels of social interaction and social adjustment (Treyvaud et al., 2012), yet this is hardly surprising because social cognition is recruited in social interactions and the effects of positive or negative social interactions build up to impact social adjustment. Findings from studies which did explicitly focus on concurrent or longitudinal relationships between more than one component of social-emotional competence suggest that the development of different components are likely to be interrelated. Lower communicative development in infancy has been shown to lead to delays in social-emotional competence in toddlerhood (Rautakoski et al., 2021), though social-emotional competence was evaluated as a unified construct. In preterm infants, social impairments are accompanied by deficits in behaviour and emotional regulation (Korzeniewski et al., 2017). However, research have not specifically investigated the relationships between emotion regulation and social cognition processes occurring at the lowest levels of social-cognition to shape social interactions.

Current study

In Study 2A, I provided evidence suggesting there may be differences as early as 9-months in emotional self-regulation that may be signs of social developmental risks. Prematurity was found to affect behavioural preference during emotional self-regulation, those born with lower birthweight showed fewer repetitive movements and greater manipulation of objects to provide attentional distraction. At a systemic, organisational level, infants born with lower birthweight showed lower entropy, indicating lower complexity of the interactions within the emotional regulation system. These findings are significant because motor stereotypies have been proposed to be an early risk factor for autism (Wolff et al., 2014), and prolonged visual examination of objects has been found to be predictive of autism (Miller et al., 2021). Repetitive and stereotyped behaviours between 18-24 months predicted social competence and autistic symptoms a year later (Watt et al., 2008). Complexity is also thought to be related to the adaptability or integrity of the system as systems achieve greater complexity by recruiting extra degrees of freedom in coordinating its components towards a goal (van Emmerik et al., 2016)

The relationship between early emotional self-regulatory differences, and social development outcomes is unlikely to be straightforward as these behavioural patterns are on a continuum with typical development. As motor stereotypies and sustained visual attention are a part of normal development and play a role in facilitating motor and cognitive development, it may be their persistence and not simply occurrence that is indicative of developmental risk (Sifre et al., 2021). As I discussed in Study 2, complexity might indicate a different underlying organisation, but may neither be good or bad as it could fluctuate during development as the system reorganises. Another measure of dynamics, trapping time, measures the overall stability of behavioural states that the system resides in over time. It indicates if the states are more or less resistant to change and could indicate risk for atypical, prolonged or persistent behavioural profiles, in future. However, the study reported in Study 2B did not find an effect of prematurity on this measure.

As outlined above, the emotion regulation contributes to socioemotional behavioural outcomes. It plays a role in social interactions, and may share common aetiology with autistic social interactive and communicative difficulties. However, there is a lack of evidence on how the development of emotion regulation influences social cognitive processes at the lowest level of social-emotional competence. Investigating the association between the two can increase understanding of the socioemotional development of preterm infants. Therefore, the aim of this study is to investigate if behavioural patterns of emotional self-regulation at 9-months is associated with autistic traits at 2-years old, including examining specific associations with autistic social cognition. I make two hypotheses, corresponding to two research questions: (1) 9-month emotional self-regulation behaviours (repetitive movements or object-oriented behaviours) is associated with 2-year autistic traits; (2) 9-month behavioural dynamics during emotional self-regulation (Entropy or trapping) is associated with autistic traits at 2-years old.

8.2. Methods

Participants

Infants from the TEBC, who participated at 9-month follow-up in the still-face paradigm, who were 2-years old by 30th October 2021 and whose parents provided information on social development with the Quantitative Checklist for Autism in Toddlers (Q-CHAT) at 2-year follow-up.

111 out of 137 infants who participated at 9-months provided usable still-face video coding data. 107 out of 111 infants were 2-years old by this date. Of the 107 infants, 59 infants (55.1%) had data on the Q-CHAT. No infants were excluded due to incomplete data on the Q-CHAT. 92% of Q-CHAT questionnaires had no missing items. Three questionnaires had one missing item, one with two missing items and one with three missing items. Table 8-1 shows the infant characteristics of the 59 infants in the analytic sample.

Table 8-1. Characteristics of infants providing data on Q-CHAT at 2-years follow-up

Characteristic	Overall, N = 59[1]	Term, N = 42[1]	Preterm, N = 17[1]
Birthweight (g)	2,891 (1,097)	3,529 (462)	1,315 (329)
Gestation (weeks)	36 (5)	39 (1)	29 (2)
Sex			

Characteristic	Overall, N = 59[1]	Term, N = 42[1]	Preterm, N = 17[1]
Male	34 (58%)	22 (52%)	12 (71%)
Female	25 (42%)	20 (48%)	5 (29%)
Ethnicity			
Any Asian background	2 (3.6%)	1 (2.6%)	1 (5.9%)
Any Mixed background	1 (1.8%)	1 (2.6%)	0 (0%)
Any White background	53 (95%)	37 (95%)	16 (94%)
Unknown	3	3	0
SIMD			
5	23 (39%)	17 (40%)	6 (35%)
4	19 (32%)	12 (29%)	7 (41%)
3	8 (14%)	7 (17%)	1 (5.9%)
2	6 (10%)	4 (9.5%)	2 (12%)
1	3 (5.1%)	2 (4.8%)	1 (5.9%)
Pregnancy			
Singleton pregnancy	53 (90%)	41 (98%)	12 (71%)
Multiple pregnancy	6 (10%)	1 (2.4%)	5 (29%)
Age at 9-month appointment	8.94 (8.72, 9.28)	8.95 (8.71, 9.30)	8.94 (8.80, 9.23)

Characteristic	Overall, N = 59[1]	Term, N = 42[1]	Preterm, N = 17[1]
Age at 2-year appointment	23.98 (23.66, 24.33)	24.08 (23.60, 24.47)	23.95 (23.85, 24.25)
Unknown	12	8	4

[1]Mean (SD); n (%); Median (IQR)

Measures

Quantitative Checklist for Autism in Toddlers (Q-CHAT) (Allison et al., 2008)

The Q-CHAT is a 25-item dimensional measure of social development. It measures parent-report of the frequency of behaviours (5-point Likert scale) on traits that characterise autism: social competence in the domains of joint attention, pretend play, and sensory and behavioural characteristics of sensory abnormalities and stereotyped and repetitive behaviours. It has been shown to be a clinically valid as a dimensional measure of autistic traits that are continuously distributed in the general population (Allison et al., 2008), demonstrating good discriminant validity and external validity with measures of cognitive functioning, language, autism symptom severity and problem behaviours (Rutaa et al., 2019), as well as good internal consistency (Magiati et al., 2015; Rutaa et al., 2019) and excellent test-retest reliability (Allison et al., 2008; Magiati et al., 2015). Factor analysis revealed that the Q-CHAT comprises two factors reflecting the DSM-V diagnostic criteria of autism, alongside a third factor reflecting non-autism specific developmental differences in speech and language (Magiati et al., 2015; Rutaa et al., 2019), although another factor analysis merged the third factor with a factor related to communication and social interaction (Gatica-Bahamonde et al., 2021). The studies largely agreed on which items loaded onto the three factors, and two out of three analyses agreed that two items did not reach threshold for the factor loadings. The factor structure of the Q-CHAT is summarised in Table 8-2.

The Q-CHAT overall score was used as a measure of autistic traits, with higher scores indicating more autistic traits. Based on the factor structure of the Q-CHAT, the subdomains of social competence (in the domains of joint attention and pretend play) along with speech/language developmental traits (Q-CHAT Social), and the non-social sensory or behavioural aspects of autism were also analysed separately (Q-CHAT non-social). Using the same conservative approach as Alison et al (2008), items with missing data was scored as zero, and questionnaires with 7 or more missing items were excluded.

Table 8-2. Factor structure of the Q-CHAT

Factor	Q-CHAT Item number and description
Social-communicative autistic traits	1. Look when name call 2. Eye contact (* did not reach threshold in Ruta et al., 2019) 5. Pointing to communicate 6. Shared interest in things 9. Pretend play (* did not reach threshold in Ruta et al., 2019) 10. Joint attention 12. Use of caregiver's hand as tool (*classified as behavioural trait in Gatica-Bahamonde, 2021) 15. Comforts others 19. Use of gestures 21. Checks caregiver reaction
Non-social or behavioural autistic traits	3. Lines objects up 7. interest in spinning objects 11. sniff or lick unusual objects 16. repetitive behaviours 20. unusual finger movements 22. restricted interest 23. repetitive object play 24. oversensitivity to noise 25. unusual visual attention
Speech/language developmental traits	4. speech 8. number of words used 17. typicality of first words 18. echolalia
No factor loadings	13. walking on tiptoes 14. adaptation to changes in routine

Behavioural measures of emotional self-regulation

As described in Chapter 3 (Methodology), the still-face paradigm was used to evoke infant's emotional self-regulation and data from the "still-face" phases were used, where their caregiver was unavailable. A data reduction strategy was employed, where data was selected from the still-face phase where infants first expressed negative affect, or the mean of the two were taken if infants did not show negative affect in either still-face phase.

Repetitive movement episodes (RME) and Object distraction/Exploration (OBJ) behaviours, expressed as proportion of time, were examined in this study as they were the emotional self-regulatory behaviours that were different in groups based on prematurity birth-status. Entropy of block structures (ENTb) and Trapping time, measures obtained from Recurrence Quantification Analysis of the dynamics of emotional self-regulation behaviours, were selected for analysis in this study as they are indicators of the organisation of the emotional self-regulatory system with potential developmental importance.

Statistical analyses

Descriptive statistics of infant characteristics (Preterm-with-birthweight (PTBW) status, birthweight, gestation, sex, SIMD) or 9-month emotion regulation variables were obtained for the 111 infants eligible for analysis, grouped by inclusion or exclusion from analysis. To determine whether exclusion from analysis due to missing data at 2-years was systematic, Pearson's chi-squared tests (PTBW, sex), Fishers Exact Test (SIMD) and Wilcoxon rank sum test (for continuous variables) were conducted to examined differences between groups. Next, means with SD Q-CHAT scores, and medians with interquartile range of 9-month emotion regulation variables and outcomes were obtained by Preterm birth status (binary variable indicating preterm birth or at birth at term-age). Boxplots and Scatterplots of each 9-month variable and Q-CHAT outcomes were obtained by PTBW and birthweight respectively to inspect the potential effect of analysing data using Preterm Birth Status instead of PTBW, due to small membership in low or very low birthweight PTBW groups.

Univariate regression was used to analyse the relationship between each measure characterising emotional self-regulation during the still-face paradigm at 9-months (independent variable) with each dependent variable: Q-CHAT Total, Q-CHAT Social and

Q-CHAT Non-Social (Models A1). Assumptions for linear regression were checked. Linearity and homoscedasticity were checked using scatter plots of residuals versus fitted values, and normality by inspecting Q-Q plots. As the residuals for RME on Q-CHAT Social showed a curvilinear trend (Figure 8-2), a nonlinear association was considered by adding a quadratic term.

As prematurity is known to have an effect on autistic traits and univariate models, the effect of preterm birth and birthweight were examined in univariate linear regression models (Models A2), and then included in bivariate regression models to adjust for the effect of prematurity. Bivariate regression analyses were only conducted for 9-month ER behavioural predictors, if they were associated with prematurity (based on the results in Chapter 5 (Study 2A)). In Models B, prematurity was included as a binary variable indicating preterm birth or birth at term age; in Models C, prematurity was a continuous variable of birthweight in 100g categories. This addresses the possibility that prematurity may distort the observed relationship between 9-month emotional self-regulation and 2-year social development, for example due to confounding or omitted variable bias. Birthweight was considered because in Chapter 5 (Study 2A), preterm with birthweight information differentiated 9-month emotional self-regulation better, but there were too few infants in the preterm group in this study to split the preterm group into low and very low birthweight groups.

Bonferroni correction was not applied as the analyses examined two independent research questions (association of ER behavioural strategy with autistic traits, and association of ER behavioural dynamics with autistic traits), and I hypothesised that at least one association would be observed between autistic traits and the ER measures identified in the literature that might be related to social development (Vickerstaff et al., 2019).

8.3. Results

Descriptive statistics

Table 8-3 shows the descriptive statistics of infants included and excluded from the analytic sample. Preterm infants were more likely to be excluded from analysis due to missing data on the Q-CHAT at 2-years old. Participant sex and SIMD were not systematically related to incomplete data. Excluded participants were also not different from those included in any of the 9-month emotion regulation measures.

Table 8-3. Comparison of infants excluded due to unavailable Q-CHAT data.

Characteristic	Excluded, N = 52[1]	Included, N = 59[1]	p-value[2]
PTBW			0.001
Term	19 (37%)	42 (71%)	
LBW	14 (27%)	6 (10%)	
VLBW	19 (37%)	11 (19%)	
Birthweight (g)	1,735 (1,210, 3,417)	3,250 (1,690, 3,710)	0.007
Gestation (weeks)	31 (29, 39)	39 (31, 40)	0.002
Sex			0.4
Male	26 (50%)	34 (58%)	
Female	26 (50%)	25 (42%)	
SIMD			0.5
5	17 (34%)	23 (39%)	
4	11 (22%)	19 (32%)	
3	8 (16%)	8 (14%)	
2	10 (20%)	6 (10%)	
1	4 (8.0%)	3 (5.1%)	
Unknown	2	0	
ENTb	2.51 (2.13, 2.70)	2.53 (2.24, 2.82)	0.4
TT	3.43 (2.78, 5.53)	3.73 (3.00, 4.36)	0.6

Characteristic	Excluded, N = 52[1]	Included, N = 59[1]	p-value[2]
OBJ	0.06 (0.00, 0.14)	0.07 (0.02, 0.18)	0.4
RME	0.18 (0.09, 0.35)	0.23 (0.12, 0.33)	0.5

[1]n (%); Median (IQR)

[2]Pearson's Chi-squared test; Wilcoxon rank sum test; Fisher's exact test

Table 8-4 shows the descriptive statistics of Q-CHAT social developmental outcomes and 9-month emotion regulation measures. Figures 8-1-a and 8-1-b depicts the distribution of these characteristics after splitting the preterm group into low and very low birthweight categories. Table 8-4 and Figure 8-1-a shows that preterm infants show higher Q-CHAT scores, but that the difference between LBW and VLBW groups are not clear, potentially due to the small number of LBW infants and preterm group as a whole. Figure 8-1-b shows trends of lower entropy, greater OBJ and lower RME behaviours in VLBW infants compared to the LBW and Term groups. This was similar to the results from Chapter 5 (Study 2A), despite having excluded almost half the eligible infants. Therefore, in accordance with the results in Chapter 5 (Study 2A), the corresponding differences in 9-month ER measures (ENTb, OBJ and RME only) between Preterm and Term groups in Table 8-4 appears to be driven by VLBW infants in the Preterm group. This may have an effect on any associations between 9-month ER measures and Q-CHAT, as Prematurity affects both Q-CHAT and 9-month ER.

Table 8-4. Descriptive statistics of outcomes (Q-CHAT) and exposures (still-face behavioural measures)

Characteristic	Term, N = 42[1]	Preterm, N = 17[1]
Q-CHAT Total	25.1 (5.3)	31.1 (6.0)
Q-CHAT Social	14.6 (3.0)	17.5 (3.8)
Q-CHAT Non-social	9 (4)	11 (4)
ENTb (bits/bin)	2.61 (2.24, 2.81)	2.45 (2.29, 2.83)
TT (s)	3.74 (2.82, 4.35)	3.73 (3.51, 4.57)

Characteristic	Term, N = 42[1]	Preterm, N = 17[1]
OBJ	0.06 (0.01, 0.12)	0.15 (0.05, 0.20)
RME	0.27 (0.14, 0.34)	0.16 (0.04, 0.32)

[1]Mean (SD); Median (IQR)

Figure 8-1-a. Descriptive plots of Q-CHAT scores by preterm group. Left: probability density plot with boxplot; Right: Scatterplot with linear trend

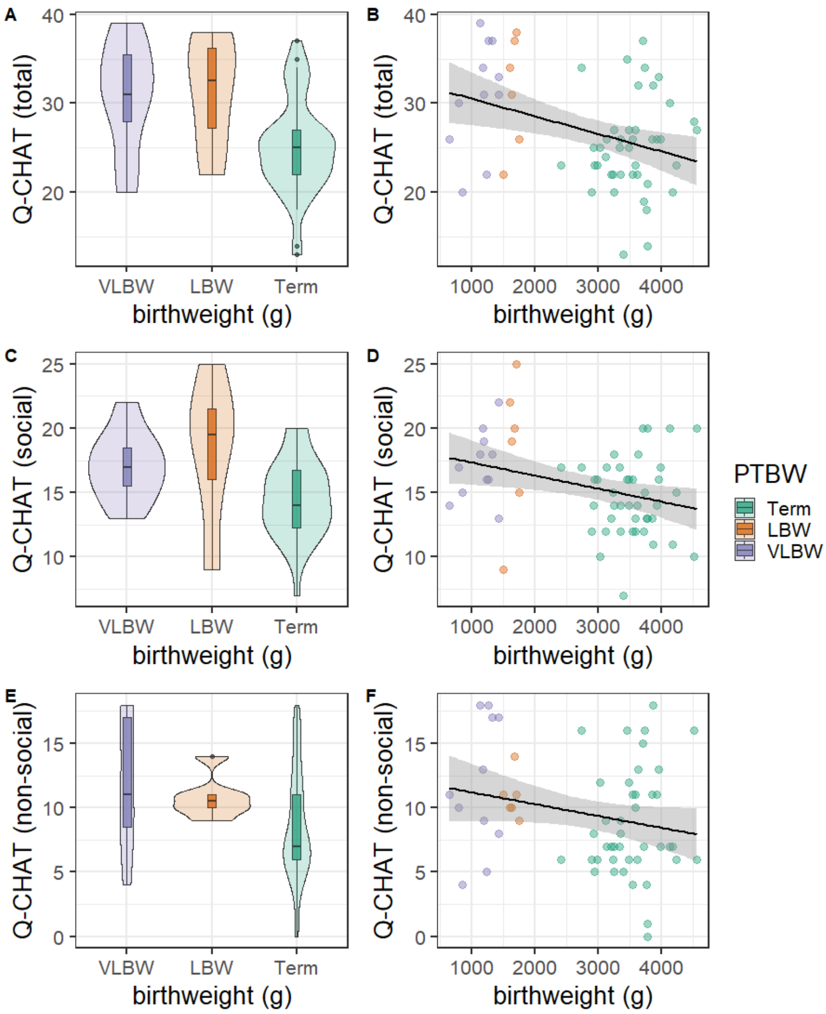
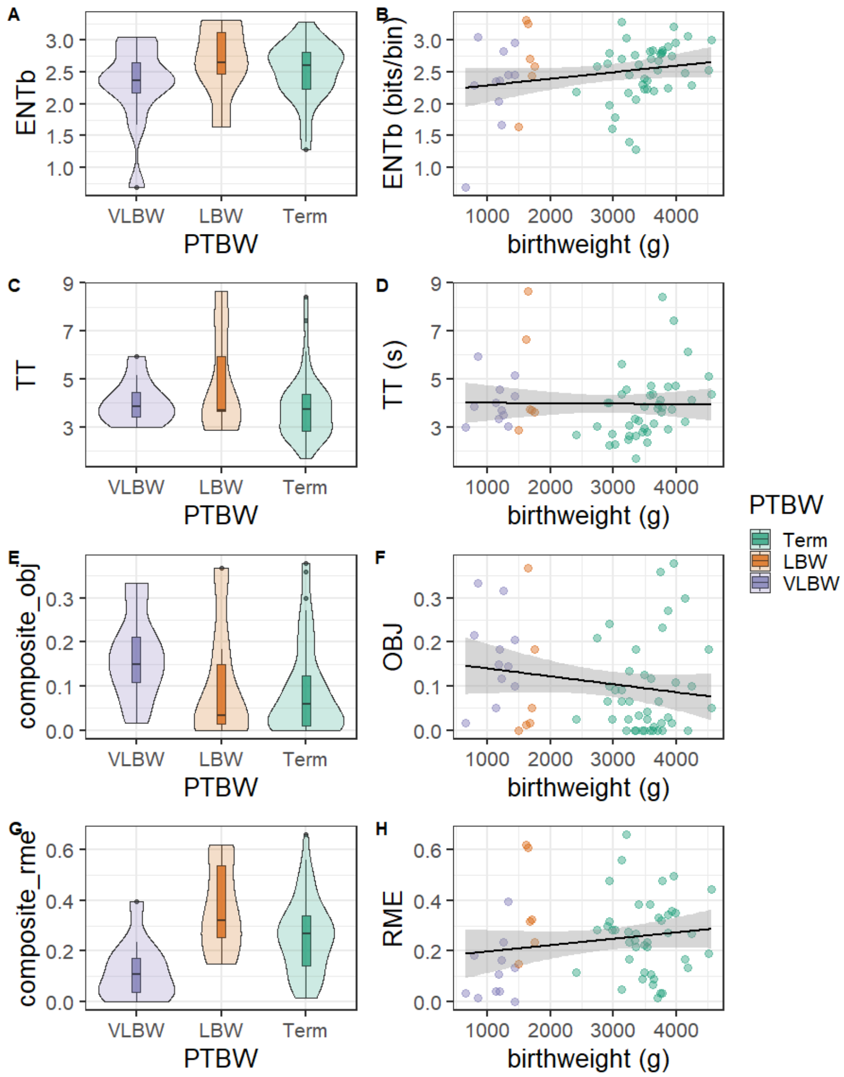


Figure 8-1-b. Descriptive plots of still-face behavioural measures by preterm group. Left: probability density plot with boxplot; Right: Scatterplot with linear trend



Univariate analyses

In univariate models, there was a trend showing greater TT and greater Q-CHAT social scores. Increase in 1s of trapping time led to 0.57 (95% CI: -0.07 to 1.21, p=0.078) points increase in Q-CHAT social scores. This model explained 5.3% of the variance in Q-CHAT Social although this did not reach significance at the 95% confidence level ($F_{1, 57} = 3.28$, p=0.078).

There was evidence of a quadratic association between RME and Q-CHAT. Infants showing very low proportions of RME behaviours had high Q-CHAT scores. This decreased for

infants with increasing proportions of RME, but increased again after a minimum of
This model explained 9.3% of the variance, an amount that also did not reach significance ($F_{2, 56}$ = 2.88, p=0.061).

Preterm birth status and birthweight predicted Q-CHAT Total, Social and Non-social scores. Preterm birth status and birthweight explained a significant amount of variance in Q-CHAT Total and Social scores, but birthweight explained only a marginally significant variance in Q-CHAT non-social scores (R^2=0.054, $F_{1, 57}$ = 3.22, p=0.078). As expected, birth preterm and lower birthweight was associated with greater Q-CHAT Total, Social and Non-social scores (see Table 8-5 and Table 8-6).

Table 8-5. Models A – Univariate models of still-face behavioural measures and prematurity on Q-CHAT

	Q-CHAT		
	Total	Social	Non-social
	Beta	Beta	Beta
Univariate models	(95% CI)	(95% CI)	(95% CI)
Models A1			
ENTb	1.35	1.36	-0.20
	(-1.77 – 4.47)	(-0.40 – 3.12)	(-2.46 – 2.05)
TT	0.31	*0.57* #	-0.27
	(-0.83 – 1.46)	*(-0.07 – 1.21)*	(-1.09 – 0.56)
OBJ	11.19	3.78	4.89
	(-3.24 – 25.61)	(-4.61 – 12.17)	(-5.61 – 15.39)
RME			
RME	-4.33	-20.52 *	-2.86
	(-14.25 – 5.59)	(-37.65 – -3.39)	(-9.99 – 4.27)
RME^2	n.a.	31.47 *	n.a.
		(3.76 – 59.19)	
Models A2			
Preterm (Ref: Term)	5.99 ***	2.96 **	2.83 *
	(2.84 – 9.14)	(1.09 – 4.82)	(0.41 – 5.25)
Birthweight	-0.20 **	-0.10 *	*-0.09* #
	(-0.33 – -0.06)	(-0.18 – -0.02)	*(-0.19 – 0.01)*

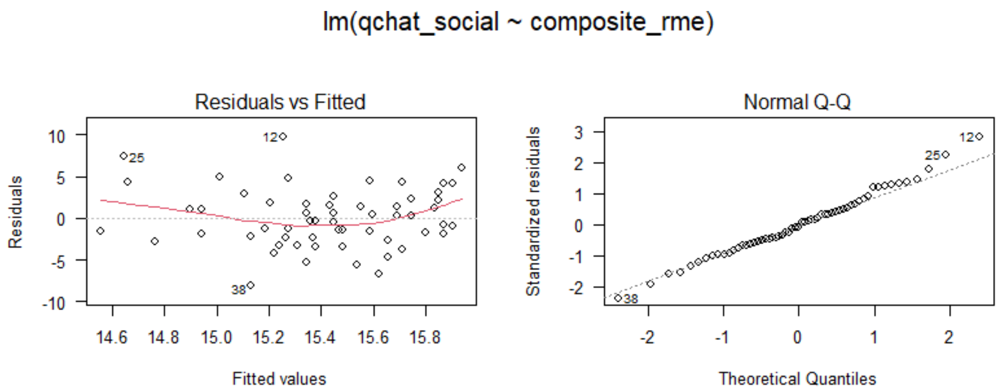
*N=59; #p<0.1 *p<0.05 **p<0.01 ***p<0.001*

Table 8-6. Models A – Model fit

Univariate models	Q-CHAT Total R^2 / R^2 adjusted	Total $F_{1,57}$	Social R^2 / R^2 adjusted	Social $F_{1,57}$	Non-social R^2 / R^2 adjusted	Non-social $F_{1,57}$
Models A1						
ENTb	0.013 / -0.004	0.75	0.040 / 0.023	2.39	0.001 / -0.017	0.03
TT	0.005 / -0.012	0.30	*0.053 / 0.037*	*3.28* #	0.007 / -0.010	0.42
OBJ	0.041 / 0.024	2.41	0.014 / -0.003	0.82	0.015 / -0.002	0.87
RME	0.013 / -0.004	0.76	*0.093 / 0.061*	*2.88* #	0.011 / -0.006	0.64
Models A2						
Preterm	0.203 / 0.189	14.48 ***	0.150 / 0.135	10.08 **	0.088 / 0.072	5.473 *
Birthweight	0.127 / 0.112	8.30 **	0.102 / 0.086	6.49 *	*0.054 / 0.037*	*3.22* #

*N=59; #p<0.1 *p<0.05 **p<0.01 ***p<0.001*

Figure 8-2: Model diagnostics of Model A1 (regression of Q-CHAT on RME). Residuals vs fitted values and Normal Q-Q plot



Bivariate analyses

Univariate analyses and descriptive statistics suggest that the effect of prematurity may mask or confound the effect of still-face behavioural measures on Q-CHAT scores, due to the association between prematurity and still-face behavioural measures.

Table 8-7 and Table 8-8 shows the results of bivariate analyses which confirms that prematurity and ENTb had independent effects on Q-CHAT Social. After including Preterm birth status, the effect estimate of ENTb on Q-CHAT Social increased, and was marginally significant (Beta =1.58, 95% CI -0.04 to 3.21, p=0.056). Prematurity, specifically lower birthweight, is not just associated with lower entropy, but also greater Q-CHAT scores. This was not controlled for in univariate models and prematurity masked the positive association of entropy on Q-CHAT, because some infants with lower entropy (i.e., Preterm VLBW infants) unexpectedly had greater Q-CHAT scores. In line with the direction of this omitted variable bias, controlling for the effect of Birthweight (rather than Preterm birth status only) led to a larger effect of Entropy on Q-CHAT social scores (Beta= 1.93, 95% CI 0.24 to 3.62, p=0.026). The independent effects of ENTb and Birthweight explained 17.9% of the variance in Q-CHAT Social ($F_{2, 56} = 6.12$, p=0.004).

Adding Preterm Birth Status or Birthweight to the quadratic model of RME with Q-CHAT social led to a reduction in the effect estimates of both the linear and quadratic RME terms, suggesting that prematurity confounded the relationship between RME and Q-CHAT Social. Very weak evidence remained that RME predicted Q-CHAT Social scores after adjusting for the effect of Preterm Birth Status or Birthweight. Therefore, the association of prematurity with Q-CHAT explained some of the quadratic relationship of RME on Q-CHAT (because infants with lower RME or higher RME were preterm infants with high Q-CHAT scores).

No association between OBJ with any Q-CHAT outcomes were identified. Bivariate analyses were not conducted for associations between TT and Q-CHAT because prematurity was not associated with TT in Chapter 5 (Study 2A).

Table 8-7. Models B and C – Bivariate models of still-face behavioural measures with prematurity on Q-CHAT

	Q-CHAT		
	Total	Social	Non-social
	Beta	Beta	Beta
Bivariate models	(95% CI)	(95% CI)	(95% CI)
Models B - Bivariate models with Preterm			
ENTb	1.79	*1.58* #	-0.00
	(-1.01 – 4.59)	*(-0.04 – 3.21)*	(-2.18 – 2.18)
OBJ	5.78	1.02	2.31
	(-7.77 – 19.33)	(-7.05 – 9.09)	(-8.14 – 12.77)
RME			
RME	-2.11	-14.31	-1.82
	(-11.17 – 6.95)	(-31.32 – 2.69)	(-8.78 – 5.13)
RME^2		22.48	
	n.a.	(-4.82 – 49.78)	n.a.
Models C - Bivariate models with Birthweight			
ENTb	2.39	1.93 *	0.24
	(-0.58 – 5.35)	(0.24 – 3.62)	(-2.03 – 2.51)
OBJ	7.86	2.01	3.33
	(-6.11 – 21.82)	(-6.19 – 10.20)	(-7.20 – 13.85)
RME			
RME	-2.10	*-15.48* #	-1.84
	(-11.64 – 7.44)	*(-33.00 – 2.04)*	(-8.97 – 5.28)
RME^2		*24.46* #	
	n.a.	*(-3.56 – 52.48)*	n.a.

*N=59; #p<0.1 *p<0.05 **p<0.01 ***p<0.001*

Table 8-8. Models B and C – Model fit

	Q-CHAT					
	Total		Social		Non-social	
Bivariate models	R^2 / R^2 adjusted	$F_{2, 56}$	R^2 / R^2 adjusted	$F_{2, 56}$	R^2 / R^2 adjusted	$F_{2, 56}$
Models B - Bivariate models with Preterm						
ENTb	0.225 / 0.198	8.14 ***	0.204 / 0.176	7.20 **	*0.088 / 0.055*	*2.69 #*
OBJ	0.213 / 0.185	7.57 ***	0.151 / 0.121	4.99 *	*0.091 / 0.058*	*2.80 #*
RME	0.206 / 0.177	7.25 ***	0.192 / 0.148	4.37**	*0.092 / 0.060*	*2.84 #*
Models C - Bivariate models with Birthweight						
ENTb	0.166 / 0.136	5.57 **	0.179 / 0.150	6.12 **	0.054 / 0.021	1.61
OBJ	0.147 / 0.116	4.81 *	0.106 / 0.074	3.32 *	0.060 / 0.027	1.80
RME	0.130 / 0.099	4.19 *	0.151 / 0.105	3.27 *	0.058 / 0.024	1.73

*N=59; #p<0.1 *p<0.05 **p<0.01 ***p<0.001*

Figure 8-3 – Predicted effects of ENTb, (bivariate model with birthweight) and TT (univariate model) with Q-CHAT Total, Social and Non-Social. Univariate models showed evidence of a positive association between TT and Q-CHAT Social and Bivariate models controlling for Birthweight revealed a positive association between ENTb and Q-CHAT social. No effects with Q-CHAT Total or Non-social were found.

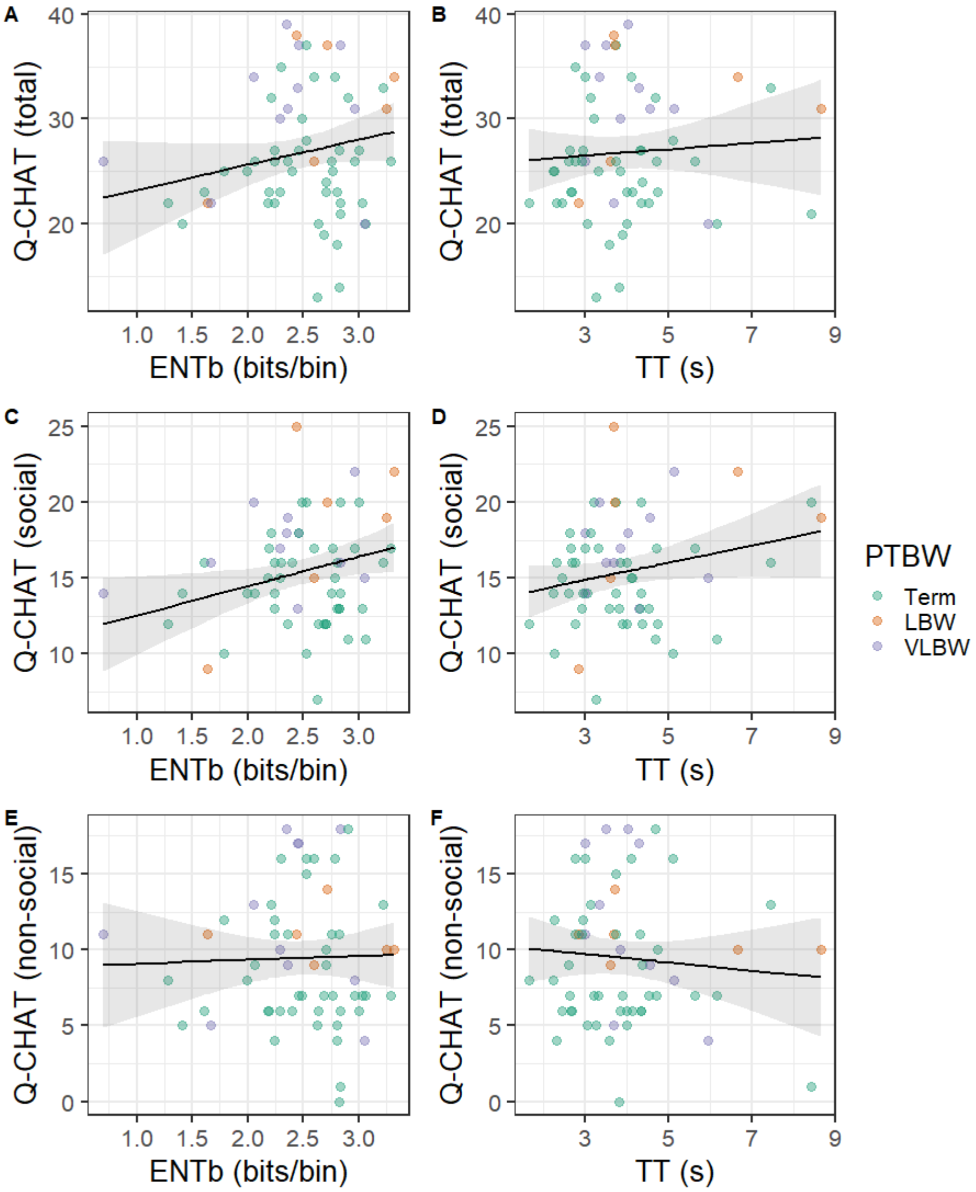
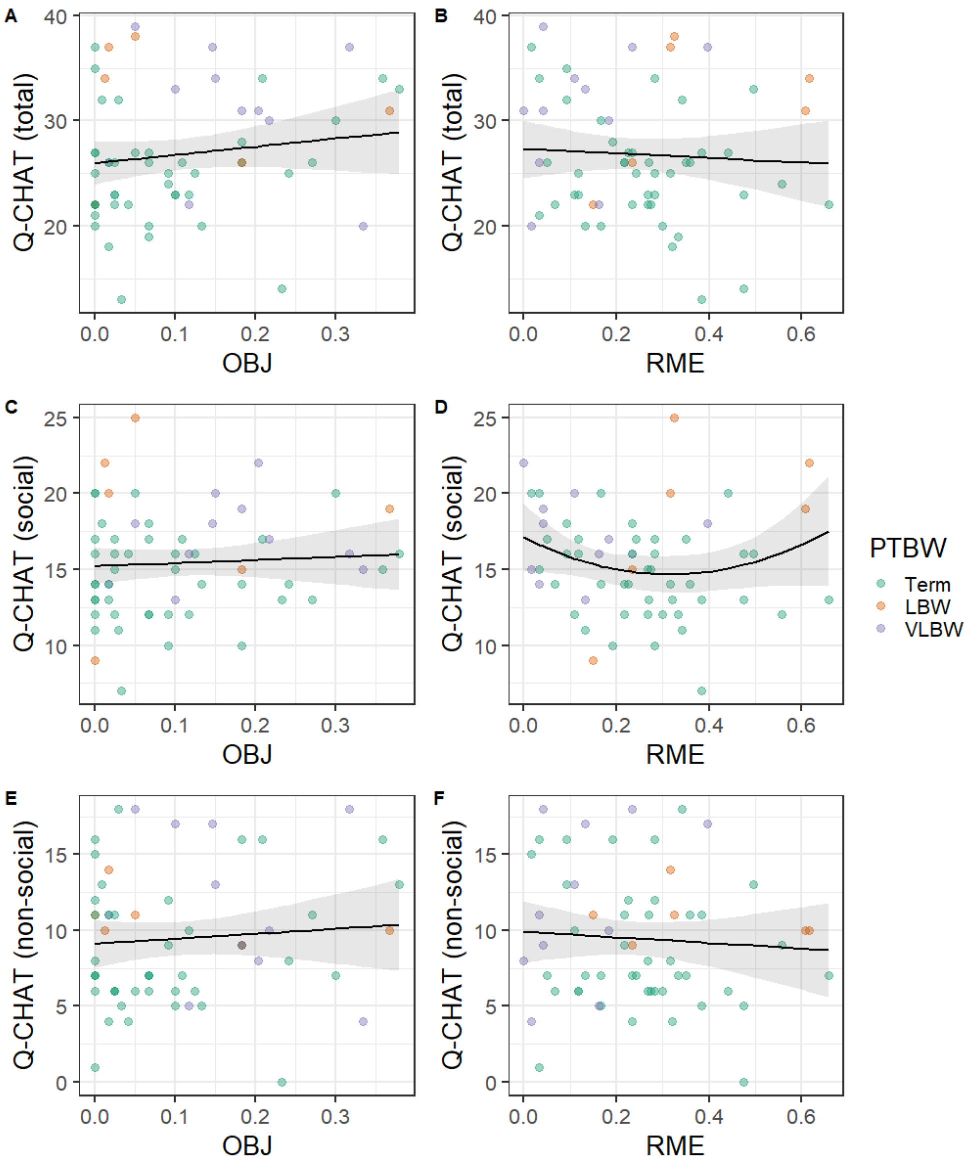


Figure 8-4. Predicted effects of OBJ and RME (bivariate models with birthweight) on Q-CHAT Total, Social and Non-Social scores. There was very weak evidence of a quadratic association between RME and Q-CHAT Social after adjusting for Birthweight. No evidence of associations with Q-CHAT were found for OBJ.



8.4. Discussion

In support of my hypotheses, emotional self-regulation at 9-months was prospectively associated with autistic traits at 2-years, an effect that is specific to traits related to social communication. Dynamics of emotional self-regulation appear to implicate social autistic traits independently of the effect of premature birth. The proportion of time using repetitive movements as a strategy for emotion self-regulation was associated with social autistic traits in a non-linear way, an association that was explained by the confounding effect of premature birth. Univariate models showed significant associations but non-significant R^2 values. Overall, these findings support the idea that emotional self-regulation affects the development of social cognitive abilities implicated in autism. Although emotional self-regulation is an important domain of social-emotional competence implicated in preterm birth, 9-month emotional self-regulation has little to no predictive power without including prematurity.

Effect of missing data

Missing data on Q-CHAT at 2-years likely led to an underestimation of the association between Preterm Birth Status or Birthweight on Q-CHAT as data was systematically missing from preterm or lower birthweight infants who also had higher Q-CHAT scores. As preterm birth and lower birthweight were also associated with lower ENTb, lower RME and greater OBJ, missing data may also bias univariate associations. Although missing data bias likely distorted the U-shaped relationship of RME on Q-CHAT social as we would expect a steeper initial decrease and a less steep increase later, it is unlikely to have biased the data towards the pattern of quadratic association if there were no such association. Nevertheless, including prematurity in bivariate models controlled for the association between prematurity and Q-CHAT, as well as accounted for other biasing mechanisms that had more important influences on the associations of interest, namely, omitted variable bias and confounding bias.

Missing data on Q-CHAT at 2-years also significantly reduced the sample size, resulting in larger standard errors of effect estimates and wider 95% confidence intervals. While I still found weak to moderate evidence of associations between TT on Q-CHAT Social, this did not reach significance at the 95% confidence level and requires further investigation to strengthen the present evidence. Additionally, although there was very weak evidence for an independent association of RME on Q-CHAT Social after including Birthweight, a higher-powered study might potentially find stronger evidence for this.

Comparison to other studies and evidence supporting our findings

A number of studies have reported that greater frequency of restricted and repetitive behaviours at 1 year of age is related to autism diagnosis at 3 years (Ozonoff et al., 2008) and RRBs were associated with social skills at 2 and 3-years of age (Chaxiong et al., 2021), supporting the present findings that RME emotional regulatory strategies are associated with social-communicative autism traits. However, one study did not find a relationship between Repetitive and Restricted Behaviours (RRBs) with socio-communicative autistic traits across the first year of life (Harrop et al., 2014) and my findings showed that the association between repetitive behaviours with autistic traits is nonlinear, at 9-months, greater use of repetitive behaviours does not necessarily mean they predict greater autistic traits. These findings are both consistent with the proposition that the occurrence of repetitive movements is part of normal development and that stereotypies may not be indicative of risk in the first year of life (Bhat et al., 2011), but it is its persistence during development that is atypical (Sifre et al., 2021).

At first glance, the lack of association between OBJ and autistic traits appear in contrast with Miller and colleagues' (2021) findings, that behaviours involving objects predicted later social behaviour. However, the different definition of object engagement and context where object engagement was examined need to be considered. Miller and colleagues defined repetitive object behaviours as unusual, prolonged visual inspection while repeatedly manipulating objects, spinning and rotating. In this study, OBJ measured movements involving objects where the function was for attentional distraction, therefore repetitive movement involving objects was only considered when the infant's attention was directed to the objects. As using objects provide attentional engagement is a useful emotional regulation strategy (Ruff, 1986), another explanation might be that that infants at lower risk for autism were also manipulating objects more during the still-face paradigm. However, this is less convincing as I showed in Chapter 5 (Study 2A) that VLBW infants who are at greater risk for autism showed the greatest OBJ behaviours relative to the term or LBW group. Another study by Elison and colleagues (Elison et al., 2014) reported that groups with increasing risk for autism show greater stereotypic behaviours, only when the measure of stereotypic behaviours included both motor stereotypies and repetitive object manipulation, and not the latter alone. Altogether, this suggests that using objects for attentional distraction may not be a risk factor in itself due to its adaptive function in emotion regulation. However, unusual, prolonged or repeated patterns of manipulating objects together with motor stereotypies may be a stronger risk factor. In this study, the measure of RME included repetitive movements involving objects alongside other repetitive motor activity (see Chapter 3 on Methodology), and is in line with Elison and colleagues (2014) findings.

By investigating the dynamics of emotional self-regulatory behaviours on top of the amount of emotional regulation strategies used, this study provides novel findings providing triangulating evidence from dynamic systems theory, on how emotional self-regulation may affect social development. First, evidence from observational studies suggest that repetitive movements might be a greater cause for concern when they occur for prolonged durations, and not just when they occur frequently in development (Bhat et al., 2011). My finding that greater trapping time of ER behavioural states is associated with greater social autistic traits supports this idea. The effect of trapping time may drive the increase in autism risk seen in infants using greater amounts of RME during emotional self-regulation, as the emotional regulation system has a greater tendency to persist in any one state. Future research could also examine if trapping time of repetitive movements specifically show stronger associations with social autistic traits. Prolonged object distraction behaviours may also be related to autistic traits as suggested by Miller and colleagues (2019).

Second, researchers have suggested that differences in neural networks involved in emotion regulation may be related to the brain compensating for other difficulties that affect emotion regulation. Using Diffusion Tensor Imaging of white matter tracts implicated in socioemotional processing, Kanel and colleagues (2021) found in preterm infants that lower fractional anisotropy (FA) in the uncinate fasciculus in the limbic system, which connects the temporo-amygdala-orbitofrontal network, was associated with better “emotion moderation”. Derived from factor analysis, this factor combines better effortful control and increased negative emotionality, and accounted for a high amount of variance in socioemotional outcomes. The authors further found that the association between white matter tract connectivity in the uncinate fasciculus was driven by greater negative emotionality in preterm infants, and proposed that these are potentially adaptive brain differences developed by preterm infants to compensate for greater negative emotionality. This finding is supported by observational evidence that greater attentional persistence protected against the effect of negative emotionality on poor social competence (Belsky et al., 2001; Nancy Eisenberg et al., 2005).

Greater entropy likely reflects the greater diversity or greater activation of functional connections within the emotion regulation system, and may reflect an adaptation to regulate emotions successfully. The association of greater entropy with greater autistic traits may suggest that infants who require greater, potentially compensatory, neural activations to regulate emotions are at greater risk for altered social cognitive development, an interpretation converges with the lines of evidence discussed.

Implications on social development

The findings relating to entropy suggest that greater neural resources allocated to emotion regulation at 9-months were related to differences in social interaction. This the hierarchical model social-emotional competence, a multilevel construct where social interactions and behavioural adjustment depend on lower-level functions, including emotion regulation. Difficulties with emotional self-regulation is not simply a downstream result of social difficulties (Happé & Frith, 2014) but is potentially implicated in the mechanisms affecting risk for social difficulties.

While this study demonstrated a prospective association between early emotional self-regulation and later autistic traits, the causal mechanisms still need to be clarified. On one hand, the findings may indicate that there are neural networks or psychological capacities implicated in the mechanistic pathway of social communication and interaction that also affect emotional self-regulation (Mazefsky et al., 2013). In this view, emotion regulation may be related to social communication and interaction via a common risk factor, but do not cause those difficulties. For example, the self-regulation of socially-oriented behaviour may depend on the same mechanisms as emotional self-regulation (Bachevalier & Loveland, 2006), to modify one's own behaviour in relation to the perceived intentions, emotions, and other mental states of others as well as awareness of the social context. A possible common neural mechanism is the disruption to serotonin transmission (Canli & Lesch, 2007). Alterations to the 5-HTTLPR gene responsible for serotonin transmission is associated with greater amygdala activation in response to negative social stimuli, and altered structure, and functional connectivity in the amygdala and associated limbic structures. It was also associated with different activity in neural structures (such as the anterior cingulate cortex and parietal regions) involved in action execution and observation, social cognition and communication. In preterm birth, exposure to stress in the NICU affects serotonin transmission via methylation of the serotonin transporter gene, in a way that affects temperamental difficulties (Montirosso et al., 2016). Therefore, systems involved in both emotional self-regulation and social cognition might depend on common neurobiological processes that could be altered by preterm birth.

On the other hand, the findings may indicate that emotional self-regulation could lie on the causal pathway leading to social difficulties. Early social interactions involve not just social cognition, but a range of processes described as the "social brain", including the amygdala network involved in emotion regulation, as well as areas involved in action understanding, mentalising and detecting emotions in others (Adolphs, 2001; Happé & Frith, 2014). Rather than maturing in silos, these systems likely interact dynamically. When one component is affected, this disrupts day-to-day social experiences, and these early social processes implicate the development of later social skills (Happe & Frith, 2013). Dean and colleagues' (2021) review identified that studies on social interactions do not identify a coherent profile of social interactional patterns, but that studies robustly implicated domain-general attentional processes in social situations. As effortful control, an important process for emotion regulation (Eisenberg et al., 2011), draws together different psychological capacities that implicate attentional and behavioural flexibility, it may be possible that emotional self-regulation may disrupt attention in social contexts, leading to altered development of social cognitive capacities which are dependent crucially on early social experiences, at a sensitive period of development. This could contribute to the greater risk for autism in preterm infants, reflecting a pathway more sensitive to early life experience. This is supported by findings that sociodemographic risk and maternal mental health are more important contributors to social behaviour (B. Dean et al., 2021).

These findings also implicate the importance of repetitive movements as a marker of social behavioural risk, and also how useful in early identification. Both too frequent or too few RME were linked to greater Q-CHAT scores at 9-months, and this quadratic association was not independent of the effects of prematurity. This suggests that prematurity explained the presence of either too frequent or less frequent RME as well as greater Q-CHAT scores which in turn is associated with risk for autistic traits. This agrees with existing research that RRBs, particularly those of a sensorimotor nature rather than later emerging Insistence of Sameness or Circumscribed interests (Morgan et al., 2008; Richler et al., 2007), are one of the earliest detectable risk factors for autism. Nevertheless, because the occurrence of repetitive movements is occur as part of normal development (Macari et al., 2017), other factors need to be considered in whether these are indicative of risk – for example, persistence in using repetitive movements, and if repetitive movements have a persistent developmental trajectory.

Strengths, limitations and future directions

This study strength is in its prospective design and its focus not just on the type of emotion regulation behaviours related to autism risk, but also the dynamics of emotion regulation which characterises another aspect of emotion regulation. However, given that these measures of dynamics are relatively recent, the interpretation of complexity in relation to the underlying neurobiological system should be regarded as speculative until further studies can validate the link between the two. A benefit in using these dynamic measures is that they also have intuitive interpretations and characterises the temporal dimension of emotional self-regulation which is discarded when researchers focus on the aggregate or simply the total amount of these behaviours. This can be seen in the direct interpretation of Trapping Time as an indicator of behavioural persistence.

In this study behavioural dynamics were related to all the emotion regulation behaviours including repetitive movements and object behaviours but also self-comforting behaviours and socially oriented behaviours, rather than separately calculated for each type of behaviour. As behavioural persistence may be indicative of risk specifically in relation to object-oriented behaviours and repetitive behaviours, this requires further investigation.

A significant limitation in this study was the follow-up rate on social outcomes at 2-years, affecting the sample size of the study. Although missing data at later timepoints is not uncommon in prospective studies, this study achieved just over 50% follow-up of social development at 2-years. This may have been affected by data collection during the COVID-19 pandemic as data collection shifted to online modes. The Q-CHAT questionnaire is one of the final questionnaires in the set of questionnaires sent out to parents, and not all parents completed the full set. In-person appointments at 2-years also tends to increase response rates but this was not possible during the pandemic lockdowns. Nevertheless, while preterm infants were more likely to have missing data on Q-CHAT at 2-years, this appears unrelated to sociodemographic variables related to socioemotional risk, or emotion regulation at 9-months. As discussed in the early sections of this discussion, bias due to missing data in the associations examined is likely to be minimal and missing data is more likely to have affected the power of this study. In this view, larger studies are warranted to show if these findings are replicable, or if any potential associations were missed.

8.5. Conclusions

Patterns of emotional self-regulation at 9-months are prospectively associated with development of social abilities implicated in autism at 2-years. Interpreted in a hierarchical framework of social-emotional competence, emotional self-regulatory skills and social cognitive processes influence social experience. These findings indicate that the development of both skills likely depend on common neural and psychological processes, but whether it indicates autism risk or causes autism in preterm birth remains to be clarified.

9. Differences at multiple timescales of movement during the still-face paradigm

9.1. Introduction

In Chapter 1, I reviewed literature on motor and socioemotional development in preterm infants. Motor delays have been widely reported in preterm infants and this population experiences poorer socioemotional outcomes than the typical population. However, there is little mechanistic understanding on why preterm-born infants achieve motor milestones later than their term-born peers and how this is related to socioemotional development.

In Chapter 2, I reviewed theories positing that movement is the product of a complex dynamic system. Instead of focusing on outcomes that are different, dynamic systems theory outlines general principles of development (Lewis, 2000) that emphasises processes that are common in "typical" and "atypical" development. Karmiloff-Smith (1998) suggests that researchers should question whether "successful behaviour, the part that is not considered disrupted, is actually reached by the same processes as in typical development". In this section I introduce how the final investigation of this thesis builds on understanding the processes behind movement, and how this framework can be applied to understand socioemotional differences.

Development of motor skills from a complex systems perspective

In Chapter 2 I showed how motor development, from the perspective of dynamic systems theory can be seen as the achievement of adaptive coordination of a high dimensional, multilevel neuromuscular system, such as to reach, sit or walk. These new motor forms come into existence, or emerge, from coupled functional interactions among lower level components. These happen not because of explicit instructions, such as encoded in genes, but through self-organisation - continuous activity and interactions within the system itself which enables exploration and settling into useful kinds of order (M. Mitchell, 2009).

The possibility of infinite numbers of combinations from the interactions of the systems' parts is part of the problem as well as the solution in acquiring new motor skills (Latash, 2012). This is because it presents the infant with the computational challenge of discovering a successful way of achieving a motor task (Bernstein, 1967). Yet, it also affords the ability to fine-tune movement, not just to be increasingly precise, but adaptable to varying and potentially unexpected, task conditions, for example when walking on a bumpy instead of a smooth surface.

To overcome this computational challenge during early stages of skill acquisition, human learners appear to "freeze" the body's degrees of freedom, i.e. imposing order among some of the parts involved (Bernstein, 1967; Vereijken et al., 2010). This simplifies the computation to identify a successful form. Once arriving at a somewhat successful form, they can then tweak the solution by releasing those degrees of freedom to discover other successful forms, which may be more successful in different situations. In infant motor development, the different forms produced during the two phases of learning have been termed "primary variability" and "secondary variability" (Hadders-Algra, 2010, 2018). Primarily variability refers to the variations in forms when infants are initially exploring what could be successful. This decreases as a successful form begins to dominate. However, secondary variability increases when infants then explore subtle differences in functional forms that are also successful. Subtle differences in the common process by which infants explore and organise movement into useful forms may be key to understanding differences in motor development.

Methodological advances in quantifying movement forms

One way to do investigate differences in movement organisation is to look at errors, or inconsistencies in movement that lead to deviations from the goal. Such variability in the outcome is measured by variance and standard deviation, and provides an indicator of the extent the learner is able to coordinate successful forms to achieve the task. However, variability in outcome, which lead to errors, need to be distinguished from functional variability, where a learner has different ways of achieving success on a task. This is demonstrated in a classic example of pistol shooting marksmen and novices. Skilled marksmen exhibit high functional variability in elbow and shoulder joints but low variability in the hand which affects the outcome – in this case, how accurate they are. In contrast, novice marksmen show more variable hand positions, which can be explained by the lack of functional upper arm variability. High amounts of functional variability typically characterise a rich behavioural state permitting skilled performance.

However, we need not measure the different combinations of functional forms to characterise the richness of a behavioural state. Recent theoretical and methodological advances have identified that the *temporal structure of variability, or complexity* provides a window to the underlying organisation of movement, i.e. an indicator of the ways body's degrees of freedom are interacting in space and time.

This draws from a core concept in information theory, that movement is a message generated by the source, the motor system, out of a number of possible messages or movement, similar to Fitts' (1954) analogy of motor system as an information communication system. Movement is a signal containing information about its source. Information content is related to the probabilities of observing the particular movement out of all the possibilities of movement (Frigg, 2004; M. Mitchell, 2009), which affects how much certainty we have in predicting future behaviour. A signal with high information content contains many different possible movements, and as such we observe new forms from moment to moment and what comes next is highly uncertain. This is unlike a signal which produces the same pattern over time, and with some time we have gained most of the information about what it would produce next and can be certain in predicting its future behaviour. In Shannon's (1948) "Mathematical Theory of Communication", he invokes uncertainty to quantify information content of a source, defined as the average amount of surprisal, uncertainty, or new information produced by the source. As Frigg (2004) accurately describes, uncertainty about the source's future behaviour, and the information transmitted by the source are "two sides of the same coin".

A family of measures have been developed to analyse the rate of information generation of a dynamic system from a signal it produces (a timeseries of data points). Kolmogorov-Sinai entropy measures the unpredictability of a dynamic system based on the range of states that the dynamical system can take. It was originally developed to characterise physical systems and require large amounts of data to quantify (Eckmann & Ruelle, 1985), but in the study of biological systems, it is usually not practical to obtain large quantities of data. Further, Approximate entropy, developed to overcome this limitation, provides a measure of information complexity in short timeseries by quantifying regularities in the patterns produced over time (Pincus, 1991). Sample entropy modifies the approximate entropy algorithm to reduce bias from including "self-matching" patterns – patterns which do not repeat itself at other times and only matches itself (Richman & Moorman, 2000). More recently, permutation entropy was developed to overcome further limitations in characterising biological signals, which contain observational noise (noise related to the measurement of the signal) and dynamical noise (intrinsic stochastic fluctuations in the source that affect its later states) (Bandt & Pompe, 2002). Entropy-based measures have been applied to movement data, and is thought to represent the movement forms contributing to information in the signal.

Empirical advances in quantifying movement dynamics

Previous studies have compared movement dynamics of at-risk groups of infants, relative to typical development (Deffeyes et al., 2011; Dusing et al., 2014; Ohgi et al., 2008; B. A. Smith et al., 2011, 2017). Studies have also analysed movement dynamics in typical development (Dusing et al., 2013; Gima et al., 2011; Harbourne & Stergiou, 2003). Although not all use entropy-based measures, these investigations show that examining movement dynamics has the potential to provide insight into development, as well as innovations to improve developmental outcomes.

First, longitudinal studies have provided insight into changes in movement dynamics over critical transitions in motor skill development. Decreases in Approximate Entropy (ApEn) of centre-of-pressure movements were seen around the time new motor skills are gained (Dusing et al., 2013), or when infants become more stable sitters (Harbourne et al., 2010, 2014). Decrease in leg movement entropy was observed in the first 9-months of life, linked to the ability to lock degrees of freedom for example to isolate the movement of the lower leg without the interference of movements in the upper leg (B. A. Smith et al., 2011). Abney and colleagues' (2014) single-subject longitudinal analysis also identified increase in determinism of leg movements, in line with the idea that leg movements showed greater similarity in temporal patterns with development. Reduction in postural ApEn was also accompanied by a reduced Lyaponov Exponent (LyE) and lower variability indicating more periodic and precise postural movements. These studies show that changes in movement dynamics appear to reflect instability as movement goes through phases of exploration and reorganisation. This is in line with theoretical ideas that high movement complexity can indicate that infants are in the exploration phase where they are producing primary variability, exploring a great number of movement configurations to discover a useful strategy, while low complexity represents the time when a successfully learnt motor skills is produced with high consistency.

Second, studies with comparison groups have increased understanding of the effect of developmental risk on motor coordination, although the direction of differences related to developmental risk are not clear. Differences related to developmental risk appear to be in the direction of reducing entropy in postural movements during sitting, and in leg movements (B. A. Smith et al., 2011, 2017). However, whether these differences are observed may depend on developmental time – as postural movements decrease in complexity with sitting development and developmental risk affects the amount and timing of this decrease (Deffeyes et al., 2011; Dusing et al., 2014, 2016). Some research suggest that relative to term-born infants, preterm-born infants show smaller reductions in postural complexity during the first 6-months of development (Dusing et al., 2014, 2016). This means that developmental trajectories might impact the direction and size of differences in movement complexity.

Finally, movement dynamics might provide a window to the coordinative processes that influence movement organisation. It has been suggested that maintaining high postural ApEn might help to cope with task demands in infants learning to sit (Dusing et al., 2013, 2014, 2016). Differences in ApEn were not observed in postural movements in the presence or absence of toy which affected visual attention, but in these situations where there is competing demands on the control of posture, infants in fact showed better postural control indexed by smaller fluctuations of the centre of pressure. Effects of constraints on movement processing has been more commonly studied in adults than in infants. In adults, visual feedback increases movement complexity and decreases motor error (Shafer et al., 2019). In conditions where there are fewer sources of information (unavailability of or reduced visual feedback), an adaptable way to command the body's available degrees of freedom might be to avoid using extra degrees of freedom that would cause more harm than good. Cognitive and attentional resources allocated to motor coordination also affect movement complexity – for example, postural movements show reduced complexity when completing a cognitive task while standing compared to standing only (Donker et al., 2007). Complexity in postural movements was reduced when visual feedback is removed, and more so in autistic adults. Early emerging coordinative differences might, therefore, tells us whether infants are learning differently and use different strategies to achieve motor success.

Earlier theories that high complexity is indicative of adaptiveness and healthy functioning (Goldberger et al., 2002) have led to the idea that infants born preterm show lower movement complexity due to brain injury impacting on the functional synergies available. However, these advances in empirical study of movement complexity show that movement complexity may not simply by an indicator of disrupted functional synergies. It may reflect differences due to the stages of motor learning or the trajectory of motor learning, as well as differences in the neurophysiological constraints influencing success in motor learning or leading to compensations for lower level differences.

Current study

Studies analysing movement dynamics have largely focused on postural control (Deffeyes et al., 2011; Deffeyes, Harbourne, Dejong, et al., 2009; Deffeyes, Harbourne, Kyvelidou, et al., 2009; Dusing et al., 2013, 2014, 2016; Harbourne et al., 2014; Harbourne & Stergiou, 2003), with two focused on leg movements (Gima et al., 2011; B. A. Smith et al., 2011, 2017) and two on arm movements (Ohgi et al., 2007, 2008). Studies have commonly defined commonly developmental risk based on a range of characteristics including preterm birth, various birth complications, developmental delays defined inclusion in the at-risk group (Deffeyes et al., 2011; Deffeyes, Harbourne, Dejong, et al., 2009; Deffeyes, Harbourne, Kyvelidou, et al., 2009; Harbourne et al., 2014; B. A. Smith et al., 2017). More rarely were at-risk infants defined using single characteristics related to the motor developmental delay such as cerebral palsy (Harbourne et al., 2010). A systematic review (C. S. N. Da Costa et al., 2013) identified only one study focused specifically on preterm-born infants (Ohgi et al., 2007, 2008). Since then two other studies have examined entropy of postural control in preterm infants (Dusing et al., 2014, 2016), but only one included a full-term comparison group (Dusing et al., 2014). Several of these studies focused on changes in motor complexity related onset of specific motor skills, resulting in a wide age range of the sample and crucially resulting in developmentally at-risk infants assessed at a later age relative to typically developing infants (as large as 10 months) (Deffeyes et al., 2011; Deffeyes, Harbourne, Dejong, et al., 2009; Harbourne et al., 2014) – but age may also influence the amount of motor experience and contribute to the direction of group differences.

This study will build on the recent advances in methodology and empirical applications of entropy-based methods to movement. In particular, the current study will examine infant's postural, arm and leg movements, to understand developmental risk specific to preterm-birth status, and will study infants similar in age compared to previous studies at 9-months-old (or 9-months corrected age for preterm infants). It will also address a limitation of earlier studies in understanding children's development. Previous work measure entropy only at a single timescale, that of the sampling rate of the device. Given that complex systems contain interactions at more than one level and timescales, it has been argued that entropy-based measures need to go beyond a timescale to characterise the structural richness of these systems (M. Costa et al., 2002, 2005). Further advances in nonlinear methods have enabled computation of multiscale entropy from a single timeseries (M. Costa et al., 2002, 2005), in other words entropy over fine and coarser timescales of the timeseries. Briefly, coarse-graining is a method to down-sample the original timeseries to a lower sampling rate and therefore a coarser timescale, by taking the average of every *n* points to produce new values in the down-sampled timeseries. Entropy is then calculated for that timescale. Surrogate analyses show that multiscale entropy provides a more accurate measure of complexity in biological timeseries data, than single scale entropy. Shuffled biological data, which destroys the temporal structure within the data, show greater entropy than the original data at the sampled timescale, but multiscale entropy accurately indicates that the original biological data is more complex.

The still-face paradigm is used to experimentally elicit distress in infants (Tronick et al., 1987). The "still-face effect" is characterised by behavioural changes in affect and social attention due to disrupted social expectations (Adamson & Frick, 2003). This effect can be said to be the result of an emotional response, characterised by biophysiological responses to the stressful situation, and behavioural responses to express emotion or self-regulate emotion. This description encapsulates the "still-face effect" as involving more than one timescale of neural activity. In Study 2, I analysed infants' movements during the still-face paradigm at the behavioural level, which elicits distress in infants experimentally. Nevertheless, these behaviours are ultimately a motor output (Adolph & Hoch, 2019), produced from an interaction between different levels and timescales of brain processing. Therefore, the still-face paradigm provides a semi-ecological setting to quantify motor patterns underlying the behaviours elicited as a result of changes in the socioemotional context, including behaviours for regulating emotions, as well as behaviours to interact with caregivers.

The current study aims to investigate the proof-of-concept of examining motor patterns to answer questions related to motor and socioemotional development, by deploying sensors to measure 9-month-old infant's movement during the still-face paradigm. The study covers two objectives: to investigate if prematurity influences infants' motor patterns in socioemotional contexts, and if motor patterns reflect changes in the socioemotional context. The specific research questions are as follows:

(1) Is there an effect of prematurity on complexity of movement accelerations across the range of timescales? I will focus on the still-face phase of the still-face paradigm, when infant's movements to regulate emotions are entirely self-generated in the absence of a responsive caregiver. I hypothesise that preterm-born infants will differ from term-born infants in movement complexity, but that the differences observed will be timescale-dependent. I do not make a specific hypothesis about the direction of difference. Based on previous research, preterm infants may show lower complexity in motor patterns reflecting difficulties with coordination, but at the same time complexity appears to be sensitive to motor skill ability. If term-born infants are at a more advanced stage of motor learning, they may show lower complexity when just learning a motor form, or higher complexity if they are diversifying the movement forms. Therefore, there are likely multiple influences on movement complexity that will be difficult to disentangle from existing understanding.

(2) What are the changes in movement complexity between transitions in the still-face paradigm, and is this different between term and preterm infants? I hypothesise that movement complexity will changes as a result of transitions between the phases of the still-face paradigm indicating changes due to social stress or caregiver unavailability. Due to the novelty of this approach, I did not have prior assumptions to guide any hypotheses on which timescale differences can be observed in or about the effect of prematurity.

9.2. Methods

Participants

This study includes a subsample of term-born infants (>37 weeks of gestation) and preterm-born infants (<33 weeks of gestation) participating in the Theirworld Edinburgh Birth Cohort (TEBC) (Boardman et al., 2020), recruited between July 2019 and March 2021, and who took part in movement assessment during the "still-face", structured, parent-child play interaction at their 9-month follow-up appointment. Infants who attended the 9-month follow-up appointment during this period were recruited to the motor assessment subsample, if a researcher trained in the motor assessment procedure was available at the visit. During the 9-month visit, if caregivers verbally declined participation in motor assessment or the still-face interaction, or if infants fussed and refused to wear the sensors, they were not recruited to this subsample. Exclusion criteria were infants who did not complete at least one still-face episode. Where sensors were removed by infants, data from the remaining sensors that were still attached were still included for analysis. Recruitment to the subsample proceeded until a minimum of 10 infants' data from each group and each sensor location met inclusion criteria for the study.

Equipment and procedure

Still-face paradigm

Infants and caregivers participated in an extended modification of the still-face paradigm, comprising five 2-minute episodes of interactions in an A-B-A-B-A structure where the caregiver is responsive during A episodes, and unresponsive during B, or "still-face", episodes. Previous experiments have shown that the second and fourth episodes where the caregiver becomes unresponsive ("SF1" and "SF2") elicit greater negative affect and regulatory behaviours in infants. The first episode ("Play") acts as a baseline when the caregiver and infant initially interact as they would normally face-to-face, and the third and final episode act as "reunion" episodes ("R1" and "R2"), where the caregiver attempts to re-engage the infant in playful interactions again following a stressful still-face episode. Infants were sat in a high chair during the paradigm and were able to move their limbs and turn their body while seated.

Movement sensor data acquisition

Infant movement was measured using five inertial magnetic units (IMUs) sensors (Xsens MTw Awinda, 100hz) placed on the torso, and left and right wrists and ankles (Paulich et al., n.d.). The sensors were small and lightweight (47mm x 30mm x 13mm, 16g), containing tri-axial accelerometers (±160 ms-2), gyroscopes (±2000 deg/s) and magnetometers (±1.9 Gauss). Prior to beginning the still-face experiment, the sensors were docked in an MT Awinda Master station which provided a wireless network enabling time synchronisation within 10µs (Paulich et al., n.d.). Using the Xsens MT Manager software, the wireless network was set up with the desired sampling frequency before undocking the sensors one by one, which connected each of it to the wireless network. The sensors were then placed in fitted pockets sewn onto a bib, wristbands and socks. With the assistance of a researcher, caregivers placed the tailored clothing on infants. The bib was secured around the infant's chest using a strap with Velcro closure around the back. Socks were put on such that sensors were located around the same level of the ankle, on the anterior side just above the foot. Wrist sensors were placed on the side of the wrist with the palm faced-down (i.e., wrist sensors face away from the body when the forearm is pronated). Where possible, wrist sensors were tucked under infant's long sleeve shirts, or an additional long sleeve shirt put on to keep the torso and wrist sensors out of sight. Recordings were started and stopped using the MT manager software. Kinematic data - namely the calibrated 3D acceleration, angular velocity and magnetic field, orientation and free acceleration (i.e., acceleration after subtracting gravity vector) - was extracted after applying the Xsens Kalman Filter profile.

Figure 9-1. Placement of 5 IMUs on infant's body. Black ovals mark the location of sensors hidden in infant clothing

Video and sensor-synchronised video data

Video recordings (1920 x 1080 pixels, 50 frames per second (fps)) from Panasonic HC-W580 cameras were obtained of the still-face paradigm with one camera facing the mother and one facing the infant. In addition, for some infants, video recordings (1024 x 768 pixels, 25 fps) synchronised to the sensor recording were obtained from a Pi camera board (v1.3) fitted to a Raspberry Pi (Rpi) (version 3 B+).

Measures

Demographic and clinical data

Clinical data on infants' prematurity status, gestational age and birthweight at birth, singleton/twin status, and demographic data on infants' sex, ethnicity, SIMD were obtained from the TEBC database hosted on a secure, web-based application Research Electronic Data Capture (REDcap).

Behavioural data

The video coding scheme described in Chapter 3 (Methodology) was used to capture a range of emotional self-regulatory behaviours (self-comforting, social attention/interaction, object-distraction and repetitive movements). Additionally, data on infant's negative affective behaviours, based on the ICEP coding scheme, were used (Ginnell et al., 2021). Infant's emotional self-regulatory and negative affective behavioural response were expressed as proportion of time. The proportion of time where caregiver moves infants during the caregiver-present phases of the still-face paradigm was also obtained as a further descriptor of the dataset, the extent it represents infant's self-produced movement.

Acceleration magnitude

Timeseries of acceleration magnitude (root-mean-square acceleration) was computed as the vector sum of tri-axial accelerometer data at each timepoint. This was then segmented to produce a timeseries with 12000 samples for each 2-min episode in the still-face paradigm.

Mean acceleration magnitude across each of the five episodes was obtained, after excluding outliers greater than 1.5 times the interquartile range. This was to remove the influence of outliers on the mean acceleration magnitude.

Movement complexity

Movement complexity was computed from each timeseries of acceleration magnitude. Permutation entropy was selected as a measure of movement complexity as it is particularly useful in the presence of dynamical and measurement noise in the study's experimental context. Infants' movement creates slight movements of the chair that may affect their ongoing movement compensations, and infants' banging on or rocking movements create artefacts in the data. Permutation entropy is robust to these dynamical and observational noise (Azami & Escudero, 2016; Bandt & Pompe, 2002; Zanin et al., 2012). As Permutation Entropy is calculated from sequences of increase or decrease in the timeseries, and not the specific amount of change, the measure is less susceptible to biases due to artefacts (Bandt & Pompe, 2002). In this study, two measures of movement complexity were used - multiscale permutation entropy and complexity index.

Multiscale permutation entropy

Multiscale permutation entropy was a measure of complexity at specific timescales. Multiscale permutation entropy examines permutation entropy at timescales corresponding to frequencies lower than the sampling frequency. This is achieved by coarsegraining the signal, by averaging every *n* points to produce a signal related to activity at that scale. Scale factors up to 50 (corresponding to a timescale of 0.5 s for a sampling rate of 100hz) were examined. This meant that the timeseries at the highest scale factor (longest timescale) would be computed from 240 data points. The Improved Multiscale Permutation Entropy algorithm (Azami & Escudero, 2016) was selected to calculate permutation entropy at each timescale. This algorithm implements the coarse-graining procedure suggested by Wu and colleagues proposed for use with relatively short timeseries, as it produces estimates of Permutation entropy with lower standard error when data is limited (Azami & Escudero, 2016; Humeau-Heurtier et al., 2015; S. De Wu et al., 2014). Permutation entropy was computed separately for 50 scale factors for 20-hz filtered data from each still-face phase, using an embedding dimension *m* of 4, and a *lag* of 1. The optimisation of the permutation entropy algorithm that led to the decision to use filtered data and the *m* and *lag* parameters is described in the next section on data processing.

Complexity index

The complexity index provides a measure of overall structural complexity, estimated as the sum of movement complexity across all timescales of interest, i.e., the area under the MSE curve (M. Costa et al., 2005). Because Preterm infants showed differences from term-born infants in the curve structure of multiscale entropy, complexity index was also computed separately over the timescales corresponding to 5 different frequency bands.

Data processing

Segmentation of sensor data

An observer watched the video or synchronised video to identify the start of the still-face paradigm. For consistency, this was relative to the start of the first still-face episode (SF1), the nearest second (rounded down) when the experimenter instructed the parent to "switch" and stop responding to the infant. If a RPi-synchronised video feed was available, video time was directly converted to sample time (multiplied by 100) to identify the start and end of the still-face paradigm. If not, the video was synchronised to the sensor recording using one of three different methods before sample time was computed: by identifying the exact start and end time of sensor recording observed on the MT manager screen in the video (n=5); identifying a repeated movement in video with a distinct number of phases and finding its corresponding sensor time (n=1); identifying a movement artefact in the signal of an additional synchronised IMU attached to a clapperboard (n=4).

Filtering

Selection of butterworth filter frequency was guided by previous research identifying that almost all the spectral power in human movement is contained within frequencies lower than 20-30 Hz (Harbourne et al., 2014; Khusainov et al., 2013). Each timeseries of acceleration magnitude across the whole still-face paradigm was filtered at 10, 20, 25 and 30 Hz and the cut-off spectral power was calculated at each frequency. 90% of the spectral power was contained within 20 Hz, therefore, to remove high frequency noise or artefactual effects on the acceleration profile, 20 Hz was chosen. A low pass filter is suitable when the phenomena of interest obey slow dynamics, where high frequency content

Permutation Entropy

IMPE The IMPE algorithm was implemented in Python (version 3.7.6) on Jupyter Notebook (version 6.0.3). The scripts were created with reference to publicly available Matlab scripts (Azami & Escudero, 2016).

Optimisation of Permutation entropy

A lag of 1 was selected as the multiscale entropy algorithm enables the calculation of permutation entropy at greater lags via coarse-graining.

The MSE curve generated from filtered and unfiltered acceleration timeseries was also compared. This confirmed that filtering affected only the part of the curve where frequencies were removed. From visual observation, the effect of filtering on the MSE curve appears to affect all infants' data in the same way (see Figure 9-2 a-b). As expected using a low-pass filter to remove high frequency power only affects complexity at low scale factors corresponding to high frequency bands where power was removed (Courtiol et al., 2016). Therefore, filtered data was used for analysis, as it is recommended that the data is as representative as possible in entropy analysis (Yentes & Raffalt, 2021).

Surrogate analysis was used to guide the selection of parameters and was aimed at testing that MSE of infant acceleration did not just represent random noise. Shuffled data visually compared to filtered, unfiltered data at embedding dimension of 4 and 5. Both show separation from shuffled data. Shuffled data had greater entropy, closer to randomness. Shuffled data at m=5 showed a steep reduction at higher timescales.

Embedding dimension of m=5 reduces data length, and the resulting effect on the MSE curve was an observable trend towards lower entropy at longer timescales – as expected (M. Costa et al., 2002). This trend was not seen when using an embedding dimension of m=4 suggesting it was more robust. The only difference between using m=4 and m=5 was that using m=5 leads to lower values of entropy, but the effect was the same across all timescales (Figure 9-2 c). Therefore, an embedding dimension m=4 was selected.

Figure 9-2-a. Optimisation of permutation entropy. Multiscale entropy across 50 time-scales using embedding dimension of m=4, including permutation entropy (pe) calculated from raw unfiltered data (in red), data filtered at 20 Hz (in blue), and raw data that was shuffled to remove temporal information (in green).

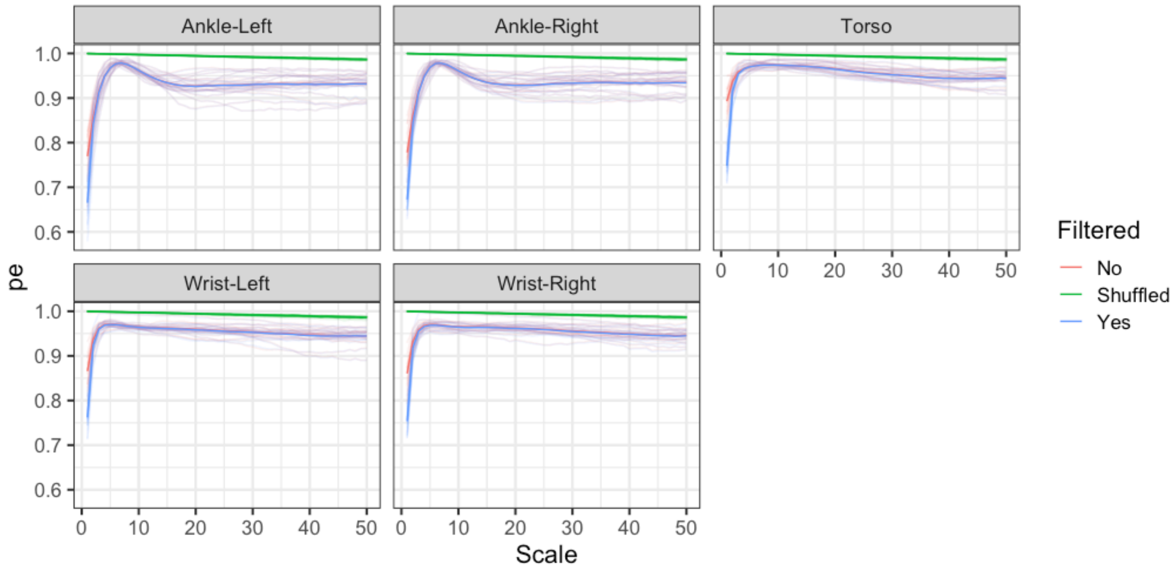


Figure 9-2-b. Optimisation of permutation entropy. Multiscale entropy across 50 time-scales using embedding dimension of m=5, including permutation entropy (pe) calculated from raw unfiltered data (in red), data filtered at 20 Hz (in blue), and raw data that was shuffled to remove temporal information (in green.

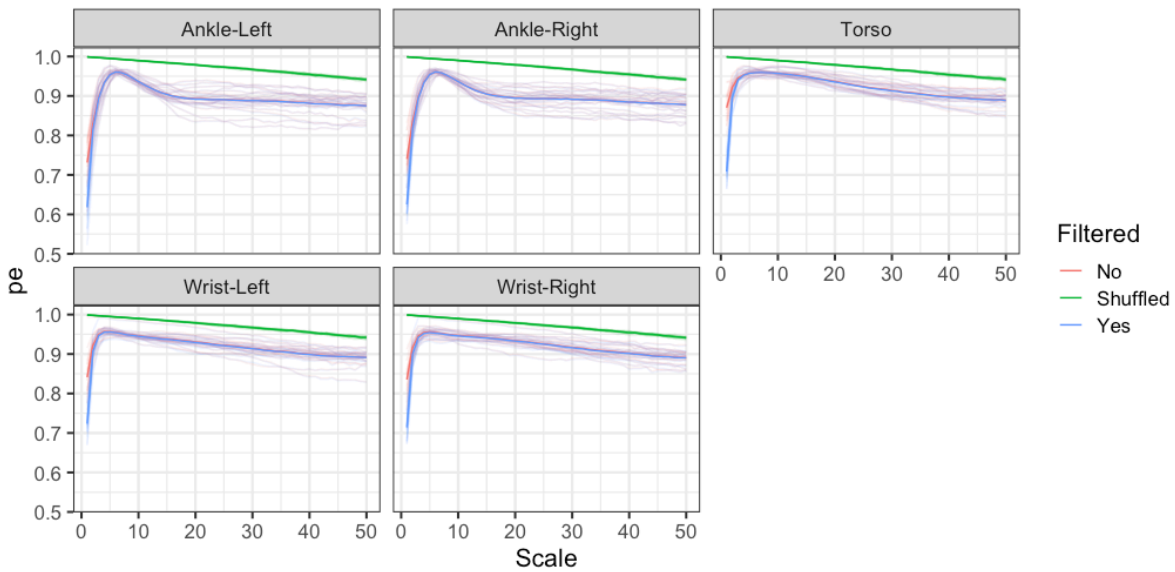
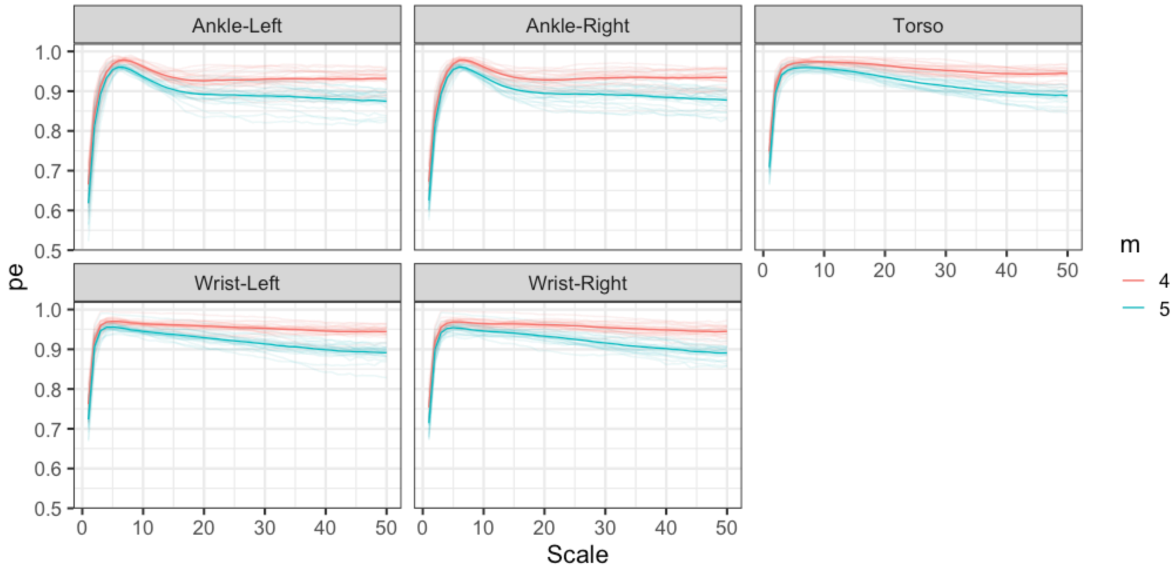


Figure 9-2-c. Optimisation of permutation entropy. Comparison of permutation entropy at embedding dimension m=4 and m=5



Statistical analysis

Statistical analyses were conducted in R version x. Two preterm infants were a twin pair, but data from these infants were assumed to be independent for the present analysis. This is because models used to account for non-independence may not converge when the sample is small and it is preferable to fit the most parsimonious model that would give reliable effect estimates (Sauzet et al., 2013).

Descriptive statistics

Sample characteristics

The demographics of the sample was described for term and preterm groups using means and standard deviations of birthweight and gestational age, age or corrected age (for preterm infants) and anthropometry data (length and weight) at 9-month follow-up, and numbers with percentages for categorical descriptors (gender, ethnicity, SES and twin birth).

Motor activity during the still-face paradigm

Boxplots of movement accelerations, grouped by prematurity status and SF phase, were obtained to describe the amount of motor activity.

Using boxplots, behavioural data (means and interquartile range (IQR) of proportion of time) by group were also described during each phase of the still-face paradigm. This includes proportion of time when caregiver moved infant during the caregiver-present phases as this provides further descriptor of the extent that sensor data resulted from infants' self-produced movement; repetitive movements and negative affect as infants may show increased motor activity as a result of greater arousal and repetitive movements have been used as an indicator of motor activity; and the other types of emotional self-regulatory behaviours which provides a description of the behavioural states that infants tend to be in.

Correlation between motor and behavioural measures

Data from SF1 was used to analyse the Spearman rank correlation coefficients of mean acceleration and complexity index with proportion of time showing repetitive motor behaviours and proportion of time showing negative affect. These two behavioural measures were selected as previous literature suggests repetitive motor behaviours indicate greater motor activity, and infants with greater physiological arousal also show greater motor activity.

Correlation between infant physical characteristics and motor/complexity measures

Pearson correlations between movement acceleration and complexity index with infant height and weight were obtained to determine if there were systematic effects of infant physical growth on movement acceleration or complexity.

Inferential statistics

Analysis of Multiscale Entropy Curve Profile

Acceleration data from SF1 was used to analyse group differences in the curve profile of Multiscale Entropy (MSE). MSE slopes can be calculated separately over a specified range of scales (Escudero et al., 2006; Lin et al., 2014; Tsai et al., 2015) or all scales entered into statistical analyses (Catarino et al., 2011). For a few number of scale factors, the second approach might be appropriate (Bisi & Stagni, 2016). Alternatively, a data reduction approach has been applied instead of including data from all 50 scales in statistical analysis, an approach that focuses on "common features" of the MSE curve, features seen in all individuals but its exact value differs (Park et al., 2007). For example, Park and colleagues (2007) analysed only a single parameter of interest characterising the local maximum of the MSE curve, and then discussed the characteristic differences in MSE curve with reference to specific frequency bands. To guide the selection of scale range, Watanabe and colleagues (2015) split the slope ranges into, high, low and very low frequencies, as with Ho et al (2011) and Takahashi et al (2010). As human brain signals are commonly split into high and low frequencies corresponding to gamma (30-45Hz), alpha (8-13.5Hz), beta (14-30Hz), theta (4.5-7.5Hz), delta (0.5-4Hz) bands, a combination of the two approaches to analysing multiscale entropy was used.

First, data was reduced to the timescales corresponding to upper and lower frequencies of each of the 5 frequency bands and visually assessed as characteristic "landmarks" of the MSE curve profile. Figure 9-5 in the results section shows that after data reduction, MSE curve retains its characteristic curve profile.

Next, a linear mixed-effects model with random intercepts was conducted to analyse the effect of prematurity at these timescales, including both a priori, main effects of sensor, location, prematurity and interaction effects with timescale. A step-down procedure was employed to determine if Sensor x Timescale interactions and a three-way interaction with Preterm was to be included. Estimated marginal means with 95% confidence intervals were obtained by each sensor and timescale for term and preterm groups. Where main effects were present, planned orthogonal contrasts with two-tailed t-tests were conducted to examine the effect of preterm relative to the term (Schad et al., 2020). As the study is interested in whether there would be a difference in the MSE curve structure between term and preterm infants (difference at any of the examined timescales would indicate a difference in the curve structure) in any of the sensor locations, only one hypothesis is being evaluated in planned contrasts and therefore does not require adjustment for comparisons at the selected timescales (Armstrong, 2014; Lakens, n.d.; Vickerstaff et al., 2019). Therefore, each null hypothesis was rejected if $p<0.05$.

Analysis of complexity index

To analyse the effect of SF phase on complexity index, Prematurity, sensor location and SF phase, and Phase x Preterm interaction were included as a priori fixed effects. Similarly, Phase x Sensor, Preterm x Sensor and three-way Phase x Preterm x Sensor interaction tested for inclusion through a step-down procedure. For all model comparisons, significance was examined at the 95% confidence level. Orthogonal contrasts were applied to examine the effect of Preterm at each sensor location as there was a main effect of prematurity and interaction effect of Prematurity x Sensor. Similarly, no correction for multiple comparisons was applied as the contrasts were planned to investigate the hypothesis of whether there would be an effect of Prematurity or Phase, at any sensor location.

Due to differences in the curve structure of MSE, to more specifically explore how Preterm and SF phase affects differences in complexity index, complexity index was further split into the five frequency bands before building a statistical model for the complexity index of each frequency band. Contrasts were planned to explore any main effects. As a main effect of Phase was identified for CI in the Gamma, Alpha and Beta band, orthogonal contrasts of the effect of each phase relative to the previous phase was obtained (at the mean across all sensor location and preterm groups). Similarly, Preterm x Sensor effects were observed in CI of all frequency bands except the alpha band, and orthogonal contrasts examined the effect of Preterm at each Sensor location for the four frequency bands (at the mean across all phases). Five hypotheses were examined in this independent analysis (that, at one or more sensor locations, there would be an effect of either Phase or Preterm, on complexity in the gamma, beta, alpha, theta and delta frequency bands). Therefore, Bonferroni correction was applied accordingly for a 95% significance level to correct for the experiment-wise error rate of 5 hypotheses, and each null hypothesis was rejected only if $p_{adj}<0.05$.

Analysis of acceleration

The same procedure was repeated for mean acceleration to compare the specificity of the effects found to complexity.

During model building where fixed effects were selected, models were fitted using maximum likelihood. Final models were then fitted using REML (Zuur et al., 2009). Linear-mixed effect models were fitted using the lmer package (D. Bates et al., 2015). Contrast analyses were conducted using the emmeans package (Lenth, 2020). Degrees-of-freedom of two-tailed tests were estimated using the Kenward-Roger method.

9.3. Results

A total of 25 infant-caregiver dyads were recruited. No caregiver declined participation in the additional motor assessment. Three infants' data were excluded as they did not complete at least one still-face episode (n=2), or due to technical issues (n=1, sensor data unavailable). Therefore 22 infants (10 born at term, 12 born preterm) formed the analysis sample. One preterm-born infant removed both wrist sensors during the experiment, data was available from 21 infants for arm movement data. Due to early termination of the still-face experiment (one in R1 and one in SF2), data from two infants were incomplete. Table 9-1 shows the demographics and characteristic of the analysis sample. Table 9-2 shows the breakdown of data available by still-face phase.

Table 9-1. Characteristics of computational motor assessment subsample

Characteristic	Overall, N = 22[1]	Term, N = 10[1]	Preterm, N = 12[1]
Age or corrected age at visit	8.72 (0.56)	8.94 (0.28)	8.53 (0.67)
Birthweight (g)	2,398 (1,077)	3,471 (371)	1,504 (432)
Birthweight Z-score	0.38 (0.64)	0.51 (0.57)	0.26 (0.71)
Gestation (weeks)	34 (5)	39 (2)	30 (3)
Sex			
Male	12 (55%)	4 (40%)	8 (67%)
Female	10 (45%)	6 (60%)	4 (33%)
Ethnicity			
Any Asian background	1 (4.5%)	0 (0%)	1 (8.3%)
Any Mixed background	2 (9.1%)	0 (0%)	2 (17%)
Any White background	19 (86%)	10 (100%)	9 (75%)
Singleton			
Singleton	20 (91%)	10 (100%)	10 (83%)

Characteristic	Overall, N = 22[1]	Term, N = 10[1]	Preterm, N = 12[1]
Twin	2 (9.1%)	0 (0%)	2 (17%)
Height (cm)	71.95 (2.50)	71.33 (1.48)	72.45 (3.09)
Weight (kg)	12.60 (16.15)	9.30 (1.24)	15.29 (21.83)

[1]Mean (SD); n (%)

Table 9-2. Description of the still-face computational motor assessment dataset

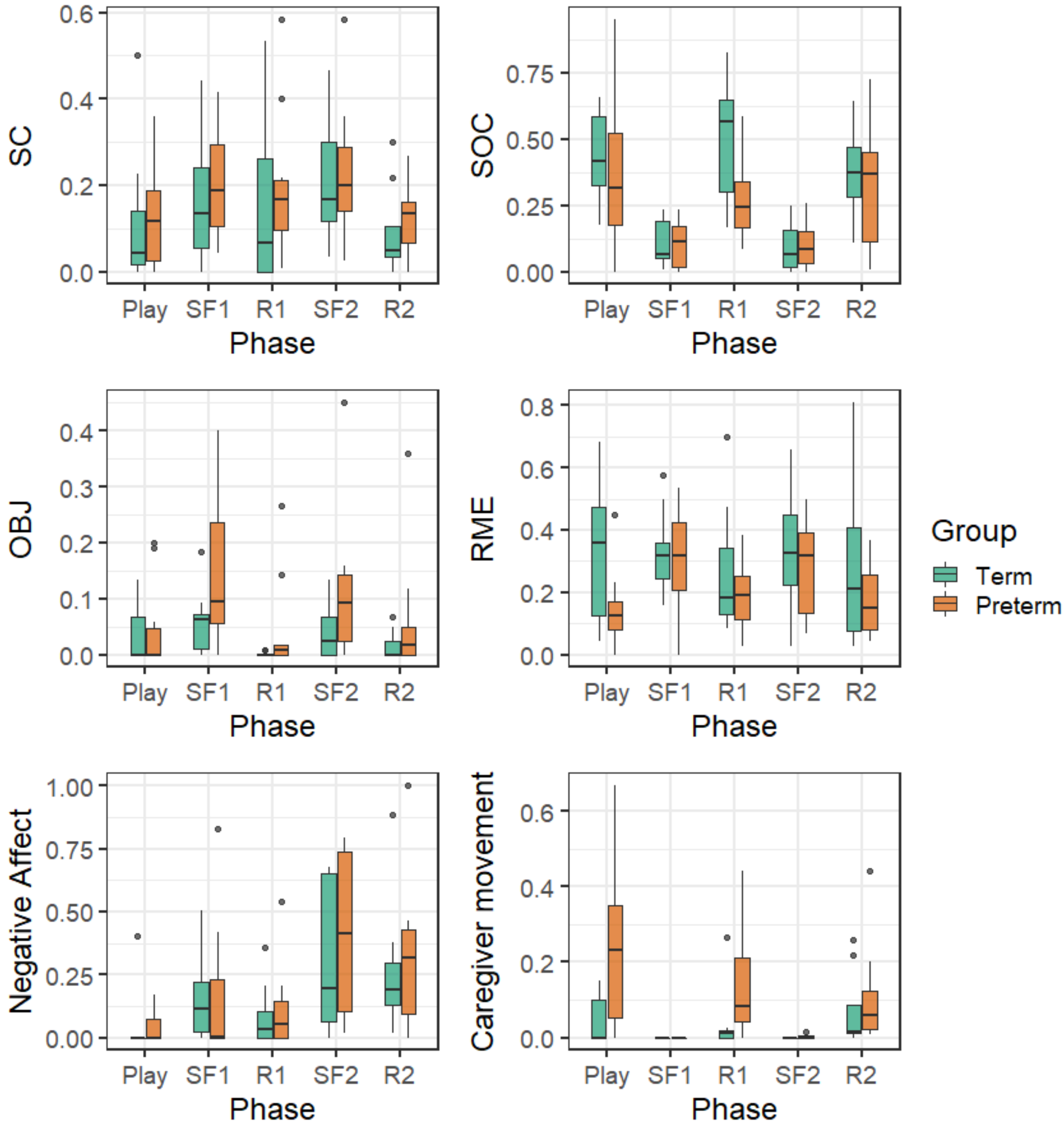
	SF phase				
	Play	SF1	Reunion1	SF2	Reunion2
Total infants	22	22	21	20	20
Total observations	108	108	103	98	98
Observations by Sensor Location					
Ankle-Left	22	22	21	20	20
Ankle-Right	22	22	21	20	20
Wrist-Left	21	21	20	19	19
Wrist-Right	21	21	20	19	19
Torso	22	22	21	20	20

Descriptive statistics

Figure 9-3 shows the boxplots of infants' behaviours during each episode of the still-face paradigm, including both emotion regulation behaviours and behavioural expressions of negative affect. There were some group differences in mean proportions of behaviours during the still-face paradigm, but also a large spread in behaviours between individuals. Most infants showed negative affect in SF2, but the largest variability in individual responses was in this phase.

Caregivers contributed to infants' movement in the caregiver-present phases, in particular in the Play phase (median, IQR). Caregivers of infants born preterm contributed more to infants' movements during these phases. Caregivers did not move infants in SF1. Most caregivers did not deliberately move infants' body in SF2, and those who did move infants did so over a negligible amount of the phase (median= 0, IQR= 0.0000 to 0.0042).

Figure 9-3. Boxplots of behavioural response during the still-face paradigm



Boxplots of the mean acceleration from each sensor location, by term and preterm groups for each still-face phase, are presented in Figure 9-4.

Figure 9-4. Boxplots of mean acceleration during the still-face paradigm

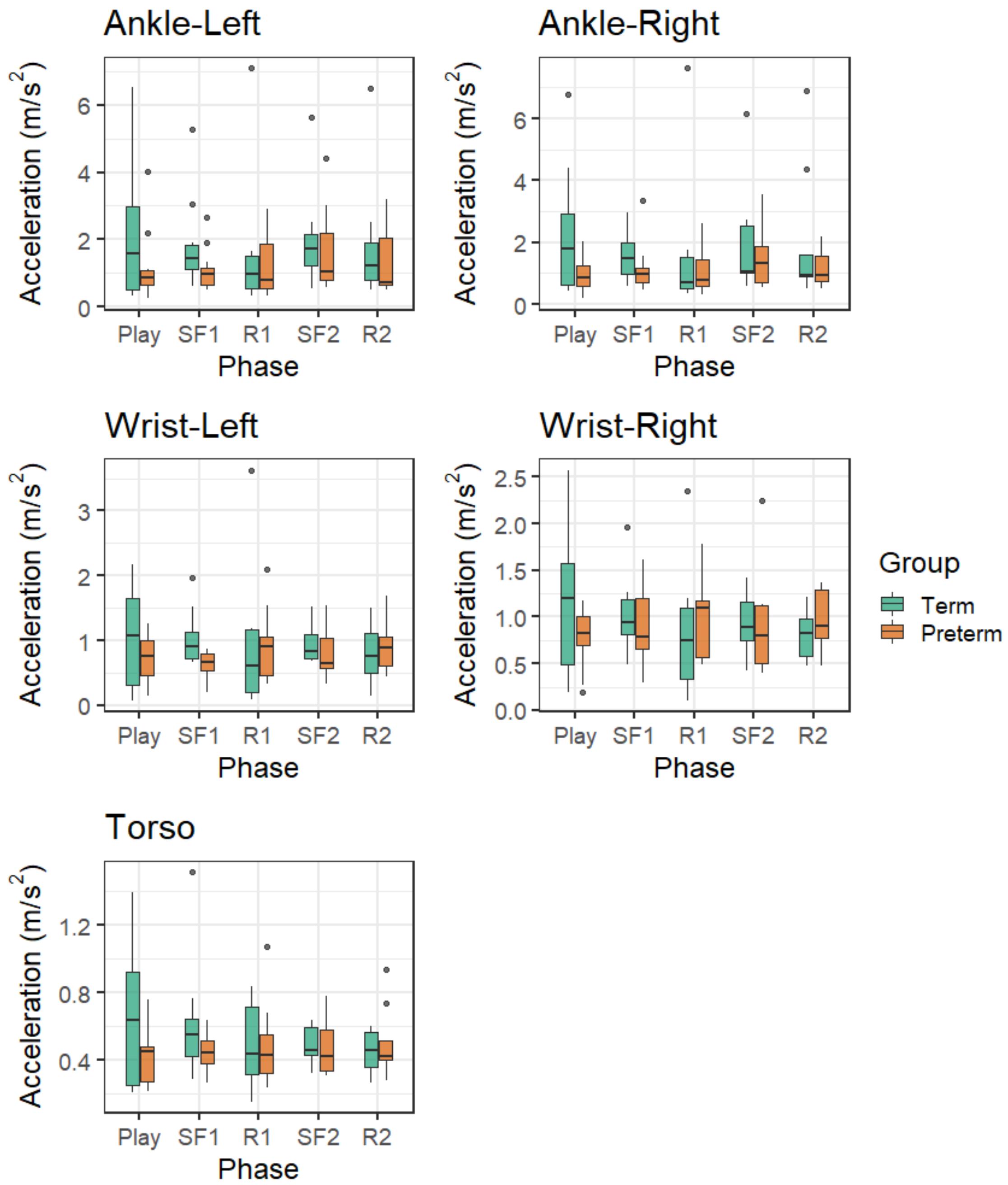


Table 9-3 shows the Spearman rank correlation coefficients between mean acceleration and complexity index, with negative affect, RME behaviours and infant height and weight, in SF1. Correlations significant at the 95% confidence level were found between the mean accelerations of torso and ankle movements and RME. Greater proportion of RME behaviours were correlated with greater mean accelerations. There were no correlations between complexity index with behavioural measures. There was no evidence that infant height and weight were correlated with any of the motor measures.

Table 9-3. Spearman rank correlation coefficients using data from SF1

	Negative affect	RME	Height	Weight
Mean acceleration				
Torso	-0.28	0.45 *	-0.01	-0.05
Wrist-Right	-0.07	0.37	-0.15	0.14
Wrist-Left	-0.09	0.29	-0.05	0.04
Ankle-Right	0.08	0.50 *	-0.26	-0.21
Ankle-Left	-0.04	0.58 **	-0.14	-0.15
Complexity Index				
Torso	-0.31	0.04	0.30	-0.07
Wrist-Right	-0.38	0.30	0.41	-0.01
Wrist-Left	-0.40	0.28	0.23	0.01
Ankle-Right	0.02	0.02	0.11	-0.01
Ankle-Left	0.25	-0.10	-0.14	-0.25

$^{\#}p<0.1$ $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

Inferential statistics

In this section, ANOVA tables are reported to interpret the presence of main effects in each linear mixed-effect model. This is followed by planned contrasts examining the hypotheses are reported, providing the corresponding main effect was present. The estimated marginal means are depicted in figures to visualise these effects. This approach is recommended by M. N. Mitchell (2021) when predictors contain several levels and several interaction effects are included in the model, making predicted coefficients of each dummy variable which represent simple effects harder to interpret. Tables showing all the beta coefficients (simple effects) of each of the final fitted models are provided in the Appendices (Chapter 12).

Following processing of permutation entropy from data available from 22 individuals in SF1 (see Table 9-2) and data reduction, 648 observations of Permutation Entropy were used for inferential statistical analysis of differences in curve structure. Step-down procedures of model-building led to the exclusion of a third-order interaction (Prematurity x Sensor x Scale factor) and the interaction effect of Prematurity x Sensor.

After processing of complexity index (summation of permutation entropy across the desired scale factors) from all available data in each still-face phase (see Table 9-2), 515 observations of Complexity Index (CI) were used for inferential statistical analysis of differences in movement complexity. In all models fitted on complexity index (CI and CI split by five frequency bands), step-down procedures led to exclusion of a third-order interaction (Prematurity x Sensor x Phase) as well as the interaction effect of Sensor x Phase.

MSE curve profile

Random intercepts indicated that the variation in Permutation Entropy between individuals was very small (Var(ID) = 1.61E-05). The small Intraclass Correlation (ICC = 0.07) shows that variance between individuals contributed to just 7% of the total variance in Permutation entropy. The model explained 97.3% of the variance in Permutation entropy, with fixed-effects accounting for most of it (Marginal R^2 / Conditional R^2 = 0.971/0.973). This is expected because the variation in individuals, modelled by random effects, were small relative to the variation in Permutation Entropy across scale factors, modelled by fixed effects.

Table 9-4 shows the ANOVA table of the final model of permutation entropy at six scale factors. All included main effects (Scale factor, Prematurity, Sensor location) and interaction effects (Scale factor x Prematurity, and Scale factor x Sensor location) were significant at the 95% confidence level. Presence of the Scale factor x Prematurity effect, and absence of the Prematurity x Sensor interaction effect indicated that Prematurity altered the curve structure, but in a way that was consistent across all sensors.

Table 9-4. ANOVA table (final model of the MSE curve profile). Sum of Squares (SS), Mean squares (MS), degrees of freedom of the numerator (NumDF) and denominator (DenDF), F statistics and p values are shown.

	SS	MS	NumDF	DenDF	F	p
Curve structure						
Scale factor	5.01	1.00	5	591.28	4368.85***	<0.001
Prematurity	0.00	0.00	1	19.20	21.70***	<0.001
Sensor location	0.11	0.03	4	593.15	114.96***	<0.001
Scale factor x Prematurity	0.01	0.00	5	591.28	11.00***	<0.001
Scale factor x Sensor location	0.13	0.01	20	591.28	28.77***	<0.001

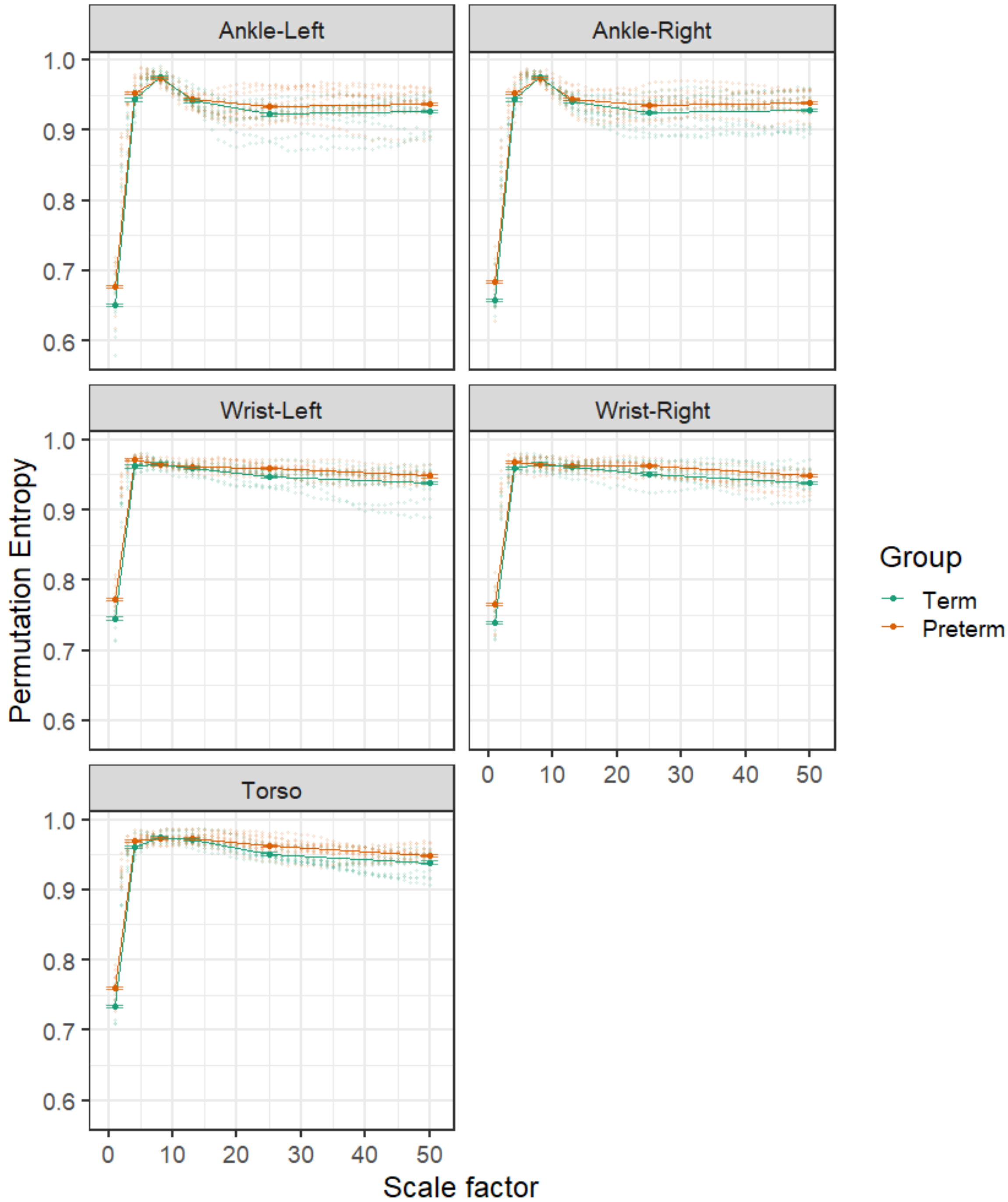
Contrasts (shown in Table 9-5) shows the mean differences that prematurity led to higher entropy at all scale factors apart from Scale Factor 8 and 13, which spanned the upper and upper frequencies of the alpha band. Figure X plotting the predicted effects (estimated marginal means) with standard errors of the final model shows that although the curve structure was different across arms, torso and ankle data, prematurity altered the curve structure similarly across all sensor locations. Although the difference between groups in permutation entropy was small, the error bars overlapped only for Scale factor 8 and 13, in line with the absence of Preterm-Term effects at these two scale factors.

Table 9-5. Planned contrasts of Preterm relative to term differences in Permutation Entropy at each Scale factor. Difference in group means with standard errors are shown. Statistics of two-tailed t-tests with 122.22 degrees of freedom are reported.

	Difference (SE)	t (122.22)	p
Contrasts of Preterm – Term at level of Scale factor			
Scale factor 1	0.027 (0.003)	-7.92***	<0.001
Scale factor 4	0.009 (0.003)	-2.77**	0.006
Scale factor 8	-0.001 (0.003)	0.34	0.733
Scale factor 13	0.002 (0.003)	-0.66	0.509
Scale factor 25	0.011 (0.003)	-3.27***	0.001
Scale factor 50	0.010 (0.003)	-2.98**	0.004

*# p<0.1, * p <0.05 , ** p <0.01, *** p <0.001*

Figure 9-5. Estimated marginal means of Permutation Entropy at 6 scale factors (solid points, with error bars), overlaid on data plotted from the original dataset containing 50 scale factors.



Complexity index

Variation in complexity index between individuals were accounted for by random intercepts (Var(ID) = 5.63). Variance between individuals contributed to 26% (ICC=0.26) of the total variance in Complexity Index. Fixed and random effects explained 66.6% of the variance in complexity index. Again, fixed-effects accounted for a large proportion of the explained variance (Marginal R^2 / Conditional R^2 = 0.551/0.666).

Table 9-6 shows the ANOVA table of the final model of Complexity Index. No main effect of Phase, or interaction of Phase x Prematurity were found, indicating that Phase did not have an effect on the overall CI. There was a main effect of Prematurity and Sensor location, and an interaction effect between the two that was significant at the 95% confidence level.

Table 9-6. ANOVA table (final model of Complexity Index). Sum of Squares (SS), Mean squares (MS), degrees of freedom of the numerator (NumDF) and denominator (DenDF), F statistics and p values are shown.

	SS	MS	NumDF	DenDF	F	p
Complexity Index						
Phase	17.04	4.26	4	479.16	0.76	0.554
Prematurity	63.83	63.83	1	20.03	11.33^{**}	0.003
Sensor location	4077.27	1019.32	4	477.66	180.94^{***}	<0.001
Phase x Prematurity	16.89	4.22	4	479.16	0.75	0.559
Prematurity x Sensor	159.70	39.93	4	477.66	7.09^{***}	<0.001

$^{\#}p<0.1$ $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

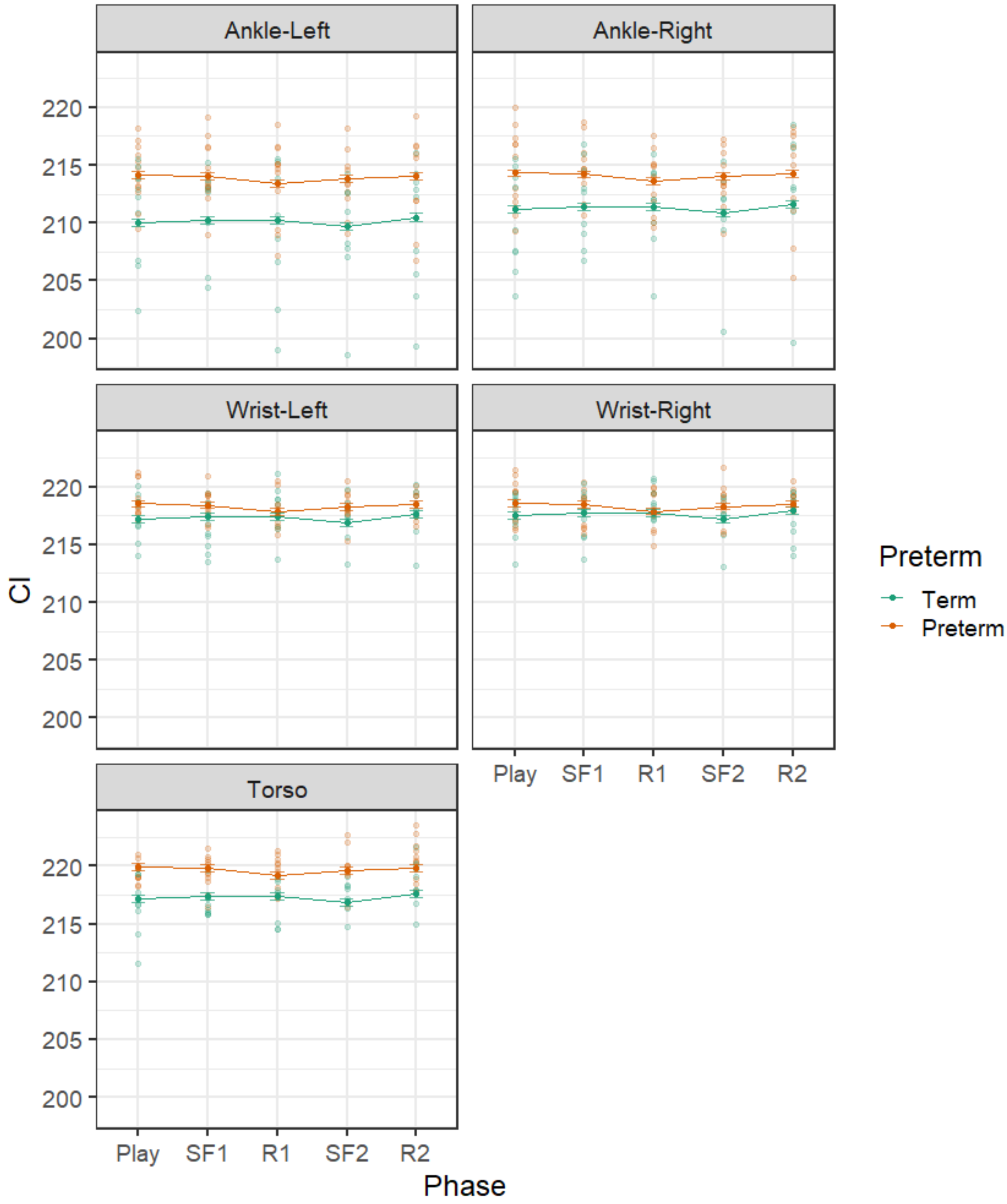
Planned contrasts (Table 9-7) showed that Preterm infants showed torso and ankle movements with greater overall complexity, but not for movements measured on the wrists. Figure 9-6 shows the predicted effects of the model depicting these differences in movement complexity due to prematurity. It can be seen that the overall movement complexity does not change markedly between Phases.

Table 9-7. Planned contrasts of the difference in Complexity Index in the Preterm group relative to Term, at the level of Sensor location. Difference in group means are reported with statistics of two-tailed t-tests (with 47.06 degrees of freedom for Torso and Ankle comparisons, and 49.05 degrees of freedom for Wrist comparisons).

	Difference (SE)	t	p
Contrasts of Preterm – Term at level of Sensor location			
Torso	2.37 (0.80)	-2.98^{**}	0.005
Wrist-Left	0.94 (0.81)	-1.17	0.246
Wrist-Right	0.71 (0.81)	-0.88	0.385
Ankle-Left	3.89 (0.80)	-4.89^{***}	0.000
Ankle-Right	2.44 (0.80)	-3.07^{**}	0.004

$^{\#}p<0.1$, $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

Figure 9-6. Estimated marginal means of Complexity Index (solid points, with error bars), overlaid on data from each individual on Complexity Index for each still-face episode.



Mean acceleration

Variation between individuals in mean acceleration were accounted for by random intercepts with a variance of 0.31. Variance between individuals contributed to 36% (ICC=0.36) of the total variance in mean acceleration. Fixed and random effects together explained almost half the variance in mean acceleration (Marginal R^2 / Conditional R^2 = 0.198/0.488).

Table 9-8 shows the ANOVA table of the final model of mean acceleration. No main effect of Phase, or interaction of Phase x Prematurity were found, indicating that Phase did not have an effect on mean acceleration either. Similar to complexity index, there was a main effect of Prematurity and Sensor location, and an interaction effect between the two that was significant at the 95% confidence level.

Table 9-8. ANOVA table (final model of mean acceleration). Sum of Squares (SS), Mean squares (MS), degrees of freedom of the numerator (NumDF) and denominator (DenDF), F statistics and p values are shown.

	SS	MS	NumDF	DenDF	F	p
Acceleration						
Phase	1.70	0.43	4	478.53	0.77	0.547
Prematurity	0.84	0.84	1	20.07	1.51	0.234
Sensor location	85.86	21.46	4	477.48	38.62^{***}	0.000
Phase x Prematurity	3.49	0.87	4	478.53	1.57	0.181
Prematurity x Sensor	11.51	2.88	4	477.48	5.18^{***}	0.000

$^{\#}p<0.1$ $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

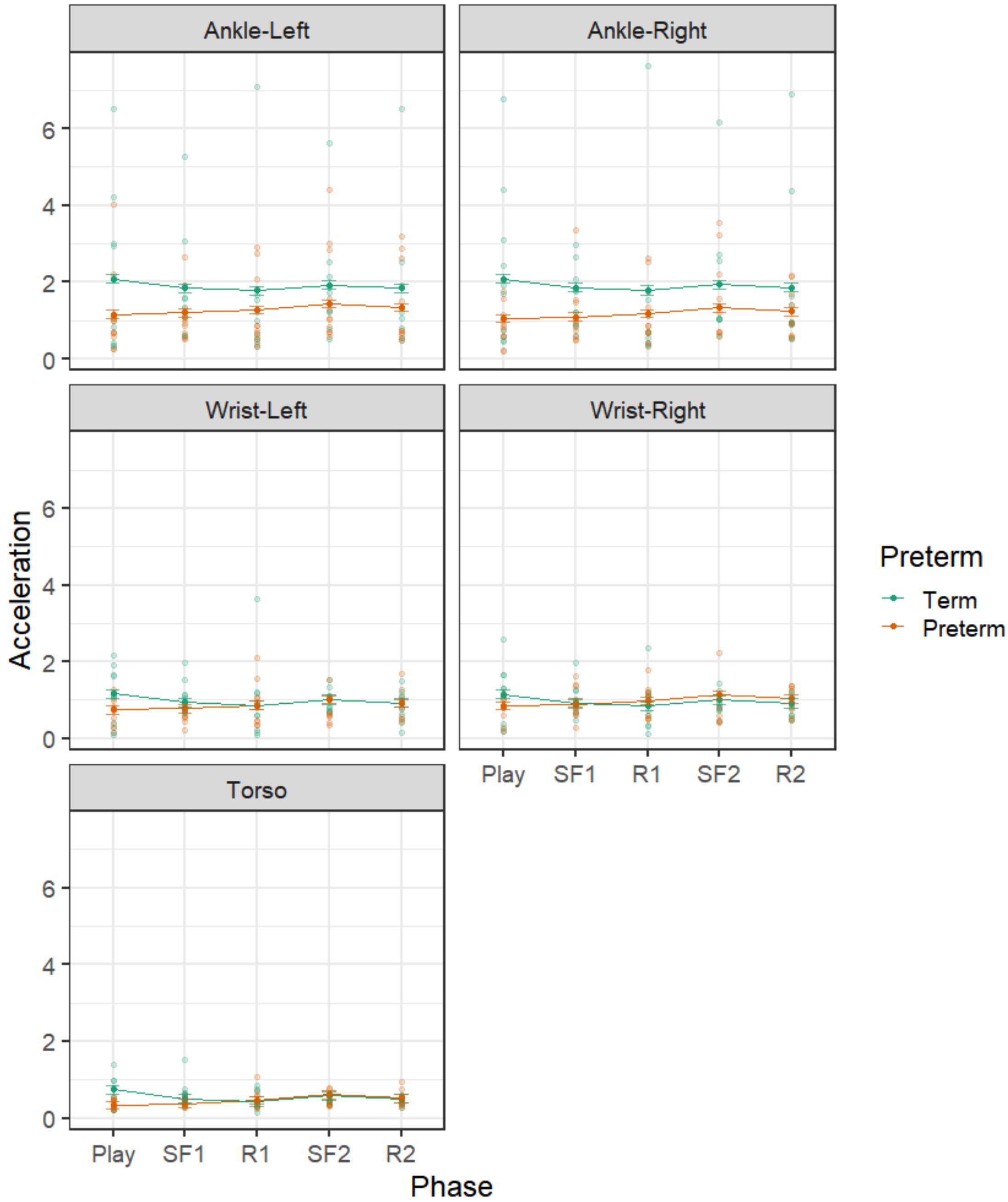
Planned contrasts (Table 9-9) showed that Preterm infants showed ankle movements with lower mean acceleration, but no difference in torso and wrist movements. Figure 9-7 shows the predicted effects of the model depicting these differences in movement acceleration due to prematurity, and, similar to overall movement complexity, shows that mean acceleration does not change markedly between phases.

Table 9-9. Planned contrasts of the difference in mean acceleration in the Preterm group relative to Term, at the level of Sensor location. Difference in group means are reported with statistics of two-tailed t-tests (with 32.43 degrees of freedom for Torso and Ankle comparisons, and 33.34 degrees of freedom for Wrist comparisons).

	Difference (SE)	t	p
Contrasts of Preterm – Term at level of Sensor location			
Torso	-0.09 (0.28)	0.32	0.753
Wrist-Left	-0.12 (0.28)	0.41	0.686
Wrist-Right	0.01 (0.28)	-0.03	0.975
Ankle-Left	-0.61 (0.28)	2.17*	0.038
Ankle-Right	-0.73 (0.28)	2.58*	0.015

*#p<0.1, * p <0.05 , **p <0.01, ***p <0.001*

Figure 9-7. Estimated marginal means of mean acceleration (solid points, with error bars), overlaid on data from each individual on mean acceleration for each still-face episode.



Complexity index at 5 frequency bands

Interestingly, Complexity Index analysed separately at five frequency bands revealed effects of Phase and Prematurity at specific frequency bands. Table 9-10 shows the Random effects ICC, and R^2 values for the final model fitted, Table 9-11 presents the ANOVA tables of linear mixed-effect models, and Table 9-12 and Table 9-13 the contrasts examining the effect of Phase and effect of Preterm, for complexity index in each frequency band. Figures 9-7 a-e show the estimated marginal means of complexity index in each frequency band.

Table 9-10. Random effects, ICC and R2 values of fitted models.

	CI Gamma	CI Beta	CI Alpha	CI Theta	CI Delta
Random Effects (Var)					
σ^2	0.09	0.02	0.03	2.97	0.37
τ_{00}	0.03 $_{ID}$	0.01 $_{ID}$	0.01 $_{ID}$	1.23 $_{ID}$	0.06 $_{ID}$
ICC	0.28	0.27	0.18	0.29	0.14
Marginal R^2 / Conditional R^2	0.664 / 0.759	0.179 / 0.397	0.300 / 0.425	0.351 / 0.542	0.689 / 0.733

Table 9-11. ANOVA tables (final models of complexity index at five frequency bands)

	SS	MS	NumDF	DenDF	F	p
CI – Gamma (30 – 50[1] Hz)						
Phase	1.45	0.36	4	478.90	4.13**	0.003
Prematurity	0.80	0.80	1	19.96	9.09**	0.007
Sensor location	114.38	28.60	4	477.52	325.10***	<0.001
Phase x Prematurity	0.45	0.11	4	478.90	1.28	0.275
Prematurity x Sensor	1.53	0.38	4	477.52	4.34**	0.002
CI – Beta (14 – 30Hz)						
Phase	0.45	0.11	4	478.40	6.11***	<0.001
Prematurity	0.07	0.07	1	19.29	*3.93*#	0.062
Sensor location	1.18	0.30	4	476.90	16.10***	<0.001
Phase x Prematurity	0.06	0.01	4	478.40	0.80	0.523
Prematurity x Sensor	0.50	0.12	4	476.90	6.75***	<0.001
CI – Alpha (8 – 13 Hz)						
Phase	0.40	0.10	4	479.36	3.82**	0.005
Prematurity	0.00	0.00	1	19.43	0.12	0.737
Sensor location	6.11	1.53	4	477.36	58.18***	<0.001
Phase x Prematurity	0.14	0.03	4	479.36	1.33	0.259
Prematurity x Sensor	0.29	0.07	4	477.36	2.73*	0.028
CI – Theta (4 – 8Hz)						
Phase	16.55	4.14	4	478.82	1.39	0.235
Prematurity	24.43	24.43	1	19.95	8.22**	0.010
Sensor location	830.43	207.61	4	477.49	69.89***	<0.001
Phase x Prematurity	9.91	2.48	4	478.82	0.83	0.504
Prematurity x Sensor	76.15	19.04	4	477.49	6.41***	<0.001
CI – Delta (2 – 4Hz)						
Phase	0.84	0.21	4	480.80	0.57	0.682
Prematurity	3.76	3.76	1	20.57	10.22**	0.004
Sensor location	464.91	116.23	4	478.65	315.92***	<0.001

Phase x Prematurity	1.70	0.43	4	480.80	1.16	0.330
Prematurity x Sensor	7.31	1.83	4	478.65	4.97**	0.001

*#p<0.1 * p <0.05 , **p <0.01, ***p <0.001*

[1]As 100Hz sampling rate was used, the movement acceleration data contained frequencies up to 50Hz (which represents the Nyquist rate, half the sampling rate)

Effect of Phase. There were significant main effect of Phase in the Gamma, Beta and Alpha band, but not the Theta or Delta band. No interaction between Phase and Prematurity was found (Table 9-11). This suggests that the still-face effect is unique to complexity index at high frequency bands. As observed in the estimated marginal means of the models in Figures 1-3, complexity can be seen to be lower in the still-face than caregiver-absent phases and the clearest pattern of this can be observed in the Beta band. Planned contrasts, also showed strongest evidence for this in the Beta band - complexity reduces from Play to SF1 ($t(476.31) =-3.84$, $p_{adj}<0.001$) increases from SF1 to Reunion1 ($t(478.93)=2.95$, $p_{adj} =0.017$), reduces from Reunion 1 to SF2 ($t(477.28)=-3.03$, $p_{adj} =0.013$), and a pattern of increase from SF2 to Reunion2, though was no longer significant after Bonferroni correction ($t(476.31)=2.02$, $p_{adj} =0.217$). Similar trends were observed in the alpha band though the difference between Reunion1 and SF2 ($t(477.92)=-2.23$, $p_{adj} =0.131$) was not significant after Bonferroni Correction, and there was no evidence of a reunion effect from SF2 to Reunion 2 ($t(476.53)=1.65$, $p_{adj} =0.501$). (see Table 9-12 and Figures 9-7 a-e)

Table 9-12. Contrasts exploring the effect of Phase, in high frequency bands where a main effect of Phase was detected. Difference in group means, representing the contrast examined, along with standard errors are shown.

	CI Gamma	CI Beta	CI Alpha	CI Theta	CI Delta
Contrasts of Phase					
SF1 – Play	*-0.10 $^{\#}$ (0.04)*	-0.07 *** (0.02)	-0.06 * (0.02)	-	-
R1 – SF1	0.02 (0.04)	0.06 ** (0.02)	0.07 ** (0.02)	-	-
SF2 – R2	-0.08 (0.04)	-0.06 ** (0.02)	-0.05 (0.02)	-	-
R2 – SF2	*0.10 $^{\#}$ (0.04)*	0.04 (0.02)	0.04 (0.02)	-	-

$^{\#}p_{adj}<0.1$, $^{*}p_{adj}<0.05$, $^{**}p_{adj}<0.01$, $^{***}p_{adj}<0.001$

Effect of Prematurity. Similar to the findings on curve structure, there was no effect of prematurity on complexity in the alpha band. Differences related to prematurity were seen in lower (i.e. the theta and delta band) and higher frequency bands (gamma and beta), and differed by Sensor location. For simplicity, results of contrasts analysis are depicted as differences in group means by Sensor location for each frequency band (Table 9-13). Contrast analysis did not reveal differences in movement complexity in the Wrist locations. Relative to term infants, Preterm infants showed more complex Torso movements, but only in the Theta band (t(36.87=-3.08, p_{adj} =0.019). For ankle movements, preterm infants showed greater movement complexity in the Theta and Delta band for both left and right ankle movements. However at higher frequencies, greater complexity was seen only in left ankle movements in the gamma (t(37.83)=-4.67, p_{adj} <0.001) and beta band (t(38.21)=-4.34, p_{adj} <0.001). While no longer significant after Bonferroni correction, contrasts showed a trend towards greater complexity in right ankle movements in the gamma band (t(37.83)=-2.67, p_{adj} =0.055). (see Table 9-13 and Figures 9-8 a-e)

Table 9-13. Contrasts exploring the effect of Prematurity at each level of Sensor, in all frequency bands except the Alpha band where an effect of Prematurity was detected. Difference in group means, representing the contrast examined, along with standard errors are shown.

	CI Gamma	CI Beta	CI Alpha	CI Theta	CI Delta
Contrasts of Preterm – Term at level of sensor					
Torso	0.20 (0.10)	0.07 (0.04)	-	1.80 * (0.58)	0.35 (0.16)
Wrist-Left	0.17 (0.10)	0.05 (0.04)	-	0.60 (0.59)	0.16 (0.16)
Wrist-Right	0.18 (0.10)	0.01 (0.04)	-	0.46 (0.59)	0.09 (0.16)
Ankle-Left	0.46 *** (0.10)	0.19 *** (0.04)	-	2.47 *** (0.58)	0.72 *** (0.16)
Ankle-Right	*0.26 $^{\#}$ (0.10)*	0.05 (0.04)	-	1.86 * (0.58)	0.59 ** (0.16)

$^{\#}p_{adj}<0.1$, $^{*}p_{adj}<0.05$, $^{**}p_{adj}<0.01$, $^{***}p_{adj}<0.001$

Figure 9-8-a. Estimated marginal means of Complexity index in each frequency band.

Gamma frequency band

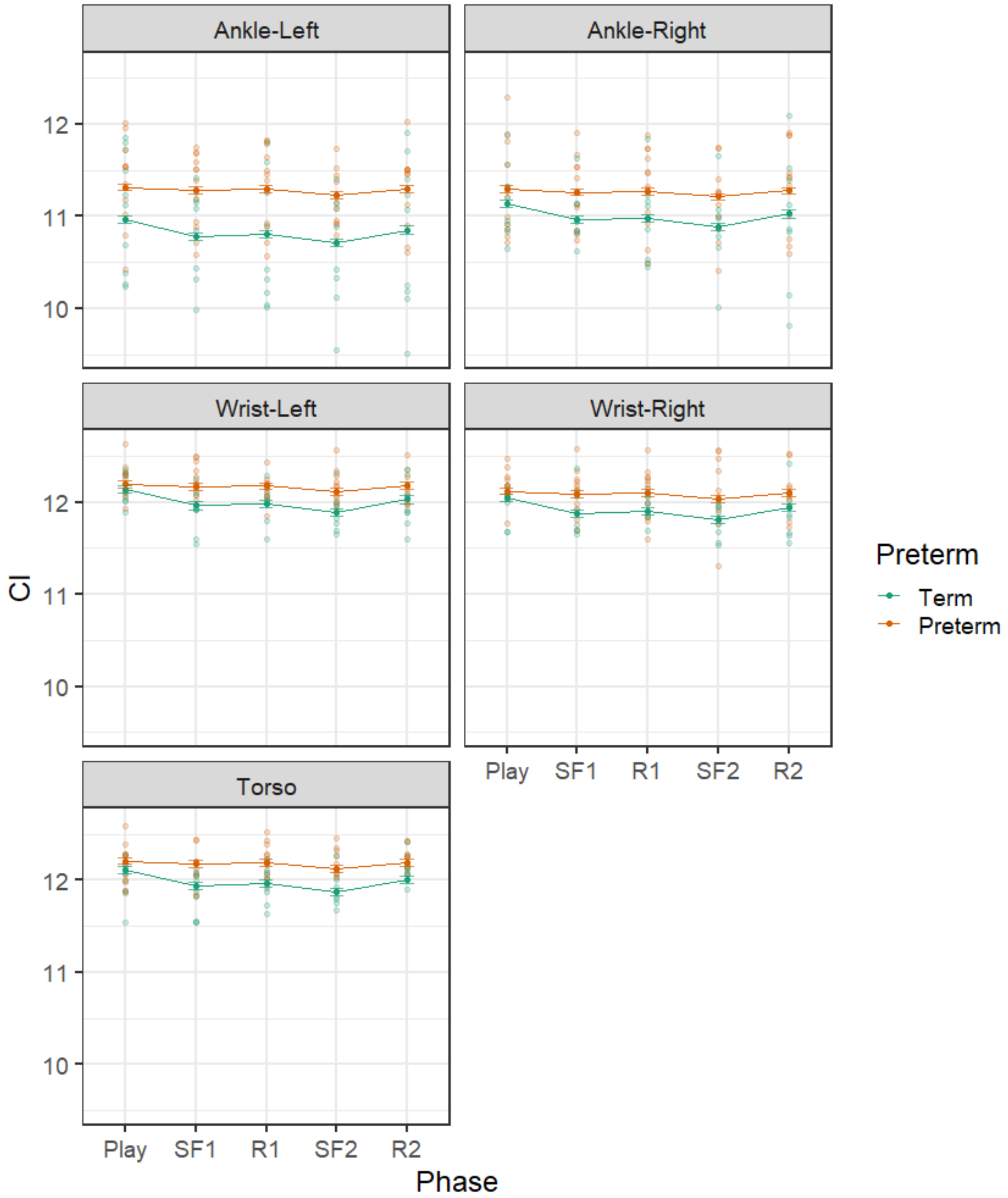


Figure 9-8-b. Estimated marginal means of Complexity index in each frequency band. Beta frequency band

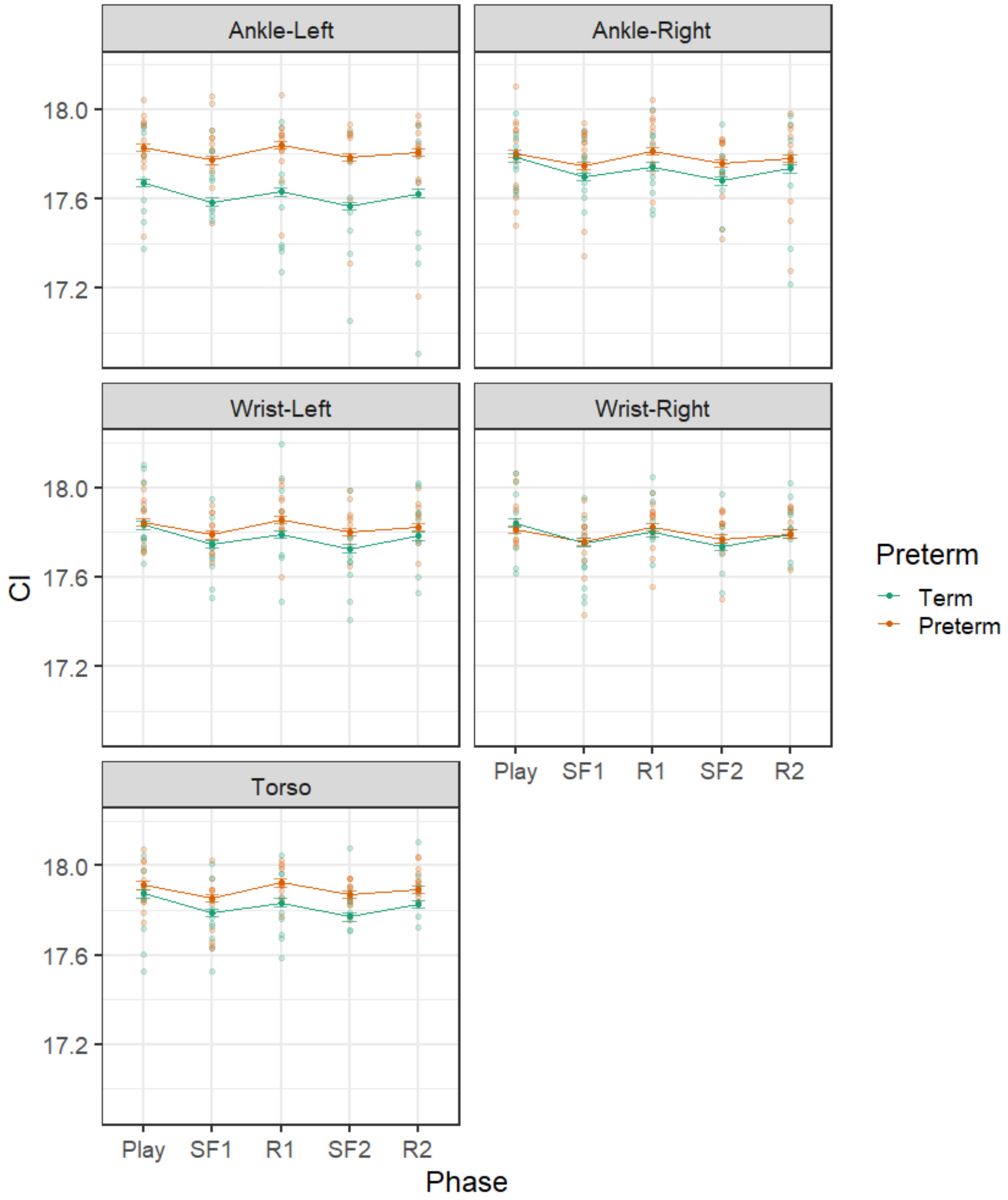


Figure 9-8-c. Estimated marginal means of Complexity index in each frequency band. Alpha frequency band

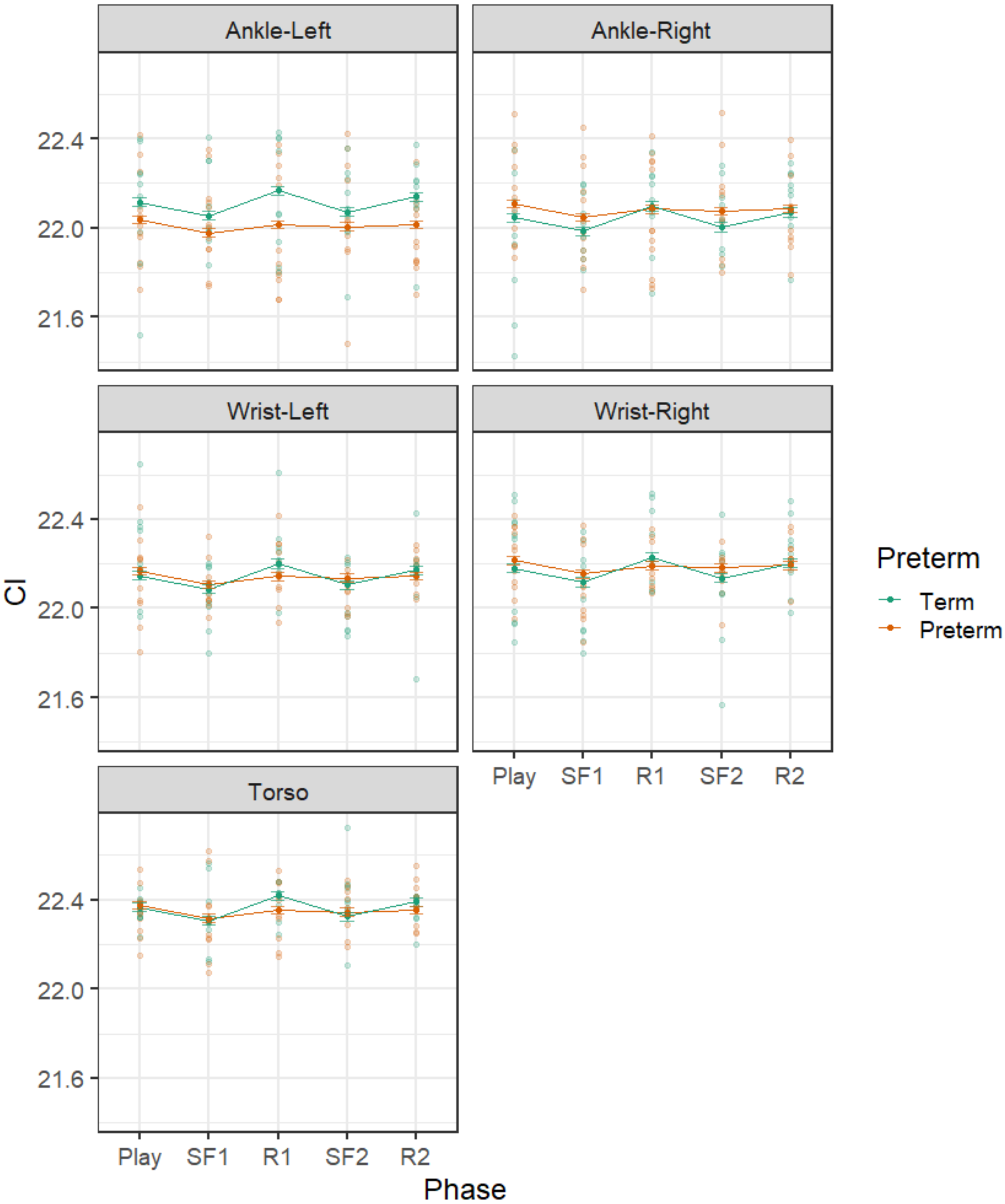


Figure 9-8-d. Estimated marginal means of Complexity index in each frequency band. Theta frequency band

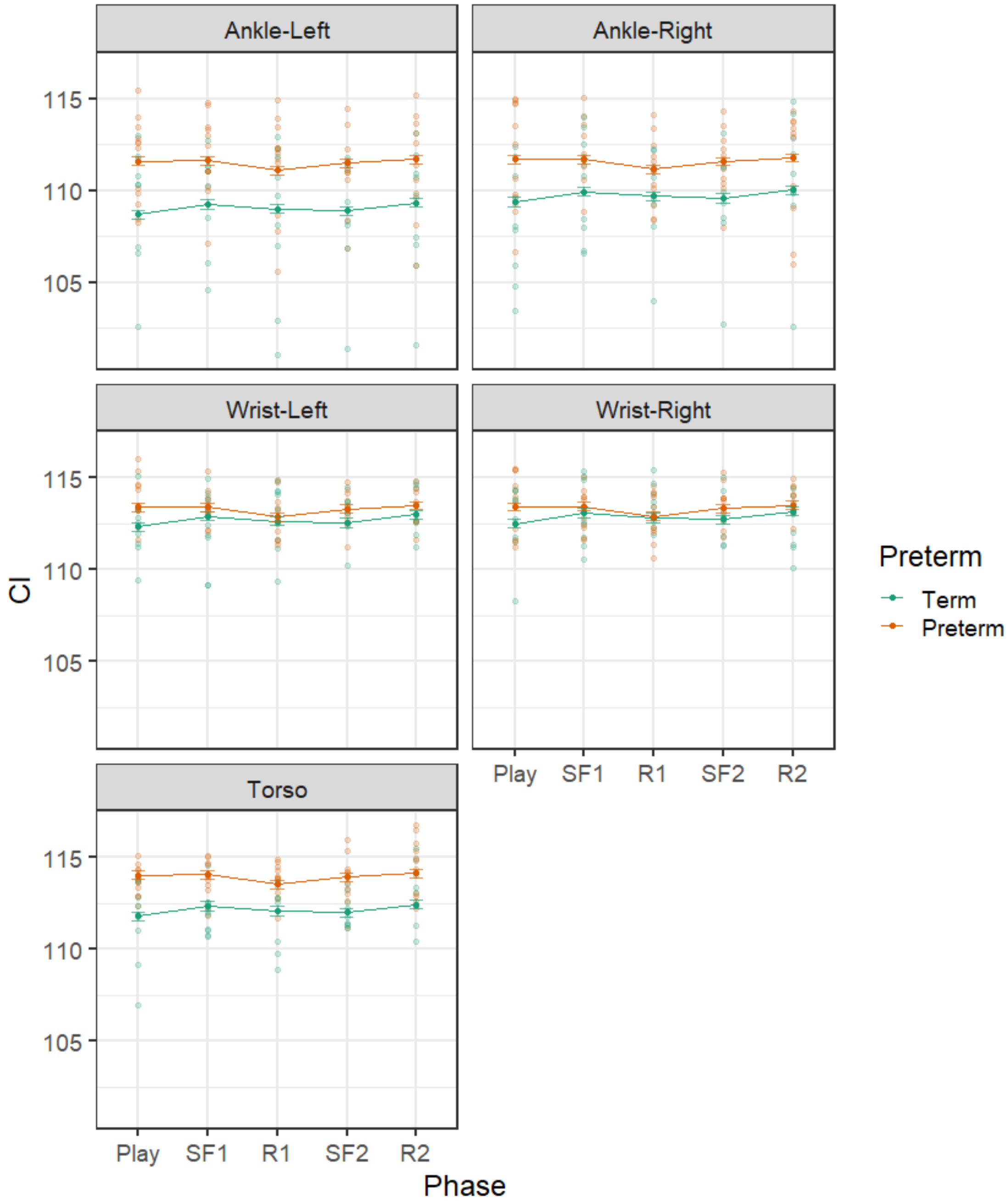
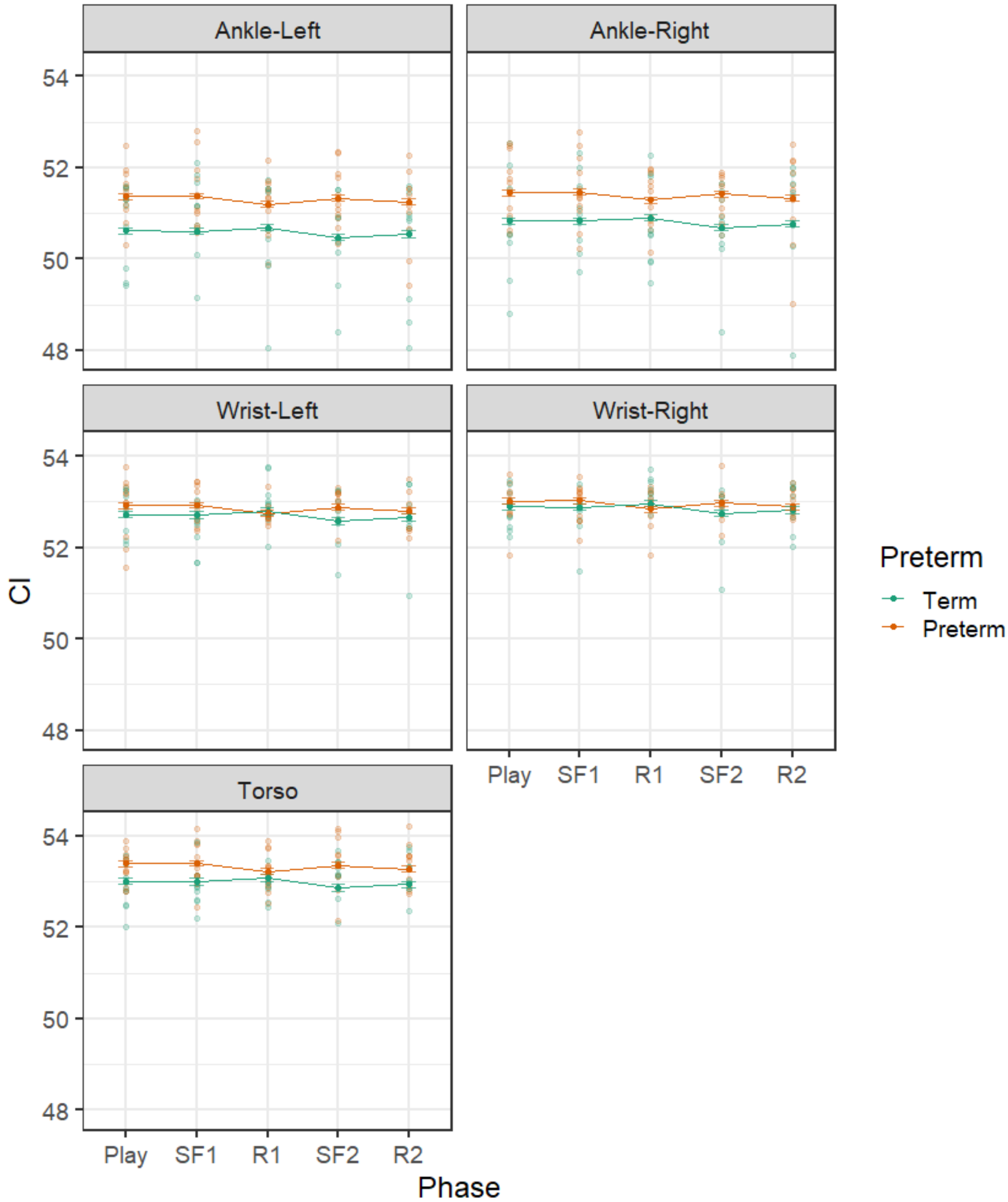


Figure 9-8-e. Estimated marginal means of Complexity index in each frequency band. Delta frequency band



9.4. Discussion

This study is the first to demonstrate the feasibility of using sensors in the still-face paradigm, and the potential insights gained from the fine-grained analysis of motor activity. The results demonstrate that signatures of social stress may be present in infant movement, and is the first to pinpoint motor differences due to prematurity in characteristic frequency bands of movement acceleration. In the following discussion, given the nature of this study as a proof-of-concept, I first focus on the strengths and limitations that affect the how confident I am with the findings, before interpreting the results in light of existing literature and identifying potential implications. This proof-of-concept study, particularly its strengths, sets the stage for future research. I comment specifically on how future work could specifically address the limitations I identified, and end by summarising the directions in which future work can focus on.

Strengths and limitations

Methodological design. My study's main strength was a large sample size (over 500 observations in each statistical analysis), relative to other studies using sensors to measure infant movement (B. A. Smith et al., 2017; R. B. Wilson et al., 2021). This marked increase in sample size was achieved through a repeated-measures design (Austin & Leckie, 2018) - with up to 25-30 observations per infant. However, this needs to be considered in light of between-individual variability, in terms of providing a high-powered analysis. Together with low between-individual variability in the curve structure, this study design provided strong evidence of an interaction effect of Preterm x Scale factor. However, group differences in the effect of phase (or interaction effect group by phase) may have been missed due to greater between-individual variability in the effect of phase, and the relatively few individuals (N=22). In particular, in the alpha-band, the mean trend of the preterm group shows attenuated changes in movement complexity between phases relative to the term group, but this did not reach significance. This could result because not all preterm infants exhibited the same attenuated changes leading to greater variability preventing detection of group differences, and warrants further investigation.

My study also built on early work applying multiscale entropy, which focused only on the first few scale factors (e.g. Bisi & Stagni (2016); Vaz et al., (2019); and others), and the timescales of interest therefore corresponded to high frequency activity only, due to the high sampling rate used. I showed novel insights gained from analysing complexity at scale factors related to low frequency activity. This is especially important given the inverse relationship between decreasing frequency and greater spectral power in human movement, a manifestation of the ubiquitous 1/f power law (He, 2014). To do so, I addressed methodological limitations of the multiscale entropy algorithm, which becomes unreliable if there is insufficient data following down-sampling to reveal activity at higher scale factors (lower frequency activity). Experts have suggested that multiscale entropy should only be analysed up to the scale factors which data length enables robust analysis (M. Costa et al., 2005), yet highlight the strength of "entropy" algorithms in analysing information in relatively short biological timeseries (Pincus, 1991). I further argue that the timescales of interest should be the first consideration in any research question and second, recognising that methodological constraints are sometimes unavoidable, selection of methodologies that suit the aims. For example, if low frequency activity is of particular interest, this should ideally be factored in the research design to determine the length of data to collect – and not the opposite, for example where behavioural data sampled at low frequencies were partitioned into smaller intervals to lengthen the data and make the calculation of sample entropy feasible (Montirosso, Riccardi, et al., 2010), even though this meant the resulting entropy values would correspond to high frequency activity. If limited by study design, such as in my study where the still-face paradigm was 10-minutes long, I restricted my analysis to smaller embedding dimensions but applied Wu and colleagues (2014) coarse-graining method to obtain robust values of multiscale entropy. I also selected permutation entropy in contrast to the popular sample entropy algorithm, due to the difficulties related to selecting the tolerance parameter *r,* which is especially problematic when sample entropy is calculated across a large range of scales (Kosciessa et al., 2020; J. Lu & Wang, 2021).

Other influences on infant motor activity. The present analysis also benefitted from a number of descriptive comparisons to assess other potential influences on movement complexity. First, during the Play and Reunion phases, caregivers of preterm-born infants, relative to term-born infants, interacted more with infants by directly moving the infants' arms or legs. However, I did not find an interaction effect of Preterm x Phase, which would reflect external influence on the movement complexity computed from sensors attached to infants. I also found that physical constraints that differ between prematurity groups and may affect movement coordination - were unlikely to contribute to differences in movement complexity found.

I further demonstrated that these findings related to the dynamics of movement acceleration, were novel and captures a facet of movement different from mean acceleration. Three lines of evidence support this. First, repetitive movements during the still-face paradigm, especially kicking and rocking movements involving the legs and torso, tend to be of high intensity (Ekas et al., 2013). Therefore, it was expected that greater RME would be correlated with motor activity, and the unique correlation with mean acceleration, and not complexity index, suggests that complexity index the two are not directly comparable. Second, the effect of prematurity affects mean acceleration and complexity differently. While comparing mean acceleration showed that preterm make slower leg movements and no differences in torso or arm movements, examining the movement complexity related to different frequency content revealed important and specific similarities (in the alpha band) as well as differences (e.g. in torso movements in the theta band). Third and most importantly, differences between still-face phases in the alpha and beta band were uniquely captured in complexity index, but not mean acceleration.

Capturing infant stress response or effect of interaction partner

A key limitation of the study was that I could not clearly determine if the effect of phase on movement complexity was due to distress, or simply a result of coordinating their movements reciprocally with a partner. Although I compared motor measures with expressions of negative affect, I did not find any relationships. Some, but not all infants' cortisol responses were measured before and after the end of the entire still-face paradigm to probe the stress resulting from the still-face paradigm. Future research could compare such a measure with movement complexity. Nevertheless, there is some evidence in my study supporting the idea that differences, particularly in the beta band, which may reflect infants' stress response. Following the first still-face phase, there was a return to similar levels of movement complexity in R1 relative to Play. However, there appears to be a stronger reunion effect in R2, where there was an attenuated increase towards the levels observed in R1, an amount that was no longer significant after Bonferroni correction. Previous research justified using a second iteration of the still-face and reunion phase as it induces a stronger reunion effect (Haley & Stansbury, 2003), and this pattern of results are in line with this. Nevertheless, future experiments could directly control for emotion, or reciprocal interaction; for example, in a non-stressful context in free play with toys with or without parents' participation, to compare the effect of interactive partners.

Do the results reflect measurement noise?

Another limitation was in addressing the potential influence of high frequency noise, when complexity of high frequency activity in the motor system are of interest (e.g. in the Gamma band). There is a division in opinion on what the “best practice” is for pre-processing data before analysing entropy. Some suggest that entropy should be analysed from raw data, as any filtering process would not just alter noise, but the captured phenomenon; others suggest that the data should represent the phenomenon of interest as much as possible (Yentes & Raffalt, 2021). Considering that high frequency artefacts may be present in the data due to banging movements on the infant chair, I decided to use permutation entropy over sample entropy, as the former known to be robust to measurement noise (Azami & Escudero, 2016; Bandt & Pompe, 2002; Zanin et al., 2012) by computing patterns of increase or decrease, rather than the exact magnitude of change. I decided to use low-pass filtering, which is similar to the coarse-graining procedure in multiscale entropy algorithms, ensuring that the data represented human movement kinematics which predominantly comprises low frequencies. As seen in the methods section on data processing, low-pass filtering to remove high-frequency content did not alter the characteristic peak of the Multiscale entropy curve, and affected only entropy at the lowest scale factors leading to lower information content because patterns in the data were removed. Furthermore, it is likely that greater motor activity would lead to more movements that could introduce noise. Surrogate analyses also confirmed that white noise shows maximal values of permutation entropy, as expected in highly irregular signals (Richman & Moorman, 2000). As term-infants showed greater mean acceleration indicating greater motor activity, the findings showing greater entropy in the preterm group is unlikely to be resulting from measurement noise corrupting the data.

Interpretation of findings

What does entropy measure?

Before delving into an interpretation of the findings, a conceptual clarification is needed on what multiscale entropy relates to. Entropy has been used to characterise motor output, specifically the various patterns seen in the temporal fluctuations of motor output – this has been termed “temporal structure of variability”. Variability in temporal patterns have also been labelled “complexity”, as the presence of variability means that the temporal output is not rigid or stereotyped, and to prevent confusion as variability often describes dispersion around the mean. This ability to produce variable output is also linked to the inherent make-up of complex systems. Complex systems contain structure at multiple levels and parts within and across levels interact to produce the resulting output. Therefore, as entropy quantifies the output, it is also linked to the structure producing it. In this study I have used the term complexity interchangeably with entropy – however, here I emphasise the mathematical implication of entropy. The algorithms developed to measure entropy all aim to quantify the information in the signal. Therefore, behind the value-laden term of complexity, entropy is actually a statistical measure of the dynamic output of complex systems that quantifies the information transmitted by the system at the time the signal is captured. It is this mathematical concept that has guided the interpretation of entropy measured from movement kinematics

Multiscale entropy of human movement is linked to functional synergies

Human movement is the product of processes in the brain operating across different timescales to activate muscular physiology. Therefore, when applied to motor data, multiscale entropy quantifies the fluctuations in movement across several timescales, which mirrors the dynamics of coordinative processes influencing motor output. Movement is coordinated synergistically, via electrical signals that move muscular groups in a coupled manner (Bernstein, 1967). This means that when there are more functional synergies, i.e., greater degrees of freedom, there are more ways the motor output can change and lead to fluctuations in the measured output over time. Additionally, as highlighted by Costa and others, multiscale entropy is sensitive to processes occurring at different timescales. Existing work have shown that both entropy and multiscale entropy are influenced by cognitive processes involved in generating the motor output, for example under different attentional demands (Vaz et al., 2019), and task demands (Ahmadi et al., 2021; Y. Wu & Song, 2017). Therefore, entropy is likely to be related to (1) the number of functional motor synergies directly resulting from the processes activating muscular physiology, as well as (2) processes operating behind the scenes to alter those activation processes.

Comparison to previous studies in neurodevelopmental populations – only single-scale entropy studied, compared heterogeneous groups of infants

My findings are in contrast to previous studies have identified lower entropy in preterm torso and leg movements. Previous studies have also identified that entropy decreases development over the first 6-9 months of life, and preterm infants may show different or delayed trajectories, and possibly smaller reductions in entropy over time (Dusing et al., 2014).

Therefore, as previous studies were usually in infants younger than 6-months, my findings of greater entropy pertaining to 9-month-old infants do not contradict the existing work. Crucially, my study provides new evidence that prematurity-related differences in entropy pertain to the slowest and fastest timescales, whereas earlier studies have focused arbitrarily on the timescales corresponding to the sampling rate of movement sensing devices. Unique patterns of coordination in the arms, legs and posture may also affect whether differences due to prematurity are detectable at 9-months. My study also supports existing literature that movement entropy is sensitive to task-demands. Changes in interactive conditions or social stress during the still-face paradigm, led to changes in arm, legs and torso movement dynamics. I will discuss these three important findings separately.

Differences in movement complexity in torso and leg movements

Lower complexity in leg movements or torso movements may suggest that term-infants have more advanced motor skills. Reduction in entropy is thought to be related to increase in skill, for example the use of specific postural movements that enable better balance, leading to more consistent and predictable temporal patterns (Hadders-Algra, 2004). This is supported by Smith et al (B. A. Smith et al., 2011) who showed that approximate entropy of spontaneous leg movements decreased across 1-9 months, and Abney and colleagues (Abney et al., 2014) single-subject paradigm finding greater determinism in leg activity over the first 10 months. In contrast, arm movements tend to be more varied due to its greater involvement in perceptually-guided movement, and infants do not develop consistent control until later (von Hofsten, 1991). Based on findings that arm movements become less deterministic with development, Abney and colleagues (2014) also suggested that arm movements may become more diverse over the first 10-months of life, rather than more stereotyped.

My interpretation is in contrast with Smith and colleagues (B. A. Smith et al., 2017) who found lower entropy in infants at-risk of developmental delays, and interpreted this as the presence of repetitive stereotyped behaviours. However, in this study I showed that entropy was not correlated to the amount of repetitive movements. This indicates that repetitive movements need not be highly rigid and stereotyped, in line with Bernstein's idea of "repetition without repetition" that humans are able to execute the same movements in different forms. Lower movement complexity is not simply attributed to the presence of repeated movements, but that movements – regardless whether they are repeated ones – are executed in a more similar form. Motor stereotypies are a part of normal development and my study suggests that term-born infants show more stereotyped leg kicks than preterm-born infants at 9-months.

Differences in torso movements appear specific to slow fluctuations in the theta-band, indicating greater similarities in slower postural movements. As infants learn to reach, arm movement can disrupt postural stability and infants learn to make torso adjustments prior or during reaching to compensate for the later destabilisation (Hadders-Algra, 2013; Van Der Fits, Otten, et al., 1999). Dusing and colleagues (2014) found that sitting postural movements became more similar when infants become better at reaching to toys. Interestingly, they measured centre-of-pressure movements at 5Hz which would correspond to theta-band activity. In my study, infants born preterm show more varied patterns of postural movements at the theta band, suggesting that prospective postural control is less developed. Postural movements during reaching also showed more varied patterns of muscular activation in preterm-born infants than term group, as well as different preferences of muscular coordination (Van Der Fits, Flikweert, et al., 1999).

Similarities in alpha-band and differences in high frequency bands

Similarities in both groups in activity in the alpha band possibly relate to common processes involved in activating functional synergies through motor units. Motor units are skeletal muscles innervated by alpha motor neurons, and form the final common output of motor commands. Rhythmic, pulsatile activity recorded from electromyography (EMG), including activity isolated from single motor units, were correlated to kinematics of the resulting movement and both contain activity at the 8-13 Hz range that are coupled in time (James J. Gross et al., 2002; Kakuda et al., 1999). By additionally using magnetoencephalography to record brain activity during finger movements, Gross and colleagues (2002) also showed that muscular EMG activity corresponded to coherent activity – i.e., correlations between two signals in the frequency domain (Bowyer, 2016) – in the sensorimotor cortex. Activity in the sensorimotor cortex were coherent with and phase-synchronised with activity in the thalamus and cerebellum, pointing to a cerebellar-thalamo-cortical loop that modulates the output from the primary motor cortex to motor units in the alpha band. It is possible that alpha activity relating to these processes dominates in the motor acceleration signals, and that these processes work in a similar manner between term and preterm groups.

High frequency fluctuations (e.g. in the gamma and beta band) likely affect the smoothness of movement. Wu and colleagues (D. Wu et al., 2018) highlighted a movement parameter quantifying minute "peaks" in the velocity profile at very small timescales. These are imperceptible when observing the gross velocity profile which take the form of "movement units" - distinct inverted U-shaped phases of increases and decreases in velocity (accelerative and decelerative phases). The authors found that these small peaks can be described by the randomness in which they occur in the velocity profile. Further, s-peaks could differentiate between movements made by children and adults, and between autistic and neurotypical individuals. In my study, greater entropy in the preterm group was observed at the scale factors corresponding to high frequency activity, and entropy is linked to greater unpredictability. Greater unpredictability of high frequency acceleration might contribute to randomness in the s-peaks in the velocity profile. My study supports the idea that "micro-movements" contain important differences about coordinative processes implicated in executed skilled movement, with implications for neurodevelopmental disorders (Torres et al., 2013).

Differences due to the "still-face" paradigm

Previous studies have showed that the still-face paradigm leads to physiological changes – the most commonly assessed measures including respiratory sinus arrhythmia (Bazhenova et al., 2001; Ham & Tronick, 2006; Ginger A. Moore et al., 2009), heart rate (Conradt & Ablow, 2010; Haley & Stansbury, 2003; Ham & Tronick, 2006), and cortisol (Haley & Stansbury, 2003)(Erikson & Lowe, 2013). Similar to Montirroso et al (2010), caregiver unresponsiveness led to reduced entropy in the still-face phases, although Montirosso and colleagues looked at entropy in relation to infant's affective and social engagement behaviours. The differences in my study could be interpreted as the influence of higher-level processes on motor output in general. First, evidence that the still-face paradigm affected all types of movements (arms, legs and torso) in the same way supports this, even though different movements are coordinated with different kinematic characteristics and would likely be subjected to different constraints. Secondly, as I will elaborate below, the differences appeared to be specific to activity in the alpha and beta band which most strongly implicated in motor processing.

Insights from Electroencephalography (EEG) which measure neural activity and commonly distinguishes activity in the alpha, beta, gamma, delta and theta bands, might help interpret these differences. To consider evidence from EEG research, crucially, the link between EEG activity with motor output needs to be established. There is evidence for this particularly in the beta band. Coherence between EEG activity and Electromyography activity of motor units in force production tasks have been demonstrated in the Beta band and attributed to the synchronous discharge of corticospinal axons, which activity are propagated to spinal motor neurons. Coherence between motor cortex field potential measuring neural activity, with EMG contractions of contralateral muscles have also been observed. Greater coherence of EEG and EMG activity was also directly related to sample entropy, with greater coherence leading to greater regularities in force output (McManus et al., 2019) as EMG activity produced by motor units becomes strongly driven by corticospinal neurons. Further evidence supporting the link between neural activity in specific frequency bands with movement complexity is the finding in this study, that selecting data on multiscale entropy corresponding to the limits of these specific frequency bands retains the broad features of movement complexity changes over all 50 scale factors.

Interestingly, the effect of the still-face paradigm on movement complexity was strongest in the beta and alpha band, where neural activity in these bands have been shown during in motor preparation and execution (Hervault et al., 2021; Rhodes et al., 2018), with beta activity most strongly implicated when motor structures are involved (Barone & Rossiter, 2021; Formica et al., 2021; Rhodes et al., 2018), and alpha band activity mainly when perception is linked to action (J. A. Pineda, 2005).

Beta activity appears to be implicated in integrating sensory feedback to movement output, including in coordinating ongoing movement or recalibrate the control aspects after a movement (Baker, 2007), and leads to improved motor performance (Kristeva et al., 2007), and reduced movement velocity to facilitate voluntary control using sensory feedback (Pogosyan et al., 2009). Reduced beta power was also linked to reduced motor inhibition in emotional relative to neutral situations, which could facilitate automatic emotional responses i.e., approach or avoidance behaviours (Siqi-Liu et al., 2018). Therefore, the changes in movement complexity in the beta band may be related to emotional influences on sensorimotor control.

Ample evidence from EEG research suggest that alpha activity may be involved in both attentional mechanisms and translating perceptual information into action (Pineda, 2005). Alpha activity is within the 8-13Hz frequency band in adults, though the boundaries may be lower at around 6-9 Hz in infancy (Marshall & Meltzoff, 2011). Alpha activity is characterised by lower frequency alpha rhythms related to posterior occipital cortices and higher frequency "mu" rhythms in the central cortical areas such as the sensorimotor cortex. Mu rhythms are observed during both action execution and action observation (Fox et al., 2016) including in infants from 8-months-old (Cuevas et al., 2014; Marshall et al., 2011; Marshall & Meltzoff, 2011; Nyström et al., 2011), and develops with age (Marshall et al., 2011; J. A. Pineda, 2005). suggesting they may be a correlate of activity in the "mirror neuron system". Southgate et al (2010) further suggested that this activity might be related to anticipation and understanding of actions, and not simply perception, as activity can occur prior to the action onset. During tasks requiring sustained attention to stimuli, decrease in peak alpha power associated with activated neural activity (or alpha "desynchronization") is observed (Orekhova et al., 2001; Xie et al., 2018), including in social interactions involving objects, when joint attention was established with adults (Hoehl et al., 2014; Michel et al., 2015). Attenuation of alpha band spectral power may be related to inhibitory attentional processes to allocate attentional resources to task-relevant information (Michel et al., 2015). Overall, alpha activity appears to represent action modulation via perceptual information in the somatosensory system (Marshall & Meltzoff, 2011). Therefore, changes in movement complexity in the alpha band may potentially be related to the transition between phases of reciprocal social interactions requiring joint attention and higher levels of perceptual monitoring to guide actions, and when those are absent.

While I did not find evidence that this affected term and preterm infants differently, this should be explored further given the non-statistically significant trend of attenuated changes in entropy in the alpha-band in preterm infants relative to term infants, as well as these speculative implications of alpha and beta-activity in sensorimotor processing.

Implications

Do group differences in entropy mean an adverse trajectory?

Smith and colleagues (2011) showed that infants with neural tube defects persistently showed lower entropy in spontaneous leg movements across the first 9-months of life, with lower entropy related to severity of condition and later onset of walking. My findings do not support a "loss of complexity" hypothesis (Goldberger et al., 2002) related to prematurity given that the direction of any differences was towards greater complexity in the preterm group relative to term. On the contrary, along the same lines of reasoning, these patterns might highlight that preterm infants are expanding more neural resources on coordinating movement output, leading to greater complexity. However, due to specific patterns of group differences observed in legs and torso movements, and none observed in arm movements, I interpreted greater movement complexity as a result of being at an earlier stage of motor learning. The interesting hypothesis that movement complexity could relate to neural integrity of or compensatory neural activity can nonetheless be explored further.

Objective measure of movement quality to support early identification

Differences in movement complexity captured in this study could provide an objective measurement of differences in movement quality. This study shows that it has predictive value of movements relating to term and preterm infants. This provides evidence that it could provide a more sensitive measure than a simple binary, yardstick of success in completing motor tasks or achieving motor milestones. Karmilnoff-Smith (1998) also highlights that scores in the "normal range" may in fact be due to compensations, and tests may not be sensitive enough to identify subtle differences after compensation.

General movement assessments involve observer ratings of the smoothness and fluency of spontaneous movements in neonates (Prechti et al., 1997). Poor quality "writhing" general movements are movements that are jerky and stiff, or as a whole show little variation in speed usually occurring up to the first two-months of life. "Fidgety" movements (Einspieler, Peharz, et al., 2016) emerge later from 3-5 months post-term, and can be unusually high amplitude, speed or jerkiness. Poor quality writhing movements and unusual fidgety general movements appear to be more common in preterm infants, especially in those infants identified with cerebral white matter abnormalities (Spittle et al., 2008) or other brain lesions (Ferrari et al., 1990). Healthy general movements are described as complex and variable, indicating a wide, in contrast to a limited, range of movement patterns in different combinations of joint movement (Hadders-Algra, 2004).

In preterm infants, general movements, especially the quality of fidgety movements which occur later (Hadders-Algra, 2004; Sustersic et al., 2012), appear to predict cerebral palsy (Hadders-Algra, 2004), motor developmental outcomes (Spittle, Boyd, et al., 2009; Sustersic et al., 2012) as well as cognitive outcomes (Einspieler, Bos, et al., 2016). Movement sensors have the potential to complement early neurological examinations to characterise movement differences related to early risk. Adde and colleagues (2018) were able to differentiate writhing and fidgety general movements through motion analysis of videos, through analysing the variability in the spatial centre of those movements – highlighting that observable-based movement differences have quantifiable kinematic characteristics. This research shows the feasibility of identifying movement differences in semi-ecological settings. Movement of infants at early developmental risk already appear different to human observers and technology may be able to detect further differences not noticeable to the human eye, or be able to quantify observable differences in an objective way. Further, research has the potential to clarify the relationship between qualitative descriptors of "complex", "variable" and "irregular" movements and quantitative measures which use similar terms to further inform the use of movement sensing in early identification.

Future directions

Future research can focus on addressing the methodological limitations of this study, test new hypotheses in relation to the interpretation and implications of the results, and also address questions related to the usefulness of deploying technology in early identification. I interpreted movement complexity changes as a function of motor skill development and may explain differences between term and preterm infants. This needs to be confirmed given the limited research on movement complexity, using different measures and studying a heterogeneous group of infants at developmental risk, and mostly focusing on postural control - a skill that subjected to different constraints compared to arm and leg movements. I also speculated on the idea that movement complexity could reflect differences in sensorimotor and perceptual processing, when emotional and attentional demands change –

however, the question remains whether movement complexity differences contain dissociable changes related to emotion or simply contextual differences. Finally, I showed that the fine-grain motor differences – and similarities – related to premature birth can be observed at 9-months-old. As motor differences can be observable from birth, investigating if, how, when and which motor differences could indicate later risk for adverse outcomes can demonstrate its potential for early identification.

9.5. Conclusions

In conclusion, this study provides evidence of prematurity-related differences in infants developing movement coordination, especially in leg movements and postural control. This study also provides novel findings characterising the "still-face effect" in infants' movement, showing that distress or social attention may influence movement output at specific timescales related to the processes that are implicated. Fine-grained motor differences using sensors have the potential for capturing motor patterns related to developmental risk, but future research is needed to establish the developmental significance of the differences identified presently.

10. General Discussion

10.1. Summary of thesis aims and findings

I examined the ways that movement is associated with socioemotional development, and the studies in this thesis provided a greater understanding of what motor differences reveal about socioemotional development. I recognised that movement can also be described by its function, and investigated motor patterns at this behavioural level to understand socioemotional development in preterm infants. I focused on behaviours implicated in emotional self-regulation, due to its importance in behavioural adjustment. I integrated two frameworks of emotional self-regulation. Emotional self-regulation was considered within a temperamental and neuroscientific framework reflecting the interaction of emotional reactivity and regulatory processes; as well as within a developmental framework of social-emotional competence reflecting its interactions with other social cognitive processes in enabling social interactions. Focusing on movement dynamics, I investigated a facet of movement that is related to the interactions within a complex system to produce movement.

Movement kinematics and socioemotional outcomes

Study 1 and 3 examined differences in movement kinematics between, respectively, autistic and non-autistic children, and between preterm and term-born infants. Both studies used novel technology and advanced the movement approach to analyse sub-second motor patterns in relation to socioemotional psychopathology (i.e., autism) and socioemotional risk due to premature birth.

In Study 1, a gamified approach to movement analysis revealed sub-second motor patterns relating to both predictive or feedforward control, and corrective feedback control were different between autistic and neurotypical groups. Crucially the pattern of differences identified appeared to result from different changes in movement kinematics with age. This different pattern of kinematic differences may result from differences in sensorimotor integration at this age, and its development. Sensorimotor integration is important for guiding movement as it unfolds using ongoing perceptual information, a process that develops very quickly around the ages of 4-5 years old examined in this study (Chua et al., 2021; S.-C. Lu et al., 2022). This study provides strong evidence supporting the notion that movement differences are an important aspect of autism, that they may be a contributing factor to the disturbance in the typical trajectory of socioemotional development in autism. These data support the motor perspective of autism, and paved the way for my subsequent chapters that focus on the relation of movement patterns in early development to understand how movement influences the development of social and emotional competencies more generally.

In Study 3, I provided a novel analysis using small, lightweight wearable movement sensors (IMU) to further understanding of sub-second motor differences in a population at risk for autism and other socioemotional difficulties – prior to toddlerhood when difficulties emerge and can be diagnosed reliably. Entropy of infant movement acceleration, indicative of movement complexity, was different between groups in torso and leg movements, but not arm movements. Specifically, differences were found in the fastest and slowest timescales (i.e. highest and lowest frequencies respectively). These findings may be related to differences between groups in emerging postural control and the stereotyped leg kicks, because during the acquisition of motor skills, infants in a more advanced stage of development may show more organised movements that are lower complexity. This study supports previous studies that motor differences can be identified by a human observer in young infants at risk for socioemotional difficulties (Einspieler & Prechtl, 2005; Örtqvist et al., 2021; Prechti et al., 1997), and provides an objective, quantitative, approach that can complement other motor metrics and psychometrics, to improve early identification of neurodevelopmental risk.

Behaviour during emotional self-regulation

The core study in this thesis, presented in Chapters 5-8, provided an in-depth examination of behavioural patterns related to the self-regulation of emotions in preterm and term-born infants. I examined both the amount of different expressive and self-regulatory behaviours observed when infants were required to self-regulate their emotions, as well as the dynamics (i.e., temporal characteristics) of these behaviours. Relative to term-born infants, preterm-born infants with very low birthweight used more object-oriented strategies and fewer repetitive movements, but no differences in social attention and interactive behaviours, or self-comforting behaviours. In relation to behavioural dynamics, preterm-born infants with very low birthweight also showed lower entropy, indicative of behavioural complexity, and a lower recurrence rate indicating that behaviours that occurred before were more less likely to occur again in time, but did not show differences in dynamic stability, relative to term-born infants. These novel findings relating to behavioural dynamics may be seen as a difference in the processes interacting to produce behaviour during emotional self-regulation, in other words, differences in the organisation of emotional self-regulation at a systemic level. Set in a birth cohort study, I then focused on investigating relationships between emotional self-regulation with relatively fixed temperamental traits, concurrent motor skills and later autistic traits. In particular, I focused my analyses on understanding the interpretation and implication of behavioural complexity.

In Study 2B, I found that behavioural complexity was associated with negative affect, providing some support that behavioural complexity is related to the underlying processes involved in emotional self-regulation. Behavioural complexity was not uniquely associated with traits related to reactivity or regulation but repetitive movements and self-comforting behaviours showed respective associations with reactivity and regulation. This supports the idea that behavioural type and behavioural dynamics measures different facets of emotional self-regulation. Further, behaviours related to emotional self-regulation are shaped by relatively fixed biological traits that are vulnerable to the effects of prematurity.

In Study 2C, I did not find effects of motor development on specific behaviours during emotional self-regulation, but found weak evidence that motor development leads to fluctuations in behavioural complexity. This could indicate that critical gains in motor skills can lead to the reorganisation of the interactions involved in emotional self-regulation – however, stronger evidence for this is needed and should be considered in future work.

In Study 2D, I found a non-linear U-shaped relationship between 9-month repetitive behaviours and 2-year autistic traits, supporting existing arguments that repetitive behaviours represent a normal part of development, but that occurrence in excess may be linked to autism risk. I also identified prospective associations between greater behavioural persistence (measured by trapping time) and greater behavioural complexity with autistic traits, although there was weaker evidence for the former association. Greater behavioural complexity could indicate that those deploying greater neural resources for emotional self-regulation are at risk for altered social development related to autistic traits. Common neurological or psychological processes underlying emotional self-regulation and social cognitive abilities may be disrupted in the aetiology of autistic social difficulties. Alternatively, emotion regulation may impact the development of social cognition by disrupting social interactions through which infants gradually build up social knowledge and learn from social cues.

10.2. Overview of discussion

In the remaining discussion, I first discuss the strengths and limitations, methodological contributions and implications for future research. I will also provide an integratory perspective of how these findings, gained from a movement approach advanced by this PhD thesis, affects clinical and theoretical understanding of socioemotional development, and implications for practice.

10.3. Strengths

The strength of this thesis was in its integrative approach to examine the role of movement in socioemotional development. This is timely in light of the increased recognition of the role of movement in socioemotional development, alongside a conundrum regarding *how* motor skills affect other, seemingly different, psychological domains. I extended the movement perspective, first applied to autism, to consider socioemotional development in general, in early development. I showed that movement can be considered not just in terms of motor skills and motor kinematics, but that movement can be described, analysed and understood at the behavioural level as well. I demonstrated rigorously in Studies 2 and 3 how applying cross-disciplinary theoretical frameworks and analytic approaches can increase understanding of behavioural and motor phenomenon in the study of infant development.

10.4. Limitations

While the integrative nature of this PhD is a strength, the findings also need to be considered in light of its novelty. Entropy methods (such as approximate entropy, sample entropy and multiscale entropy) have previously been applied to study motor development, including in infants, and changes to motor patterns as a result of disease. However, entropy is a relatively recent methodology, with continuing debates surrounding its application. In particular, entropy methods involve selecting parameters that can alter the value of entropy and there continues to be debates over the effect of incorrect parameter selection (Kosciessa et al., 2020). The calculation of sample entropy requires identifying pattern matches in the sample, and involves parameter selection of a "tolerance parameter", r, to determine how closely values are for patterns to be counted as a match. This is especially problematic when there are artefacts in the data (M. Costa et al., 2005), and when entropy at multiple timescales are of interest. As such, I decided to apply permutation entropy in Study 3 which avoids the selection of a tolerance parameter, as permutation entropy only involves identifying permutations of increases or decreases in values, without requiring a match in the amount of increase or decrease. Nevertheless, the literature applying entropy methods have predominantly focused on sample entropy and approximate entropy, and differences in the algorithms calculating entropy might mean that the direction of differences identified may not be directly comparable.

As discussed in Chapter 5 (Study 2A), the interpretation of entropy is debatable. Making the interpretation of my study's findings more difficult, mine was one of the few studies to date which have analysed the dynamics of emotional self-regulatory behaviours (Wenzel et al., 2021), or behavioural states (Montirosso et al., 2010). In adults, higher entropy of motor behaviours or emotional regulatory strategies (Wenzel et al., 2012) is normally associated with more adaptive functioning, in line with the idea that more complex systems are more adaptable (Goldberger et al., 2002). However, in developing children, entropy of motor postural control has been shown to fluctuate with development (Harbourne & Stergiou, 2003), reflecting the freezing of degrees-of-freedom to facilitate skill learning, and releasing degrees-of-freedom to diversify skilful movement (Bernstein, 1967).

Due to these variations in interpretations, I decided to interpret entropy based on its mathematical definition – as a measure of information, suggesting differences in the underlying organisation relating to behavioural output. I related this to the neurobiological structure and functioning of the emotion regulatory system, which can be altered by premature birth (e.g. in Chapter 5), as well as altered by rising distress (e.g. in Chapter 6). Similarly, in Chapter 9, I linked entropy at multiple timescales to neurobiological processes operating at those timescales. The present thesis relies on a key assumption that movement is the output of brain processing, alongside correlational evidence, inference from theory and evidence linking entropy to neural systems' integrity in other fields to interpret the significance of differences in entropy. However, whether signatures of neurobiological functioning might be observed in movement entropy remains to be empirically tested.

My video coding scheme aimed to comprehensively capture the full range of behaviour and analyse it within a dynamic systems framework relating emotional expression and emotional regulation. However, a key limitation is that different behaviours may unfold at different timescales. For example, object-oriented behaviours tend to occur for a longer period of time, while social interactive movements tend to last no more than two seconds each time, simply due to the nature of each type of behaviour. I addressed this limitation in Chapter 5 (Study 2A) by analysing whether the proportion of RME or OBJ behaviours influenced the overall behavioural dynamics, and by doing so, strengthened the argument that prematurity-related group differences did not simply depend on the different behavioural preferences of each group. However, as discussed in Chapter 8 (Study 2D), the dynamics relating to specific emotion regulation behaviours may also be important. For example, measuring the persistence of repetitive behaviours specifically, or object-oriented behaviours specifically, may tell us more about autism risk. Although the Chromatic-RQA approach is able to differentiate different types of behavioural states and could enable focusing on the dynamics of different types of behaviours during emotion regulation, I chose to capture the dynamics pertaining to the system as a whole, instead of a subsystem involved in each kind of behaviour. This is because the variability across individuals in their behavioural response, i.e., that not all infants will use the same range of behaviours during the still-face paradigm, would likely lead to a smaller sample for each analysis.

The focus of my coding scheme was on infants' behaviour during the still-face paradigm, developed to meet a gap in existing coding schemes. The ICEP scheme characterising infant socio-affective engagement alongside a separate dimension of self-regulation, is the most widely used, but focuses only on oral self-comforting and self-clasp behaviours for the self-regulation dimension. Another scheme was developed to capture affect, gaze, and self-regulation on three distinct dimensions. My coding scheme, intended for use to understand infants' self-regulatory behaviours, characterised behavioural states based on gaze as well as behavioural patterns. I suggested that affect may be coded in a separate dimension, and that my coding scheme may add to the ICEP scheme by capturing more comprehensively the dimension of self-regulatory behaviours. However, to date there is no "gold-standard" in how behaviours during the still-face paradigm should be characterised, and the limitations of my coding scheme should be recognised. Notably, my coding scheme focuses on infant behaviours, and may be more suitable for the still-face phases as it may not effectively capture dyadic interactions when infant and parent behaviours and affect are of interest.

Further, I proposed that the coded behaviours related to emotional self-regulation, but in fact the behaviours do not necessarily measure emotional self-regulation in an emotionally "neutral" situation. For example, engaging in objects is also very common in the Play phase of the still-face paradigm, when infants are less aroused and participating in social interactions with parents. In these situations, object-oriented behaviours may be related to the regulation of competing sources of attention to engage in social interactions, rather than to regulate emotional states. This is in line with Nigg's (2017) conceptualisation that emotional self-regulation is a domain-specific process, relying on processes such as attentional regulation that may serve more general functions. To address this, my subsequent studies focused on the still-face phase where negative affect was reliably elicited. Additionally, I applied this coding scheme to study emotional self-regulation in the still-face phases only where infants' emotional states are influenced by self-initiated behaviours.

10.5. Methodological contributions

My thesis built on existing applications of technology deployment to measure movement, and increased understanding of its strengths and limitations. My thesis also contributed to the measurement of socioemotional functioning in terms of its dynamics, integrating existing tools with relatively new approaches to do so.

Deployment of technology. I showed the insights gained from two different approaches of technology deployment to sample different characteristics of motor phenomena. In my first study, I analysed finger ("swipe") movements made from smart-tablet gameplay of a commercial game. I showed the benefit of making motor assessment fun for children as this enabled my analysis of almost 4000 swipes. Furthermore, smart-tablet gameplay is suitable in an ecological setting, enabling research to be brought to participants, in particular reducing the inertia for children to participate in research. To study motor patterns at even younger ages - in infants - in my third study, I chose to use commercially available, small and lightweight Inertial Magnetic Units suitable for immediate deployment in research as there are already validated filtering procedures to extract kinematic data from the raw sensor output. This was suitable for the purpose of my thesis to investigate motor phenomena from a developmental lens, rather than to develop a new sensing system.

The use of technology can enable young children to participate better in research, such as in Study 1, where using serious games as a medium to collect movement data made research possible in educational and health settings. Technology also enables participation in research to be fun – but this can make it more important to address ethical issues related to children's informed participation. For example, where suitable for their age, children's understanding of the research could be enhanced further to inform them about the reason they are asked to play these games. This can support children to be informed decision-makers and active participants in the scientific process, on top of obtaining consent from parents. This could be embedded in the research process to allocate time for sharing the importance of research with children in child-friendly language.

Feasibility of technology. While other studies have similarly used IMUs in infancy (e.g., Smith et al., (2011); Trujillo-Priego & Smith (2017); Wilson et al (2021)), mine is the first to deploy it within a birth cohort study in an established developmental paradigm. Previous studies using such sensors to study infant development have sampled movements measured over an entire day in the home environment. For data over these long periods to be useful for answering research questions, accurate labelling of data periods is required. As it is not feasible for an experimenter to do so, this depends on the research participant, or in the case of infant research, caregivers to do so. Having hours of data may not always be useful and ultimately depends on the study design. In previous studies, these whole-day data were ultimately reduced to shorter segments. Periods relating to particular types of activity were selected to enable a similar comparison across research participants. Nevertheless, there will ultimately be differences in the environment and the complexity of the activity that cannot be controlled in an ecological setting.

In my study, I achieved a compromise, using IMU sensors in a semi-ecological setting. As a proof-of-concept of the use of IMU sensors in an experimental setting, the features of the "still-face" paradigm guided my study design. To investigate differences in motor kinematics between term and preterm infants, I focused on the data period when caregivers were asked to remain unresponsive, such that infants' movements were self-regulated. I also investigated how motor data with experimentally controlled variables, such as emotional stress. However, this approach also presented with some limitations. First, as the still-face paradigm was designed to measure infant self-regulation, using sensors in the same paradigm alters the context. Importantly, in the still-face paradigm, transitions from interactional to still-face phase typically lead to increases in attentional engagement with the proximal or distal environment, and vice-versa for transitions from still-face to interactional phase. Sensors can act as objects that distracts infants. For this reason, I did not use sensors attached to a headband to measure head movements as originally intended, because infants were highly distracted by it. As described in the methodology, sensors were attached to clothing, hidden in pockets made from different coloured material (to facilitate data management). The novelty of the clothing and bright colours of the pockets may distract infants and subsequently I modified the protocol to hide the sensors on the upper body using a plain white long-sleeve shirt. Only one infant removed wristbands containing sensors, and this was when the sensors were placed on the inner ("palm-face-up") side, instead of the outer side of the wrist, and a long-sleeve shirt was not used to hide the wristbands due to the weather on that day. Some infants were distracted by sensors hidden in the socks, but may have been drawn to the colour of the sensor pockets. However, most infants did not engage with the sensors for a prolonged period of time. Therefore, a consideration with using IMUs in an experimental setting is the additional tactile stimulation from clothing used to attach the sensors, and that infants with better fine motor skills may be able to remove the clothing. In my study, in coding infants' behaviour during the still-face paradigm, I assumed that sensor and clothing are part of infants' clothing, and if either was removed, they were then considered part of the environment.

Characterising the temporal dimension of behaviour. Socioemotional functioning is often characterised using standardised questionnaires that are based on report of occurrence of behaviours demonstrating abilities or difficulties. Another approach is to use behavioural observation during experimental paradigms that elicit socioemotional skills. I advanced methods to characterise the temporal dimension of behaviour, which is normally overlooked in traditional questionnaire and observational approaches. My study built on recommendations by previous studies that both aggregate measures and measures of dynamics can be informative about the behaviour. In Chapter 3 (Methodology), I used State Space Grids (Hollenstein, 2013) as a model to visualise how infants' behaviour move between all the behavioural states available to the system. Aggregate measures relate to the overall amount of time spent in each state, while measures of dynamics quantify temporal patterns within, and between states. For example, in relation to infant locomotor states throughout the day, it would be possible to quantify how much time infants spend walking, crawling, scooting. However, measures of dynamics can also tell us how stable a behaviour is, for example, if infants are walking for a long or short period at one go, if they get up to walk after falling, or if they switch to crawling. I focused on the measure of entropy, a measure which characterises the information in all the temporal patterns and which been studied extensively. This measure can be seen as characterising the richness in the patterns of state transitions.

Development of a video coding scheme. I created a video coding scheme aimed at comprehensively capturing all the behaviours related to the emotional self-regulation during the still-face paradigm. I organised the behaviours based on the function of behaviour enabled by lower-level processes; for example body-directed behaviours that engage perceptual processes by stimulating tactile or oral receptors; repetitive motor behaviours that primarily involves action by stimulating the motor system; object-oriented behaviours that recruit action to seek visual perceptual input, or direct visual attention; and socially-oriented behaviours that use action including arm movements and postural control to participate in, or elicit social interaction. Although there are already several coding schemes related to the still-face paradigm, mine is the first to recognise that all of infants' behaviours during the still-face paradigm may be related to self-regulatory processes, including the regulation of attention and behaviour, to modulate emotional physiology and expression. Most studies have only defined self-regulation behaviours as self-comforting behaviours, those that involve oral stimulation through mouthing, or tactile stimulation through self-clasp.

My findings in Chapter 6 (Study 2B) shows that self-comforting behaviours and object-distraction behaviours were the most strongly related to negative affect, supporting previous work that they are likely to be behaviours that are more successful in self-regulating emotional states. Nevertheless, these relationships are correlational, and future research can consider whether there is a temporal relationship between affect and behaviour, for example to demonstrate the successful reduction of negative affect after using the behaviour, or the use of the behaviour following occurrence of negative affect. I also showed that repetitive movements were not just a behavioural reaction to distress, but are under the control of self-regulatory processes.

Approaches to analyse motor and behavioural phenomenon. I showed that movement can be conceptualised at more than one level and demonstrated suitable approaches to investigate them. At the motor level, I demonstrated kinematic analysis of discrete movements, and multiscale entropy analysis of continuous streams of movement data. This contrasts with Smith and colleagues' approach which applied machine-learning to identify discrete movements for kinematic analysis in long, continuous data stream, which is more computationally intensive. This shows that different sources of motor data may be more suited to particular analytic approaches. I integrated novel analytic methods with existing tools in developmental psychology to approach infant behaviour. Infant behaviour is often characterised by video coding, and behaviours can be coded at equally-spaced intervals in time, yet this temporal information is normally discarded in analysis of the aggregate or total amount of behaviours. Like Montirosso et al (2010), I approached this behavioural data as a timeseries data. Montirosso et al (2010) selected a prevailing technique to analysing information in timeseries data, sample entropy, but I built on their approach by identifying another potential approach, Recurrence Quantification Analysis (RQA). I selected this method as it was suitable to the categorical nature of behavioural data, and enabled quantification of temporal dynamics in shorter datasets – which would be the case for behavioural data are usually sampled at a lower frequency e.g., 1 Hz, or 1-second intervals, and a very long measurement period would be needed to obtain sufficient data for typical timeseries analysis methods. Further, I extended the application Chromatic-RQA, a method developed to analyse dynamics of coupled systems, and which distinguishes qualitatively different states, hence the term "chromatic" (Cox et al., 2016). I extended this to auto-recurrence, using the chromatic method to focus my analysis specifically on the recurrence of defined emotional regulation behavioural states, and not those undefined behavioural states.

10.6. Future research

Methodological development

Future research can focus on validating the measure of entropy, in particular how entropy related to neurobiology or brain activity. For example, as discussed in Chapter 5 (Study 2A) and Chapter 8 (Study 2D), behavioural complexity may be related to white matter connectivity particularly connectivity amongst emotional processing structures. How development affects multiscale entropy and behavioural entropy also needs to be further understood, this might be achieved by comparing entropy between infants at different sitting stages (Harbourne & Stergiou, 2003).

Further development of methodologies to examine the still-face paradigm can focus on integrating various coding schemes to identify strengths for dyadic analysis and individual analysis, for example if the focus is on dyadic regulation, or self-regulation like in my thesis. There are also other physiological measures that are feasible to use in the still-face paradigm, and could enable a rich behavioural, physiological and motor characterisation of infant behaviour in the still-face paradigm.

Hypothesis development

The main contribution of this thesis to future research is that researchers should consider how socioemotional skills and difficulties are shaped by underlying processes. In turn these processes underlie experiences of the physical and social world through movement. This thesis was grounded in the position that higher-level mental functions are embodied. Especially in Study 2 and 3, I integrated the investigation of movement using the perspectives and methods offered by dynamic systems theory. Through the lens of dynamic systems theory, movement can be studied as the interaction of different mental and sensorimotor processes. I demonstrated this in three studies, where I identified motor or behavioural differences and considered how these differences arose from underlying processes.

Perception and action in motor processing. In Chapter 4 (Study 1), I looked at differences in the sub-second kinematics of goal-directed movement. I applied a theoretical framework where motor kinematics reflected the interaction of perceptual and motor processes over time as a goal-directed movement unfolds (Elliott et al., 2010, 2017).

Reactivity and regulation in emotional processing. In Chapter 5 and 6 (Study 2A and 2B), I considered movement at a macro, behavioural level, focusing on the self-regulation of emotions, a crucial process involved in socioemotional functioning. I applied new methods to characterise temporal patterns in emotional self-regulatory behaviours, including entropy. a measure of information which is related to the complexity of the micro-level interactions involved in generating the behaviour. Entropy was understood in a temperamental framework recognising that emotional self-regulation involves the interaction of processes involved in emotional reactivity, and behavioural and attentional regulation.

Social and emotional processing in behavioural adjustment. In Chapter 8 (Study 2D), I again increased the level of investigation, instead considering emotion regulation as a lower level process, which interact with other low-level processes to enable successful social interactions. The pattern of social interactions, over a longer timescale, may then influence the development of behavioural adjustment. This multilevel framework of social-emotional competence helped to conceptualise how emotion regulation and social cognitive abilities such as joint attention and processing of social-affect, may also share common lower-level processes such as attention, and depend on common neurobiological processes.

Bridging motor skills and socioemotional capacities. Finally, I attempted to bridge two phenomena normally investigated separately, motor phenomenon and socioemotional capacities. In Chapter 7 (Study 2C), I looked at whether motor skills influence emotional self-regulation behaviours, as motor skills form the substrate for infants' behavioural capabilities. My results highlight the importance of considering not just motor skills but infants' participation in everyday interactions, experiences that lead to the development of socioemotional capacities. In Chapter 9 (Study 3), I analysed movement accelerations using the assumption that these contain the signatures of both micro- and macro-level processes. This is based on the recognition that the brain is a complex system where neural processes interact at different timescales to control movement output. I referred back to theories of motor control, which provided a framework for the first study, showing that information in motor kinematics could represent the contribution of coordinative processes working in time and space to produce a structured motor output, for example, greater organisation (lower complexity) of coordinative processes leading to stereotyped leg kicks, or greater complexity and variability of movement patterns as infants are better able to respond to postural fluctuations. Interpreting the results in terms of neural processing within characteristic frequency bands, these novel results also draw attention to how motor output might reflect signatures of neurobiological processes involved in generating motor commands, and secondly how differences in socioemotional contexts alter the socioemotional processes involved. These processes (e.g. behavioural inhibition, attentional and perceptual processes monitoring self and others' actions in reciprocal interactions) occur at different timescales, and may therefore contribute to timescale-specific changes in the motor output.

Summary. The development of motor, as well as mental functions can be understood better by recognising the dynamic interactions involved, as I have demonstrated in this thesis, perception and action in goal-directed movement; emotional reactivity and regulation comprising physiological, motor, attentional and cognitive processes; and how a range of social-cognitive abilities and emotion regulation together enable successful social interactions. In other words, research on socioemotional development can benefit more from a modular view of maturing socioemotional capacities. The interpretations of my results, supported by evidence, can shape future hypotheses. For example, future work can test hypotheses related to the micro-level processes shaping movement in different contexts, in particular, manipulating sensorimotor integration to understand how it shapes social cognition, and how attentional differences related to preterm birth may affect both social interactions and emotion regulation.

In the next section I consider what my thesis reveals about development through applying such a multilevel framework.

10.7. Clinical and theoretical contributions

Development in the context of constraints

My studies identified different motor patterns or behavioural patterns in groups which differ in socioemotional outcomes or socioemotional risk. In the previous section I discussed how the different frameworks used can identify underlying processes shaping movement or behaviour. In this section I draw together how my studies reveals the different constraints on these lower-level processes and how these differences in those processes might explain socioemotional differences.

Constraints on sensorimotor neurophysiology

In the first study, different motor patterns during goal-directed control was attributed to the efficiency of involvement of feedforward or feedback processes. The neurophysiology of these sensorimotor processes was identified as constraints on autistic children's movement. For example, greater noise can make feedforward motor processes less accurate, leading to a reliance on feedback control with more corrective movements. Neurophysiological processes also constrain the optimal strategy to achieve goals and could explain why a different pattern of kinematic differences was obtained in autistic relative to neurotypical individuals in making repetitive arm movements. In contrast to goal-directed movements requiring accurate movements and therefore a reliance on slower feedback processes, the most effective strategy for autistic individuals when this constraint is not present, was to move as fast as possible (Cook et al., 2013; Mari et al., 2007).

Sensorimotor constraints on social cognition

Instead of viewing motor differences as deficits, these differences may be seen as a "strategic optimisation" of development under different sensorimotor neurophysiology. As discussed in the introduction, motor organisation can guide learning from one's movement outcomes with the physical and social world. Differences in motor organisation may therefore constrain the higher-level processes relying on it. Study 1's findings showed that there are differences in the kinematic organisation of movement, pointing to differences in the underlying integration of visual feedback on ongoing movement – these sensorimotor differences could be what affects some aspects of social cognition, for example, learning about what goes on in other peoples' minds through perceiving the outcomes of oneself and others' actions (Cook, 2016; Colwyn Trevarthen & Delafield-Butt, 2013).

If perception of others' movements is tightly linked to one's own experience (Cook, 2016; Colwyn Trevarthen & Delafield-Butt, 2013), successful social communication and creating shared social knowledge will depend on interpreting social information in the same way. This can be seen as creating bidirectional challenges to social interactions not only for autistic individuals, but also neurotypical individuals (Cook, 2016), as social meaning is intersubjective (Delafield-Butt et al., 2020). Recent advances examining communication between autistic adults, between non-autistic adults, or between autistic and non-autistic adults support this (Crompton et al., 2020)). In this innovative study, each group participated in a "diffusion chain" to convey a story through every individual in the chain. The study found that the chain comprising only autistic adults or only non-autistic adults were equally successful in retaining details of the story throughout the chain, and also reported high levels of rapport. However, the mixed chain comprising autistic and non-autistic adults were less successful in doing so, losing details at a greater rate through the chain, along with reports of lower levels of rapport. This demonstrates that the social "deficits" that characterise autism should be seen as a bidirectional challenge for both autistic and non-autistic people (Crompton et al., 2020; Delafield-Butt et al., 2019; Fletcher-Watson & Bird, 2020; Milton, 2012).

Constraints on emotional neurophysiology

In the second study, differences in the amount of and temporal pattern of emotional self-regulatory behaviours were attributed to differences in reactive and/or regulation, as well as the overall interaction between reactivity and regulation. In Chapter 6 (Study 2B), I showed how biological or genetic characteristics related to infants' reactivity and regulation can influence behaviour during emotional distress. For example, occurrence of repetitive behaviours was correlated negatively with behavioural reactivity to fear, despite previous acknowledgement that repetitive behaviours represent a reactive behavioural response to emotions. This is not counterintuitive if emotional reactivity constrains the subsequent development of regulation, i.e., greater behavioural inhibition in infants who show greater reactivity to fear. I also showed how early temperament shape emotional neurophysiology – infants who enjoyed greater physical closeness with caregivers used more self-comforting behaviours to regulate emotions.

I also showed that there are competing influences on emotional neurophysiological processes. Complexity is linked to the degrees of freedom underlying the behaviour. Lower behavioural complexity due to premature birth in may indicate difference in biological constraints, altering the connectivity of neural structures involved in emotional reactivity and regulation. Yet, greater complexity was correlated with the amount of negative affect during distress, albeit in the more distressing second still-face phase only. I showed in Study 2D that prematurity and behavioural complexity during emotional self-regulation were independently associated with social autistic traits. Importantly, prematurity led to greater social autistic traits, but did not do so via its effect on reducing behavioural complexity. In fact, greater behavioural complexity during emotion regulation, which might result from greater neural demands, was associated with greater autistic traits. Therefore, early biological constraints on emotional systems affects, but does not determine emotional neurophysiology. Emotional neurophysiology is influenced by other factors, in a way that affects the development of social cognition.

Constraints on behavioural adjustment

Externalising and internalising behavioural problems have been described as "under-controlled" and "over-controlled" behaviours (Liu, 2004). Self-regulatory capacities are recognised as a key process enabling well-adjusted socioemotional behaviours (Nancy Eisenberg et al., 2009, 2010). However, it is increasingly recognised that differences in emotional neurophysiology of reactivity and regulation constrains higher-level behavioural adjustment. Fearful temperament, combined with poorer regulatory skills were linked to anxiety and inhibited behaviours during social interactions (N. A. Fox et al., 2005). Regulation may also be differentiated into domain-specific processes to gain insight on the constraints on behavioural risk. In children showing greater reactivity to fear, better attentional regulation was associated with lower anxiety risk, whereas high levels of inhibitory control increased anxiety risk (White et al., 2011). Better regulation of emotions, as well as attentional and behavioural inhibitory control in non-emotional contexts, were linked to low-risk developmental trajectories of externalising behaviours (Perry et al., 2018).

Preterm infants have been reported to be more prone to distress (Langkamp et al., 1998), or show hyporeactive physiological responses to stress (Lammertink et al., 2021) or under-regulated temperaments (Cassiano et al., 2020). These alterations to emotional neurophysiology have been shown to be linked to early exposure to a hyper-stimulating postnatal environment, painful procedures, as well neural differences. However, parenting factors have also been highlighted to play a crucial role in infants' emotional neurophysiology. In term-born infants, maternal sensitivity, on top of infants own self-regulatory abilities, was found to influence the patterns of emotional reactivity over time. Infants who showed less regulation were more likely to have greater increases in emotional reactivity over time, but the steepness of the increase was dampened in those exposed to more sensitive parenting (Braungart-Rieker et al., 2010). In preterm infants, next to white matter abnormalities, a less sensitive parenting style were the top two predictors of poorer self-regulatory abilities (C. A. C. Clark et al., 2008). However, better regulatory abilities did not contribute to lower negative reactivity; instead, lower neonatal distress alongside lower parenting stress was linked to lower negative reactivity (Voigt et al., 2013). In particular, negative parenting affected preterm infants' self-regulatory skills mainly in those who were more prone to distress or have a more difficult temperament. This suggests that the early social environment may be particularly important for preterm infants' whose emotional neurophysiology makes them vulnerable to exposure to emotional stress. Infants' emerging self-regulatory abilities then enable them to cope effectively with emotional situations. In line with this, my study showed a positive correlation between greater cuddliness and greater self-comforting behaviours, highlighting parents' involvement in nurturing self-regulatory abilities, and Atkinson et al (2021) found that greater self-soothing in the first year of life led to greater use of more complex modes of self-regulation.

Sociodemographic factors also shape behavioural adjustment (Harland et al., 2002)), by acting on the early socioemotional environment that influences emotional neurophysiology. This includes parental unemployment, parental separation (Harland et al., 2002) and in general coming from a lower socioeconomic background (Hosokawa & Katsura, 2018). In preterm birth, lower socioeconomic status (SES) dramatically increased the occurrence of internalising and externalising behavioural problems – with each standard deviation decrease in SES resulting in almost 1.5 times increase in total problems (Potijk et al., 2013). Therefore, difficulties with behavioural adjustment may be seen as the result of development under biological and environmental constraints. In particular, the modifiable impact of parenting and environmental factors on behavioural outcomes demand clinical and public health attention.

Emotional constraints on social cognition

Study 2D supports the involvement of emotional self-regulation in the mechanisms affecting social difficulties, and not just the result of social difficulties. Considering the constraints on emotional regulation and other social cognitive processes in social interactions, I proposed two possible mechanisms. First, both processes may depend on the same neurophysiology, such that disrupting neurophysiology affects both processes. Secondly, they may compete for the same processes, such that greater demands on emotional regulation affects social cognition. In particular, the strong involvement of attentional processes in emotional regulation may hinder engagement in rich social interactions and disrupt social learning, as these processes which also rely on attention.

Summary

Providing a high-powered analysis of motor differences between autistic and neurotypical children, I provided strengthened the existing evidence that sensorimotor neurophysiology may explain differences in goal-directed control, as well as contribute to social cognition. Extending the movement perspective beyond motor skills, I probed the processes behind emotional self-regulation to understand how emotional neurophysiology may be altered in preterm birth, and act as constraints on behavioural adjustment. I considered how macro-level processes - emotional self-regulation and other social cognitive processes - may be constrained by differences at a lower-level. Therefore, I showed that our understanding of socioemotional development can be informed by considering different constraints interacting to implicate higher-level functions.

10.8. Implications for practice

Motor skill delays and difficulties

Delays in motor skills and difficulties with motor coordination likely indicates differences in lower-level neurophysiology, such as sensorimotor and attentional differences that are involved in everyday interactions to enable motor development. Motor skill delays also need to be considered in the context of affecting everyday interactions that affect experiences contributing to socioemotional learning. Therefore, difficulties in the motor domain demand clinical attention, as well as wider consideration for other factors that can multiply the risk for negative socioemotional outcomes.

Although motor skill delays are not considered a diagnostic criterion for autism, this could be seen as the development of successful compensatory strategies that enable catch-up in motor skills. Kinematic differences in motor control may continue to show differences in movement coordination, and may have potential to support late diagnoses.

Socioemotional behavioural difficulties

A multilevel approach recognises the interaction of biological differences with environmental risk factors. This is particularly important for preterm infants who experience both. The development of self-regulatory abilities is crucial to address given the long-term implication on behavioural adjustment, and that there are modifiable factors associated with it. In particular, early interactions with caregivers support its development, but caregivers and preterm infants are faced with a host of challenges that disrupt these early interactions. Differences in infants' emotional neurophysiology may make it difficult for caregivers to interpret infants' cues, and neurobehavioural and regulatory difficulties including sleep disturbances, sensory, attentional and emotional reactivity also disrupt parent-child interactions. Impact of preterm birth on parents, including parental psychological distress and physical separation, can also disrupt the development of an attachment relationship, crucial for scaffolding infants' development of self-regulation. Therefore, caregivers should be supported psychologically as well as to understand infants' cues and react contingently to support infants' active social participation. A number of interventions have been developed for this, including skin-to-skin kangaroo care to promote infant-mother closeness (Jefferies et al., 2012), and parenting interventions that provide information and parenting strategies towards promoting positive social interactions (Colditz et al., 2019)).

Early identification

Sub-second motor patterns have received burgeoning attention in their potential as biomarkers for autism and machine learning methods have been predominantly applied to identify motor patterns that successfully distinguish autism and neurotypical groups. In contrast limited research have focused on the implications of sub-second motor differences on motor development itself. Study 1, which identified kinematic patterns affecting goal-directed control, along with Dawson and colleagues (2018) identification of differences in postural control, provide support that sub-second motor differences are related to different sensorimotor processes. Machine learning may be able to capitalise on these developmentally-important differences to improve algorithmic detection of autism risk through motor biomarkers.

This study also advanced another potential biomarker, entropy-based measures. Study 3 show that multiscale entropy appears to differentiate motor patterns of preterm and term groups even in a small sample. As discussed in Study 3 this may complement early observations of motor quality by clinicians and supports the idea that motor signatures may serve as biomarkers supporting early identification (Torres & Donnellan, 2015). However, not all preterm infants develop socioemotional difficulties. Further investigation is needed to determine the predictive value of multiscale entropy as a marker of socioemotional risk.

Behavioural-based markers may be less useful for early identification on its own but may complement other risk factors. First this is because behavioural measures may not specifically relate to particular risks. Study 2A showed that prematurity is associated with differences in behavioural complexity during emotional self-regulation. Fixed effects explained only 4% of the overall variability in behavioural complexity, while together with random effects accounting for variation between individuals, explained 40% of the variability. This indicates that prematurity has little predictive value on behavioural complexity because there are many other sources of variability that influence behavioural complexity, such as mood on the day, the range of behaviours used, and temperament. Secondly, Study 2D shows that is has limited value in prediction of later outcomes. Similarly, behavioural persistence explained only 5% of the variation in social autistic traits 2 years later, an amount that was not statistically significant. Entropy contributed to explaining 5% of the variance in social autistic traits, on top of preterm birth status. These results should be interpreted as identifying possible mechanistic relationships between prematurity, emotion regulation and autistic traits, but does not demonstrate the predictive ability of emotion regulation on autistic traits. However, there may be a potential for behavioural complexity to be considered alongside other variables to support early identification. This is because behavioural complexity and preterm birth status together explained 20% of the variance in autistic traits. Thirdly, for it to be feasible for use in a clinical setting, technological advances such as in computer vision to reliably identify behaviours, would be needed, as behavioural data typically requires time-intensive manual behavioural coding.

Implications for the field of education

Three take-home messages for practitioners and researchers can be gathered to advance the field of education: the importance of increasing attention to movement and motor skills, embracing the use of technology in movement research, and increasing curiosity and knowledge on the constraints affecting movement – in particular to understand and support socioemotional behavioural difficulties in practice. I expand more on each point in turn.

First, early years and health practitioners should not overlook motor delays and difficulties with motor skills. These may be a sign for different underlying sensorimotor constraints and may warrant further consideration on how underlying sensorimotor differences may impact learning and emotional development

Second, researchers in education can consider using new technology as research tools to enable data collection in ecological settings, bringing research into schools and classrooms. Technology can facilitate data collection not just to increase the sample size and ease of data collection, but also the richness of data on movement. Further, these tools have the potential to complement existing questionnaire and task-based assessments of motor development. Researchers can work more closely with educational and health professionals to understand how these technological tools can be deployed in standard practice.

Finally, it is important not to equate movement with motor skills. Paying attention to how behaviour unfolds can reveal constraints underlying behavioural patterns and help us understand the reasons for a behaviour, including the coping mechanisms at work. When identifying behavioural challenges, it is important not just to label the behaviours, but consider constraints and how to address them. Approaches that take into consideration different needs and constraints behind behavioural difficulties have proved to be effective. The National Autistic Society (n.d) developed the Structure, Positive approaches and expectations, Empathy, Low arousal, Links (SPELL) framework to create a conducive learning environment for autistic children, focusing on addressing sensory constraints that impact behaviour in classrooms and cater to autistic children's need for structure. Another framework, the TEACCH framework, caters to autistic children's learning needs by structuring teaching around strengths and using appropriate mediums to enhance communication (Mesibov et al., 2005). Early years practitioners at an individual level, can be perceptive of individual children's behavioural needs. Researchers applying a systems perspective have the potential to increase knowledge on key constraints impacting behaviour at different levels, and in future can further increase the effective approaches we have for supporting children's learning and development.

10.9. Conclusions

This PhD thesis presents the use of innovative technology, rigorous application cross-disciplinary methods, and integratory theoretical perspectives. Focusing on dynamics places "old" phenomena in developmental psychology under a new lens, enabling insight into the micro-level processes interacting to produce movement. My findings converge on a common theme, of socioemotional development under constraints. I show that a dynamic systems approach can be more useful than a modular perspective of socioemotional capacities, as this shines a light on the interaction of multiple internal processes and environmental factors shaping socioemotional capacities. I demonstrate how movement, at the level of motor kinematics and behaviour - can provide insight into the neurophysiological constraints underlying social cognitive difficulties characteristic of autism.

11. References

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Appendix I. Function of Movement and Behaviour Coding Scheme (Version 2)

Infant Function of Movement and Behaviour Phases Video coding scheme

A. Introduction

This coding scheme comprehensively capture the range of movement and behaviours used by infants to self-regulate emotions during the stressful still-face interaction. The codes are characterised by the intention of infant movement and behaviours, such as regulatory, reactive, stimulatory, social and attentional functions. The scheme is developed with reference to earlier video coding schemes characterising infant self-regulation behaviours and research substantiating the function of infant behaviours during still-face.

For the first run, code each 1 second period for infant self-regulation state. If there is a transition between states during the 1s period, code the new behavioural state. Use the concurrent behaviour code only if two behaviours occur concurrently. For periods where infant movements do not meet criteria for any of the regulatory motor behavioural states, use Mmov for other movement and Mna for absence of movement.

This video scheme was developed with a secondary aim to accompany the codes for Infant Engagement Phases in the Infant Caregiver Engagement Phases (ICEP), which would additionally capture the affective dimension of infant emotional regulation. This video scheme was developed mainly for use in the still-face phases but also includes codes to specify periods in play and reunion phases where the caregiver can move the infant, as this means the infants may use less self-regulation strategies.

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B. Operational definitions

1. **(Msc) Self-comforting behaviours.** The function of infant's movement is to obtain oral or tactile stimulation. This includes when infant is using their own body to provide oral self-stimulation (infant mouths on a part of a body, or initiates oral contact with objects), infant is exploring or manipulating objects on self (eg clothing), or touching parts of their own body (eg, touching head, clasping hands, or bracing feet), for 1s or longer

2. **(Mobj) Object exploration/distraction.** The function of infant's movement is to provide attentional distraction by exploring the perceptual properties of objects. This includes reaching and fine motor behaviours which enables infant to manipulate or move to objects not on self, while infants' gaze is directed towards the object, for 1s or longer

3. **(Msoc) Social interactive/monitor behaviours.** The function of infant's movement is to engage in or solicit social interaction. This includes gestures or motor behaviours containing social interactive intention. Social interactive intention is defined by: infant-initiated arm movements, such as reaching, which result in increased proximity or touch of any part of the caregiver, and gestures or behaviours with social meaning, such as pointing or clapping. See note on clapping. Social monitor is defined as instances where the infant attends to the caregiver's face for 1s or longer.

4. **(Mrme) Repetitive motor behaviours**. The function of infant's movement is to provide motor self-stimulation. This includes repetitive movements of the torso, arms or legs (such as banging, leg kicking, body rocking, arm waving, clapping – see note on clapping), defined by an identical pattern of flexion, extension, rotation, abduction, adduction or elevation in all possible directions, at least two times consecutively within a 3 second or smaller window.

5. **(Mdis) Distancing behaviours.** The function of infant's movement is to increase their physical distance from the caregiver. This includes when infant tries to escape or get away from the caregiver by twisting, turning away from the caregiver, without engaging an object, for 1s or longer

6. **(Mmov/Mna) Other spontaneous or no movement.** The function of infant's movement for emotion regulation is not apparent. This includes all instances of motor activity that cannot be described by other emotion regulatory function or if Infant is not moving.

7. **(Musc) Unscorable.** Camera angle obscured infant movement

C. Additional coding guidelines

Concurrent behaviours. Infant is engaging in more than one type of motor behaviour concurrently. If infant shifts between behavioural states in the period, code the most recent state achieved at the end of the period. Do not code Mmov/Mna as a concurrent behaviour.

Sensors. Code Msc.t **i**f infant is touching sensor clothing. Code Mobj if infant is pulling or tugging at sensor clothing, or removes sensors and starts manipulating sensors/clothing.

Repetitive movements involving objects. Code Mobj.rme if infant repeatedly touches an object (at least twice within a 3s window) with gaze directed towards the object. Code Mrme.obj if infant repeats an identical movement that involves an object, without gaze directed towards the object (eg. banging chair)

Clapping. Code as Msoc_Mrme.armB

Msc. Msc.o for instances where infant uses oral self-comforting, Msc.ml for instances where infant two hands or feet are touching, and Msc.t if infant is touching objects on self or parts of their own body. Code Msc.ml even if hands or feet are lightly touching and not clearly or forcefully clasped, for 1s or longer. Code Msc.t only if infant is actively exploring the area touched, ie do not code if infant arm is not moving with hand resting on leg or accidental touches, for example if infants' hands touch while manipulating objects or if infant is repetitively kicking and feet brushes past each other. Code concurrent Msc and Mrme states, for example, in the event of repeated 1s or longer periods of clasping or touching

Mobj. Code Mobj from the period where movement begins and is continuous with the final period where the movement contacts an object. Stop coding Mobj if infant touch remains on an object but gaze is no longer on the object. If view of infant hands is partially obscured by infant chair and it is unclear (for example, if infant is manipulating an object or touching clothing), use adjacent periods if possible, where view is unobscured, to determine the correct code.

Msoc. Code Msoc.att if infant is attending to the caregiver's face. Do not assume social interactive intent unless it meets the definition described. For example, if infant is holding their arm wide and caregiver responds by holding the infant, or if infant is expressing fussiness in response to caregivers' attention, or looking at caregiver while making repetitive movements. If infant moves to touch caregiver and touch remains on caregiver, continue coding Msoc only if infant is actively moving the effector or has attention directed at the touch. Code Msoc.c for periods where caregiver is moving the infant, in addition to, if any, other motor behavioural states are shown by the infant.

Unscorable periods. For analyses where some extent of missing data can be tolerated**,** optionally code Mmov.usc for periods where camera obscures infant movement fully or partially such that it is not possible to determine the function of motor behaviour.

D. Composite scores

Repetitive motor behaviours composite. In a separate code, for periods involving repetitive movements, indicate if movement involved head, torso, and/or bilateral or unilateral arms or legs.

Table 1. Composite scores.

Composite score	Definition
Repetitive motor behaviours regulation composite	Sum of all periods containing Mrme, Mrme.obj, Mobj.rme Breakdown by head, torso, bilateral/unilateral arms and legs
Object-oriented regulation composite	Sum of all periods containing Mobj, Mrme.obj, Mobj.rme
Self-comforting regulation composite	Sum of all periods containing Msc.o, Msc.ml, Msc.t
Social regulation composite	Sum of all periods containing Msoc, Msoc.att
ER composite	Sum of all periods containing Mrme, Mobj, Msc and Mdis codes

E. Violations

Coding violations. Coding violations are incurred when it is not possible to code according to the scheme, such as if parts of the infant's body are obscured due to camera view, if infant turns away from camera, or caregiver obstructs camera view. To minimise the impact of violations on identification of infant self-regulatory behaviours, periods where there is not enough information to assign a code due to the obstruction are coded as absence of behaviour, along with an 'unscorable' label (this is equivalent to imputation of missing values). Code as normal if there is sufficient information to assign a code in the event of partial obstruction. Indicate 'estimated' in the event of partial obstruction and the code was estimated, such as due to information from adjacent periods or information from audio. Indicate estimated for absence of behaviour only if information from adjacent periods or audio indicate the possibility of an ER behaviour, but do not do so sufficiently. Exclude from timeseries analysis if more than 15% of the phase contained unscorable periods. Exclude from still-face analysis if 25% or more of the phase contained unscorable periods.

Still-face violations. Violations of the still-face paradigm are incurred when the still-face procedure is not maintained. This could be due to early termination, interruptions during the still-face, when caregiver does not follow the procedure (touches infant during still-face, does not maintain a still-face), when there are objects introduced to the still-face such as soothers and props, which are not usually considered as part of the setting. Sensors are considered part of the infants' clothing and as an object if infant removes the clothing or the sensor or is distracted by it.

Caregiver moves infant. When caregiver moves the infant during play and reunion phases, infant self-regulatory behaviours may be lower. This is not a violation of the still-face procedure, but potentially implicates the extent of self-regulatory behaviours used by the infant when the caregiver is available.

F. Glossary

Table 2. Glossary of codes and appending codes.

Infant function of motor behaviour	Appending codes
1. (Msc) Self-comforting behaviours	Msc.o, Msc.ml, Msc.t
2. (Mobj) Object exploration	Mobj.rme
3. (Msoc) Social interactive behaviours	Msoc.att, Msoc.c
4. (Mrme) Repetitive motor behaviours	Mrme.obj
5. (Mdis) Distancing behaviours	
6. (Mmov) Other spontaneous or no movement	Mmov.usc
Concurrent codes (Code with underscore between codes or multiple behavioural streams)	eg. Mobj_Msc

Appendix II. Supplemental Material for Chapter 4

Supplementary material

Developmental Differences in the Prospective Organisation of Goal-Directed Movement Between Children with Autism and Typically Developing Children: A Smart Tablet Serious Game Study

Supplemental Methods

Selection of filter frequency

4-8 Hz frequency filters are commonly used in human movement analysis (Bartlett, 2007) and an 8 Hz filter was chosen based on comparison of 100 randomly chosen position vectors filtered at 4, 6 and 8 Hz. Filtering at 8hz had minimal or no perceptible distortion of signals, and reducing the frequency further to 6Hz and 4Hz led to perceptible and increasing distortion of coordinate profiles. After filtering x and y position vectors, x and y velocity vectors were obtained through numerical differentiation using the five-point stencil (Abramowitz & Stegun, 1964). This method allows more accurate derivatives as noise in data can be amplified as a result of finite differentiation, and has been applied to finger movement position data (Rachaveti et al., 2018).

Model building

A top-down model building approach was used, first fitting the full model with all random intercepts, random slopes and fixed effects (including interaction effects) (Model Re1). In Step 2, using the full model, we determined if a random slope should be included, both fitted using the REML estimator (Model Re2). A random slope was included if Akaike Information Criterion (AIC) was lower in Model Re1. In Step 3, using the random effects structure optimised in Step 2, the fixed effects structure was optimised by fitting models using the Full Information Maximum Likelihood estimator with an interaction effect removed at each step and nested models compared using a likelihood ratio test (Models Fe1-4). Inclusion of interaction effects was guided by effect estimates and likelihood ratio tests. Models fitted in the model building procedure (Re1-2, Fe1-4) are reported in the Supplemental Tables 4 and 5.

Models were tested for residual normality, homogeneity of variance and linearity, by examining residual q-q plots, scatter of residuals against fitted values, and scatter of residuals against observed values, respectively. MU was visually inspected to follow a Poisson distribution and the final model was checked for overdispersion.

Supplemental Table 1.

Full breakdown of swipes excluded according to exclusion criteria.

	Total n(%total)	TD n(%total)	ASD n(%total)
Food-to-Plate swipes	4917 (100%)	3233 (65.8%)	1684 (34.2%)
Not suitable for analysis	159 (3.2%)	50 (31.4%)	109 (68.6%)
Non-task-conforming swipes	832 (16.9%)	590 (70.9%)	242 (29.1%)
Swipes from excluded participants (criteria: <10% total swipes comprising food-to-plate swipes[†])	55 (1.1%)	22 (40%)	33 (60%)
No movement units	265 (5.3%)	221 (83.4%)	44 (16.6%)
Movement Time outliers (criteria: >2.0s)	186 (3.8%)	149 (80.1%)	37 (19.9%)
Target Distance outliers (criteria: 10mm<Dist<70mm[‡])	80 (1.6%)	56 (70.0%)	24 (30.0%)
Straightness ratio outliers (criteria: >1.5)	246 (5.0%)	142 (57.7%)	104 (42.3%)
	Total n(%total)	**TD n(%total)**	**ASD n(%total)**
Total swipes excluded	991 (20.2%)	640 (64.6%)	351 (35.4%)
Analysis sample (Goal-directed swipes)	3926 (79.8%)	2593 (66.0%)	1333 (34.0%)

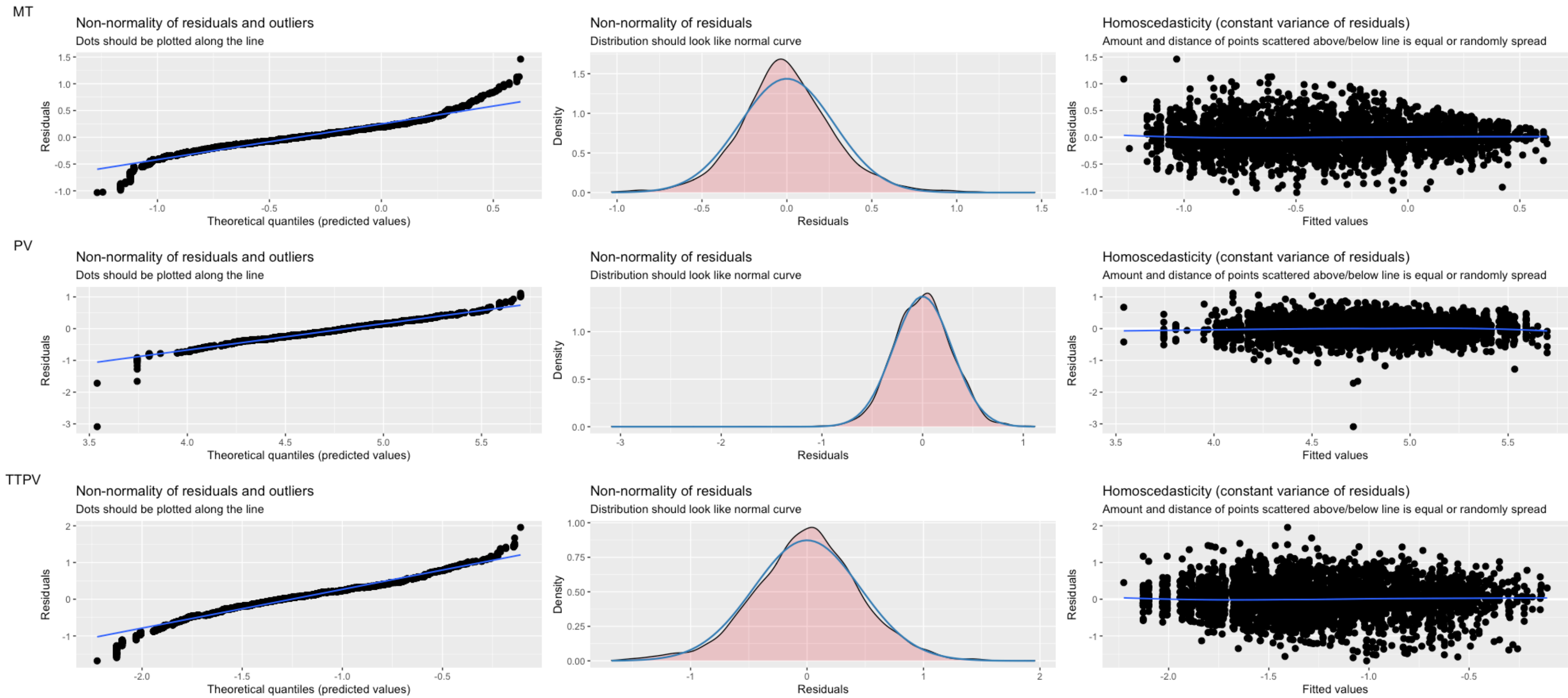
[†]swipes from 11 participants were excluded

[‡]only 1 swipe with Dist<10mm

Supplemental Figure 1A-1B. Model diagnostics (Linear mixed-effect models).

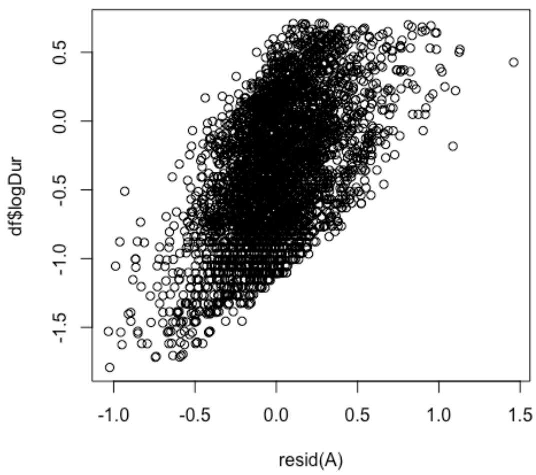
A: (Right to left) Normality of residuals (Quantile-quantile plot and density plot) and homoscedasticity of residuals

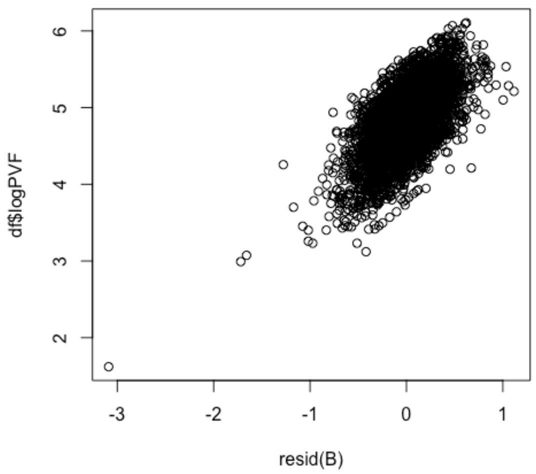
Top to bottom: Model diagnostics for log-transformed MT, PV and TTPV

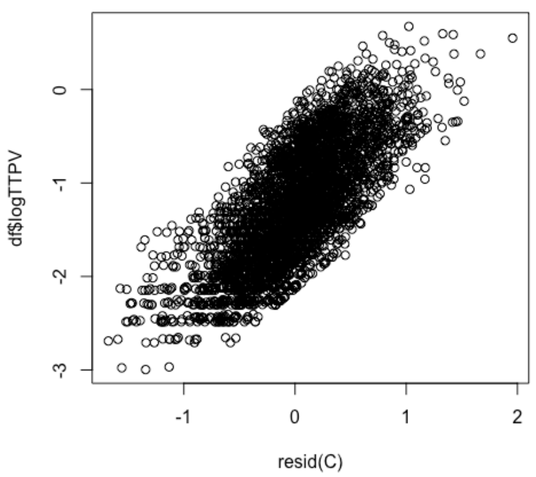


B: Linearity

Top to bottom: Model diagnostics for MT, PV, TTPV







Supplemental Table 2. Final Models.

Zero-truncated Poisson and Linear Mixed Effect Movement Units, Peak Velocity 1MU, Deceleration Phase. The model for Peak Velocity 1MU did not meet assumption for homogeneity of variance and was the only model where including Target distance x Age improved model fit. 16.6% of the total variance was attributed to participant variation, and conditional on this, fixed effects explained only 1% of the total variance.

	Movement Units	**PV1 (mm/s)**	**%Dec (%)**
Fixed effects	*Incidence Rate Ratios (95% CI)*	*Coefficient (95% CI)*	*Coefficient (95% CI)*
Intercept	0.86 (0.73 – 1.01)	116.34 *** (106.78 – 125.90)	55.62 *** (53.52 – 57.72)
Target Distance	1.26 *** (1.21 – 1.31)	14.74 *** (12.86 – 16.63)	-0.78 ** (-1.32 – -0.24)
Age	0.63 *** (0.54 – 0.72)	24.54 *** (15.94 – 33.14)	1.38 (-0.39 – 3.15)
ASD	1.43 ** (1.11 – 1.85)	-15.35 * (-29.36 – -1.34)	-2.09 (-5.33 – 1.15)
ASD x Age	1.32 * (1.04 – 1.68)	n.a	n.a
ASD x Target Distance	0.94 * (0.88 – 0.99)	n.a	n.a
Target Distance x Age	n.a	4.89 ** (2.78 – 6.99)	n.a
Random Effects			
σ^2	0.18	2169.57	254.89
τ_{00} Subject	0.24	1044.46	44.57
τ_{11} Subject. Target distance	0.00	39.44	2.56
ρ_{01} Subject	-0.91	0.66	-0.41
Observations	3926	3926	3926
Marginal R^2 / Conditional R^2	0.364 / 0.721	0.236 / 0.509	0.012 / 0.166
Deviance	n.a	41574.682	33090.719
AIC	7991.987	41574.333	33101.574

* *p<0.05* ** *p<0.01* *** *p<0.001*

Supplemental Table 3. Sensitivity analyses.

Mixed effects models for Movement Time, Peak Velocity, Time to Peak Velocity, Peak Velocity 1MU-b, Movement Units APV. In sensitivity analysis we reran the final models on a stricter sample including only swipes that began with an acceleration phase or with the first velocity minima occurring within 5mm of contacting the touchscreen surface, and ended with a deceleration phase or reaching a velocity minima within 5mm of touch ended. This produced comparable parameter estimates across the models. Notably, this slightly altered the effect estimates for the ASD x Age effect on PV and MU-APV.

	MT (s)	**PV (mm/s)**	**TTPV (s)**	**PV1-b**	**MU-APV**
Fixed effects	*Coefficient (95% CI)*	*Coefficient (95% CI)*	*Coefficient (95% CI)*	*Odds Ratios (95% CI)*	*Incidence Rate Ratios (95% CI)*
Intercept	0.70 *** (0.63 – 0.78)	114.40 *** (106.24 – 123.19)	0.28 *** (0.25 – 0.32)	4.35 *** (3.34 – 5.68)	0.30 *** (0.25 – 0.37)
Target Distance	1.10 *** (1.09 – 1.12)	1.17 *** (1.15 – 1.18)	1.13 *** (1.11 – 1.15)	0.75 *** (0.70 – 0.81)	1.32 *** (1.25 – 1.39)
Age	0.71 *** (0.64 – 0.79)	1.26 *** (1.16 – 1.35)	0.74 *** (0.65 – 0.83)	1.92 *** (1.54 – 2.41)	0.61 *** (0.52 – 0.73)
ASD	1.14 (0.97 – 1.34)	0.95 (0.85 – 1.06)	1.20 (1.00 – 1.43)	0.55 ** (0.37 – 0.82)	1.36 * (1.01 – 1.82)
ASD x Age	1.31 ** (1.09 – 1.57)	0.82 ** (0.72 – 0.93)	1.22 (1.00 – 1.50)	n.a	1.26 (0.94 – 1.69)
ASD x Target distance	n.a	n.a	n.a	n.a	0.91 * (0.84 – 1.00)

* *p<0.05* ** *p<0.01* *** *p<0.001*

	MT (s)	**PV (mm/s)**	**TTPV (s)**	**PV1-b**	**MU-APV**
Random effects	*Estimates*	*Estimates*	*Estimates*	*Estimates*	*Estimates*
σ^2	0.08	0.08	0.21	3.29	1.16
$\tau_{00\ Subject}$	0.13	0.06	0.13	0.63	0.29
$\tau_{11\ Subject.TargetDistance}$	0.00	0.00	0.00	0.03	0.01
$\rho_{01\ Subject}$	-0.47	-0.44	-0.18	-0.45	-0.78
Observations	3684	3684	3684	3684	3684
Marginal R^2 / Conditional R^2	0.302 / 0.736	0.353 / 0.631	0.200 / 0.515	0.125 / 0.269	0.163 / 0.328
Deviance	1285.348	1450.230	5049.671	3727.794	5819.282
AIC	1327.093	1494.604	5089.542	3741.794	5837.282

Supplemental Tables 4A – 4H. Model building (Random effects).
Models Re1 and Re2 for MT, PV, TTPV, and PV1, %Dec, MU-APV, PV1-b, and MU-APV

A. MT (log-transformed)

	Re1	Re2
Predictors	*Estimates*	*Estimates*
(Intercept)	0.68 *** (0.61 – 0.76)	0.69 *** (0.62 – 0.76)
TargetDist.c	1.11 *** (1.10 – 1.13)	1.11 *** (1.10 – 1.12)
Age.c	0.72 *** (0.65 – 0.81)	0.74 *** (0.66 – 0.83)
ASD.f [ASD]	1.20 * (1.00 – 1.42)	1.18 (0.99 – 1.40)
TargetDist.c * Age.c	0.99 (0.98 – 1.01)	0.99 ** (0.98 – 1.00)
Age.c * ASD.f [ASD]	1.33 ** (1.11 – 1.60)	1.26 * (1.04 – 1.53)
TargetDist.c * ASD.f [ASD]	0.98 (0.96 – 1.00)	0.98 * (0.97 – 1.00)
Random Effects		
σ^2	0.08	0.08
τ_{00}	0.13 Subject.f	0.12 Subject.f
τ_{11}	0.00 Subject.f.TargetDist.c	
ρ_{01}	-0.48 Subject.f	
ICC	0.61	0.60
N	71 Subject.f	71 Subject.f
Observations	3926	3926
Marginal R^2 / Conditional R^2	0.291 / 0.726	0.276 / 0.713
Deviance	1540.544	1577.926
AIC	1601.680	1637.438

* *p<0.05* ** *p<0.01* *** *p<0.001*

B. PV (log-transformed)

Predictors	Re1 Estimates	Re2 Estimates
(Intercept)	114.73 *** (106.42 – 123.69)	114.67 *** (106.38 – 123.60)
TargetDist.c	1.16 *** (1.14 – 1.18)	1.16 *** (1.15 – 1.17)
Age.c	1.24 *** (1.15 – 1.35)	1.24 *** (1.15 – 1.34)
ASD.f [ASD]	0.90 (0.80 – 1.02)	0.90 (0.80 – 1.02)
TargetDist.c * Age.c	1.00 (0.99 – 1.02)	1.01 (1.00 – 1.01)
Age.c * ASD.f [ASD]	0.88 (0.77 – 1.00)	0.89 (0.78 – 1.01)
TargetDist.c * ASD.f [ASD]	1.01 (0.99 – 1.04)	1.01 (1.00 – 1.03)
Random Effects		
σ^2	0.09	0.09
τ_{00}	0.06 Subject.f	0.06 Subject.f
τ_{11}	0.00 Subject.f.TargetDist.c	
ρ_{01}	-0.32 Subject.f	
ICC	0.41	0.40
N	71 Subject.f	71 Subject.f
Observations	3926	3926
Marginal R^2 / Conditional R^2	0.348 / 0.613	0.339 / 0.600
Deviance	1859.320	1896.650
AIC	1922.733	1958.790

* *p<0.05* ** *p<0.01* *** *p<0.001*

C. TTPV (log-transformed)

	Re1	Re2
Predictors	*Estimates*	*Estimates*
(Intercept)	0.28 *** (0.25 – 0.32)	0.28 *** (0.25 – 0.32)
TargetDist.c	1.13 *** (1.10 – 1.15)	1.13 *** (1.11 – 1.14)
Age.c	0.74 *** (0.66 – 0.84)	0.75 *** (0.66 – 0.84)
ASD.f [ASD]	1.20 (1.00 – 1.44)	1.19 (1.00 – 1.43)
TargetDist.c * Age.c	0.99 (0.97 – 1.01)	0.99 (0.98 – 1.00)
Age.c * ASD.f [ASD]	1.21 (0.99 – 1.48)	1.20 (0.98 – 1.47)
TargetDist.c * ASD.f [ASD]	1.00 (0.96 – 1.03)	1.01 (0.98 – 1.03)
Random Effects		
σ^2	0.21	0.22
τ_{00}	0.14 Subject.f	0.14 Subject.f
τ_{11}	0.00 Subject.f.TargetDist.c	
ρ_{01}	-0.10 Subject.f	
ICC	0.40	0.38
N	71 Subject.f	71 Subject.f
Observations	3926	3926
Marginal R^2 / Conditional R^2	0.199 / 0.516	0.198 / 0.504
Deviance	5397.585	5426.409
AIC	5454.910	5482.472

* *p<0.05* ** *p<0.01* *** *p<0.001*

D. PV1 (mm/s)

	Re1	Re2
Predictors	*Estimates*	*Estimates*
(Intercept)	116.95 *** (107.05 – 126.85)	117.76 *** (107.60 – 127.91)
TargetDist.c	14.76 *** (12.39 – 17.13)	15.46 *** (14.13 – 16.79)
Age.c	28.28 *** (18.12 – 38.45)	31.58 *** (20.78 – 42.38)
ASD.f [ASD]	-16.72 * (-32.47 – -0.96)	-18.81 * (-35.01 – -2.61)
TargetDist.c * Age.c	4.95 *** (2.83 – 7.08)	5.00 *** (3.74 – 6.26)
Age.c * ASD.f [ASD]	-10.55 (-26.46 – 5.37)	-20.10 * (-38.14 – -2.06)
TargetDist.c * ASD.f [ASD]	0.03 (-3.87 – 3.93)	0.33 (-2.02 – 2.69)
Random Effects		
σ^2	2169.93	2239.36
τ_{00}	1005.15 Subject.f	1056.43 Subject.f
τ_{11}	39.86 Subject.f.TargetDist.c	
ρ_{01}	0.63 Subject.f	
ICC	0.35	0.32
N	71 Subject.f	71 Subject.f
Observations	3926	3926
Marginal R^2 / Conditional R^2	0.251 / 0.512	0.276 / 0.508
Deviance	41573.078	41643.942
AIC	41567.505	41636.414

* *p<0.05* ** *p<0.01* *** *p<0.001*

E. MU

Predictors	Re1 *Incidence Rate Ratios*	Re2 *Incidence Rate Ratios*
(Intercept)	0.85 * (0.72 – 1.00)	0.86 (0.74 – 1.00)
TargetDist.c	1.27 *** (1.22 – 1.32)	1.25 *** (1.21 – 1.29)
Age.c	0.60 *** (0.51 – 0.71)	0.60 *** (0.51 – 0.71)
ASD.f [ASD]	1.44 ** (1.11 – 1.86)	1.42 ** (1.12 – 1.80)
TargetDist.c * Age.c	1.02 (0.98 – 1.05)	1.01 (0.98 – 1.04)
Age.c * ASD.f [ASD]	1.32 * (1.04 – 1.68)	1.34 * (1.03 – 1.74)
TargetDist.c * ASD.f [ASD]	0.93 * (0.88 – 0.99)	0.94 * (0.89 – 0.99)
Random Effects		
σ^2	0.18	0.39
τ_{00}	0.24 $_{Subject.f}$	0.21 $_{Subject.f}$
τ_{11}	0.00 $_{Subject.f.TargetDist.c}$	
ρ_{01}	-0.91 $_{Subject.f}$	
ICC	0.56	0.35
N	71 $_{Subject.f}$	71 $_{Subject.f}$
Observations	3926	3926
Marginal R^2 / Conditional R^2	0.389 / 0.734	0.301 / 0.544
AIC	7999.112	8006.590

* *p<0.05* ** *p<0.01* *** *p<0.001*

F. %Dec (%)

	Re1	Re2
Predictors	*Estimates*	*Estimates*
(Intercept)	55.32 *** (53.16 – 57.47)	55.31 *** (53.22 – 57.39)
TargetDist.c	-0.57 (-1.25 – 0.10)	-0.53 * (-0.98 – -0.08)
Age.c	0.70 (-1.57 – 2.97)	0.50 (-1.73 – 2.72)
ASD.f [ASD]	-1.36 (-4.82 – 2.11)	-1.18 (-4.53 – 2.18)
TargetDist.c * Age.c	0.20 (-0.42 – 0.82)	0.17 (-0.26 – 0.60)
Age.c * ASD.f [ASD]	1.42 (-2.33 – 5.18)	1.97 (-1.81 – 5.75)
TargetDist.c * ASD.f [ASD]	-0.53 (-1.67 – 0.61)	-0.75 (-1.55 – 0.05)
Random Effects		
σ^2	254.90	259.39
τ_{00}	44.48 $_{\text{Subject.f}}$	41.24 $_{\text{Subject.f}}$
τ_{11}	2.57 $_{\text{Subject.f.TargetDist.c}}$	
ρ_{01}	-0.37 $_{\text{Subject.f}}$	
ICC	0.16	0.14
N	71 $_{\text{Subject.f}}$	71 $_{\text{Subject.f}}$
Observations	3926	3926
Marginal R^2 / Conditional R^2	0.010 / 0.165	0.011 / 0.147
Deviance	33089.096	33110.513
AIC	33102.487	33122.037

* *p<0.05* ** *p<0.01* *** *p<0.001*

G. MU-APV

Predictors	**Re1** *Incidence Rate Ratios*	**Re2** *Incidence Rate Ratios*
(Intercept)	0.29 *** (0.24 – 0.35)	0.30 *** (0.25 – 0.35)
TargetDist.c	1.33 *** (1.26 – 1.41)	1.31 *** (1.25 – 1.37)
Age.c	0.60 *** (0.50 – 0.73)	0.61 *** (0.50 – 0.73)
ASD.f [ASD]	1.36 * (1.01 – 1.83)	1.35 * (1.03 – 1.77)
TargetDist.c * Age.c	1.00 (0.96 – 1.05)	1.00 (0.96 – 1.04)
Age.c * ASD.f [ASD]	1.36 * (1.02 – 1.80)	1.36 * (1.01 – 1.83)
TargetDist.c * ASD.f [ASD]	0.91 * (0.84 – 0.99)	0.91 * (0.85 – 0.99)
Random Effects		
σ^2	1.17	1.25
τ_{00}	0.30 Subject.f	0.24 Subject.f
τ_{11}	0.01 Subject.f.TargetDist.c	
ρ_{01}	-0.86 Subject.f	
ICC	0.20	0.16
N	71 Subject.f	71 Subject.f
Observations	3926	3926
Marginal R^2 / Conditional R^2	0.168 / 0.332	0.156 / 0.294
Deviance	6083.554	6092.208
AIC	6103.554	6108.208

* *p<0.05* ** *p<0.01* *** *p<0.001*

H. PV1-b

	Re1	Re2
Predictors	*Odds Ratios*	*Odds Ratios*
(Intercept)	4.62 *** (3.52 – 6.06)	4.49 *** (3.47 – 5.79)
TargetDist.c	0.74 *** (0.68 – 0.82)	0.76 *** (0.70 – 0.82)
Age.c	2.18 *** (1.65 – 2.88)	2.15 *** (1.64 – 2.83)
ASD.f [ASD]	0.52 ** (0.34 – 0.79)	0.53 ** (0.36 – 0.79)
TargetDist.c * Age.c	0.99 (0.91 – 1.08)	1.00 (0.93 – 1.07)
Age.c * ASD.f [ASD]	0.68 (0.44 – 1.07)	0.69 (0.44 – 1.07)
TargetDist.c * ASD.f [ASD]	1.02 (0.88 – 1.18)	1.00 (0.89 – 1.12)
Random Effects		
σ^2	3.29	3.29
τ_{00}	0.60 $_{\text{Subject.f}}$	0.53 $_{\text{Subject.f}}$
τ_{11}	0.03 $_{\text{Subject.f.TargetDist.c}}$	
ρ_{01}	-0.54 $_{\text{Subject.f}}$	
ICC	0.16	0.14
N	71 $_{\text{Subject.f}}$	71 $_{\text{Subject.f}}$
Observations	3926	3926
Marginal R^2 / Conditional R^2	0.138 / 0.273	0.135 / 0.255
Deviance	3943.365	3950.188
AIC	3963.365	3966.188

* $p<0.05$ ** $p<0.01$ *** $p<0.001$

Supplemental Tables 5A – 5H. Model building (Fixed effects).

Models Fe1 – Fe4 for MT, PV, TTPV, and PV1, %Dec, MU-APV, PV1-b, and MU-APV

A. MT (log-transformed)

	Fe1	Fe2	Fe3	Fe4
Predictors	*Estimates*	*Estimates*	*Estimates*	*Estimates*
(Intercept)	0.68 *** (0.61 – 0.76)	0.68 *** (0.61 – 0.76)	0.70 *** (0.63 – 0.77)	0.71 *** (0.63 – 0.79)
TargetDist.c	1.11 *** (1.10 – 1.13)	1.11 *** (1.10 – 1.13)	1.10 *** (1.09 – 1.12)	1.10 *** (1.09 – 1.12)
Age.c	0.73 *** (0.65 – 0.81)	0.71 *** (0.64 – 0.79)	0.71 *** (0.64 – 0.79)	0.79 *** (0.72 – 0.87)
ASD.f [ASD]	1.19 * (1.01 – 1.42)	1.20 * (1.01 – 1.42)	1.13 (0.97 – 1.32)	1.09 (0.93 – 1.29)
TargetDist.c * Age.c	0.99 (0.98 – 1.01)			
Age.c * ASD.f [ASD]	1.33 ** (1.12 – 1.59)	1.34 ** (1.13 – 1.60)	1.33 ** (1.12 – 1.59)	
TargetDist.c * ASD.f [ASD]	0.98 (0.96 – 1.00)	0.98 (0.96 – 1.00)		
Random Effects				
σ^2	0.08	0.08	0.08	0.08
τ_{00}	0.12 Subject.f	0.12 Subject.f	0.12 Subject.f	0.13 Subject.f
τ_{11}	0.00 Subject.f.TargetDist.c	0.00 Subject.f.TargetDist.c	0.00 Subject.f.TargetDist.c	0.00 Subject.f.TargetDist.c
ρ_{01}	-0.49 Subject.f	-0.49 Subject.f	-0.49 Subject.f	-0.38 Subject.f
ICC	0.60	0.60	0.60	0.62
N	71 Subject.f	71 Subject.f	71 Subject.f	71 Subject.f
Observations	3926	3926	3926	3926
Marginal R^2 / Conditional R^2	0.298 / 0.719	0.315 / 0.726	0.303 / 0.722	0.229 / 0.706
AIC	1562.360	1561.580	1562.313	1569.739

* *p<0.05* ** *p<0.01* *** *p<0.001*

B. PV (log-transformed)

	Fe1	Fe2	Fe3	Fe4
Predictors	*Estimates*	*Estimates*	*Estimates*	*Estimates*
(Intercept)	114.75 *** (106.67 – 123.45)	114.91 *** (106.83 – 123.61)	114.12 *** (106.19 – 122.63)	113.18 *** (105.17 – 121.79)
TargetDist.c	1.16 *** (1.15 – 1.18)	1.16 *** (1.14 – 1.18)	1.17 *** (1.15 – 1.18)	1.17 *** (1.15 – 1.18)
Age.c	1.24 *** (1.15 – 1.34)	1.25 *** (1.16 – 1.35)	1.25 *** (1.16 – 1.35)	1.20 *** (1.12 – 1.27)
ASD.f [ASD]	0.90 (0.80 – 1.01)	0.90 (0.80 – 1.01)	0.92 (0.82 – 1.03)	0.94 (0.84 – 1.05)
TargetDist.c * Age.c	1.00 (0.99 – 1.02)			
Age.c * ASD.f [ASD]	0.88 * (0.78 – 1.00)	0.88 * (0.77 – 0.99)	0.88 * (0.78 – 1.00)	
TargetDist.c * ASD.f [ASD]	1.01 (0.99 – 1.04)	1.01 (0.99 – 1.04)		
Random Effects				
σ^2	0.09	0.09	0.09	0.09
τ_{00}	0.06 Subject.f	0.06 Subject.f	0.06 Subject.f	0.06 Subject.f
τ_{11}	0.00 Subject.f.TargetDist.c	0.00 Subject.f.TargetDist.c	0.00 Subject.f.TargetDist.c	0.00 Subject.f.TargetDist.c
ρ_{01}	-0.33 Subject.f	-0.34 Subject.f	-0.33 Subject.f	-0.30 Subject.f
ICC	0.39	0.39	0.39	0.40
N	71 Subject.f	71 Subject.f	71 Subject.f	71 Subject.f
Observations	3926	3926	3926	3926
Marginal R^2 / Conditional R^2	0.353 / 0.607	0.357 / 0.609	0.355 / 0.608	0.331 / 0.601
AIC	1881.129	1879.697	1879.008	1880.927

* *p<0.05*   ** *p<0.01*   *** *p<0.001*

C. TTPV (log-transformed)

	Fe1	Fe2	Fe3	Fe4
Predictors	*Estimates*	*Estimates*	*Estimates*	*Estimates*
(Intercept)	0.28 *** (0.25 – 0.31)	0.28 *** (0.25 – 0.31)	0.28 *** (0.25 – 0.31)	0.29 *** (0.25 – 0.32)
TargetDist.c	1.13 *** (1.10 – 1.15)	1.13 *** (1.11 – 1.15)	1.13 *** (1.11 – 1.15)	1.13 *** (1.11 – 1.15)
Age.c	0.74 *** (0.66 – 0.84)	0.74 *** (0.66 – 0.83)	0.74 *** (0.66 – 0.83)	0.79 *** (0.72 – 0.87)
ASD.f [ASD]	1.20 * (1.01 – 1.44)	1.20 * (1.01 – 1.44)	1.20 * (1.01 – 1.43)	1.17 (0.98 – 1.39)
TargetDist.c * Age.c	0.99 (0.97 – 1.01)			
Age.c * ASD.f [ASD]	1.21 (0.99 – 1.47)	1.21 (0.99 – 1.47)	1.21 (0.99 – 1.47)	
TargetDist.c * ASD.f [ASD]	1.00 (0.96 – 1.03)	1.00 (0.96 – 1.03)		
Random Effects				
σ^2	0.21	0.21	0.21	0.21
τ_{00}	0.13 Subject.f	0.13 Subject.f	0.13 Subject.f	0.13 Subject.f
τ_{11}	0.00 Subject.f.TargetDist.c	0.00 Subject.f.TargetDist.c	0.00 Subject.f.TargetDist.c	0.00 Subject.f.TargetDist.c
ρ_{01}	-0.10 Subject.f	-0.11 Subject.f	-0.11 Subject.f	-0.01 Subject.f
ICC	0.38	0.38	0.38	0.39
N	71 Subject.f	71 Subject.f	71 Subject.f	71 Subject.f
Observations	3926	3926	3926	3926
Marginal R^2 / Conditional R^2	0.202 / 0.507	0.205 / 0.508	0.204 / 0.508	0.174 / 0.498
AIC	5419.400	5418.315	5416.337	5417.542

* $p<0.05$ ** $p<0.01$ *** $p<0.001$

D. PV1 (mm/s).

Fe3 and Fe4 failed to converge

	Fe1	Fe2	Fe3	Fe4
Predictors	*Estimates*	*Estimates*	*Estimates*	*Estimates*
(Intercept)	116.98 *** (107.35 – 126.61)	115.19 *** (105.31 – 125.07)	117.00 * (107.79 – 126.22)	116.37 *** (107.01 – 125.73)
TargetDist.c	14.76 *** (12.44 – 17.07)	14.06 *** (11.40 – 16.73)	14.77 *** (12.92 – 16.62)	14.74 *** (12.89 – 16.60)
Age.c	28.28 *** (18.40 – 38.17)	19.16 *** (10.06 – 28.27)	28.28 (18.40 – 38.17)	24.52 (16.09 – 32.95)
ASD.f [ASD]	-16.73 * (-32.06 – -1.40)	-16.12 * (-31.91 – -0.34)	-16.79 * (-30.51 – -3.07)	-15.37 * (-29.08 – -1.65)
TargetDist.c * Age.c	4.97 *** (2.89 – 7.04)		4.97 (2.89 – 7.04)	4.89 (2.82 – 6.97)
Age.c * ASD.f [ASD]	-10.62 (-26.11 – 4.86)	-8.80 (-24.42 – 6.81)	-10.62 (-26.09 – 4.85)	
TargetDist.c * ASD.f [ASD]	0.03 (-3.78 – 3.84)	0.06 (-4.31 – 4.42)		
Random Effects				
σ^2	2169.82	2169.21	2169.80	2169.53
τ_{00}	948.55 Subject.f	1010.09 Subject.f	949.41 Subject.f	1000.77 Subject.f
τ_{11}	37.15 Subject.f.TargetDist.c	56.26 Subject.f.TargetDist.c	37.15 Subject.f.TargetDist.c	37.63 Subject.f.TargetDist.c
ρ_{01}	0.65 Subject.f	0.64 Subject.f	0.65 Subject.f	0.67 Subject.f
ICC	0.34	0.36	0.34	0.35
N	71 Subject.f	71 Subject.f	71 Subject.f	71 Subject.f
Observations	3926	3926	3926	3926
Marginal R^2/ Conditional R^2	0.254 / 0.505	0.167 / 0.466	0.254 / 0.505	0.239 / 0.503
AIC	41594.902	41611.862	41592.903	41592.591

* *p<0.05* ** *p<0.01* *** *p<0.001*

E. MU

Predictors	Fe1 *Incidence Rate Ratios*	Fe2 *Incidence Rate Ratios*	Fe3 *Incidence Rate Ratios*	Fe4 *Incidence Rate Ratios*
(Intercept)	0.83 * (0.71 – 0.98)	0.84 * (0.72 – 0.99)	0.90 (0.77 – 1.04)	0.86 (0.73 – 1.01)
TargetDist.c	1.27 *** (1.22 – 1.32)	1.26 *** (1.21 – 1.31)	1.23 *** (1.19 – 1.27)	1.26 *** (1.21 – 1.31)
Age.c	0.60 *** (0.51 – 0.70)	0.63 *** (0.54 – 0.72)	0.62 *** (0.54 – 0.72)	0.69 *** (0.62 – 0.78)
ASD.f [ASD]	1.44 ** (1.12 – 1.84)	1.43 ** (1.11 – 1.83)	1.23 (0.99 – 1.52)	1.36 * (1.06 – 1.75)
TargetDist.c * Age.c	1.02 (0.99 – 1.05)			
Age.c * ASD.f [ASD]	1.32 * (1.05 – 1.67)	1.32 * (1.05 – 1.67)	1.33 * (1.06 – 1.68)	
TargetDist.c * ASD.f [ASD]	0.93 * (0.88 – 0.99)	0.94 * (0.88 – 0.99)		0.93 * (0.88 – 0.99)
Random Effects				
σ^2	0.19	0.19	0.19	0.19
τ_{00}	0.23 Subject.f	0.23 Subject.f	0.23 Subject.f	0.24 Subject.f
τ_{11}	0.00 Subject.f.TargetDist.c	0.00 Subject.f.TargetDist.c	0.00 Subject.f.TargetDist.c	0.00 Subject.f.TargetDist.c
ρ_{01}	-0.98 Subject.f	-0.97 Subject.f	-0.94 Subject.f	-0.96 Subject.f
ICC	0.54	0.53	0.54	0.55
N	71 Subject.f	71 Subject.f	71 Subject.f	71 Subject.f
Observations	3926	3926	3926	3926
Marginal R^2 / Conditional R^2	0.397 / 0.720	0.372 / 0.708	0.351 / 0.700	0.332 / 0.699
AIC	7967.920	7967.121	7969.720	7970.555

* *p<0.05* ** *p<0.01* *** *p<0.001*

F. %Dec (%)

	Fe1	Fe2	Fe3	Fe4
Predictors	*Estimates*	*Estimates*	*Estimates*	*Estimates*
(Intercept)	55.32 *** (53.23 – 57.41)	55.36 *** (53.26 – 57.45)	55.54 *** (53.48 – 57.60)	55.62 *** (53.56 – 57.68)
TargetDist.c	-0.57 (-1.23 – 0.09)	-0.59 (-1.25 – 0.07)	-0.78 ** (-1.32 – -0.24)	-0.78 ** (-1.32 – -0.24)
Age.c	0.69 (-1.51 – 2.90)	0.88 (-1.25 – 3.01)	0.92 (-1.21 – 3.04)	1.37 (-0.36 – 3.10)
ASD.f [ASD]	-1.34 (-4.71 – 2.03)	-1.36 (-4.74 – 2.01)	-1.87 (-5.07 – 1.33)	-2.08 (-5.25 – 1.09)
TargetDist.c * Age.c	0.19 (-0.41 – 0.80)			
Age.c * ASD.f [ASD]	1.41 (-2.24 – 5.06)	1.36 (-2.28 – 5.01)	1.31 (-2.33 – 4.95)	
TargetDist.c * ASD.f [ASD]	-0.54 (-1.65 – 0.57)	-0.54 (-1.65 – 0.58)		
Random Effects				
σ^2	254.91	254.93	254.88	254.90
τ_{00}	41.62 Subject.f	41.75 Subject.f	41.88 Subject.f	42.53 Subject.f
τ_{11}	2.33 Subject.f.TargetDist.c	2.34 Subject.f.TargetDist.c	2.47 Subject.f.TargetDist.c	2.47 Subject.f.TargetDist.c
ρ_{01}	-0.38 Subject.f	-0.39 Subject.f	-0.39 Subject.f	-0.42 Subject.f
ICC	0.15	0.15	0.15	0.15
N	71 Subject.f	71 Subject.f	71 Subject.f	71 Subject.f
Observations	3926	3926	3926	3926
Marginal R^2/ Conditional R^2	0.010 / 0.156	0.011 / 0.157	0.012 / 0.158	0.012 / 0.160
AIC	33110.909	33109.305	33108.171	33106.646

* *p<0.05* ** *p<0.01* *** *p<0.001*

G. MU-APV

Predictors	**Fe1** *Incidence Rate Ratios*	**Fe2** *Incidence Rate Ratios*	**Fe3** *Incidence Rate Ratios*	**Fe4** *Incidence Rate Ratios*
(Intercept)	0.29 *** (0.24 – 0.35)	0.29 *** (0.24 – 0.35)	0.31 *** (0.26 – 0.37)	0.30 *** (0.25 – 0.36)
TargetDist.c	1.33 *** (1.26 – 1.41)	1.33 *** (1.26 – 1.41)	1.29 *** (1.23 – 1.35)	1.33 *** (1.26 – 1.41)
Age.c	0.60 *** (0.50 – 0.73)	0.61 *** (0.51 – 0.72)	0.61 *** (0.51 – 0.72)	0.67 *** (0.59 – 0.77)
ASD.f [ASD]	1.36 * (1.01 – 1.83)	1.36 * (1.01 – 1.83)	1.15 (0.88 – 1.49)	1.29 (0.96 – 1.74)
TargetDist.c * Age.c	1.00 (0.96 – 1.05)			
Age.c * ASD.f [ASD]	1.36 * (1.02 – 1.80)	1.35 * (1.02 – 1.80)	1.36 * (1.02 – 1.81)	
TargetDist.c * ASD.f [ASD]	0.91 * (0.84 – 0.99)	0.91 * (0.84 – 0.99)		0.91 * (0.83 – 0.99)
Random Effects				
σ^2	1.17	1.17	1.17	1.17
τ_{00}	0.30 Subject.f	0.30 Subject.f	0.30 Subject.f	0.31 Subject.f
τ_{11}	0.01 Subject.f.TargetDist.c	0.01 Subject.f.TargetDist.c	0.01 Subject.f.TargetDist.c	0.01 Subject.f.TargetDist.c
ρ_{01}	-0.86 Subject.f	-0.86 Subject.f	-0.79 Subject.f	-0.82 Subject.f
ICC	0.20	0.20	0.20	0.21
N	71 Subject.f	71 Subject.f	71 Subject.f	71 Subject.f
Observations	3926	3926	3926	3926
Marginal R^2/ Conditional R^2	0.168 / 0.332	0.166 / 0.331	0.155 / 0.326	0.149 / 0.324
AIC	6103.554	6101.565	6104.143	6103.817

* *p<0.05* ** *p<0.01* *** *p<0.001*

H. PV1-b

	Fe1	Fe2	Fe3	Fe4
Predictors	*Odds Ratios*	*Odds Ratios*	*Odds Ratios*	*Odds Ratios*
(Intercept)	4.62 *** (3.52 – 6.06)	4.61 *** (3.52 – 6.02)	4.57 *** (3.52 – 5.92)	4.45 *** (3.43 – 5.78)
TargetDist.c	0.74 *** (0.68 – 0.82)	0.75 *** (0.68 – 0.82)	0.75 *** (0.70 – 0.81)	0.75 *** (0.70 – 0.81)
Age.c	2.18 *** (1.65 – 2.88)	2.16 *** (1.65 – 2.82)	2.16 *** (1.65 – 2.82)	1.89 *** (1.52 – 2.35)
ASD.f [ASD]	0.52 ** (0.34 – 0.79)	0.52 ** (0.34 – 0.79)	0.53 ** (0.36 – 0.78)	0.56 ** (0.38 – 0.82)
TargetDist.c * Age.c	0.99 (0.91 – 1.08)			
Age.c * ASD.f [ASD]	0.68 (0.44 – 1.07)	0.68 (0.44 – 1.07)	0.68 (0.44 – 1.07)	
TargetDist.c * ASD.f [ASD]	1.02 (0.88 – 1.18)	1.02 (0.88 – 1.18)		
Random Effects				
σ^2	3.29	3.29	3.29	3.29
τ_{00}	0.60 Subject.f	0.60 Subject.f	0.60 Subject.f	0.62 Subject.f
τ_{11}	0.03 Subject.f.TargetDist.c	0.03 Subject.f.TargetDist.c	0.03 Subject.f.TargetDist.c	0.03 Subject.f.TargetDist.c
ρ_{01}	-0.54 Subject.f	-0.53 Subject.f	-0.53 Subject.f	-0.52 Subject.f
ICC	0.16	0.16	0.16	0.16
N	71 Subject.f	71 Subject.f	71 Subject.f	71 Subject.f
Observations	3926	3926	3926	3926
Marginal R^2/ Conditional R^2	0.138 / 0.273	0.136 / 0.271	0.135 / 0.270	0.123 / 0.263
AIC	3963.365	3961.406	3959.460	3960.211

* *p<0.05* ** *p<0.01* *** *p<0.001*

Appendix III. Chromatic state space: coding recurrence with concurrent codes

TS2 / TS1	1	2	3	4	5	6	12	13	14	15	23	24	25	34	35	45	123	124	125	134	135	145	234	235	345
1	ER						ER	ER	ER	ER							ER	ER	ER	ER	ER	ER			
2		ER					ER				ER	ER	ER				ER	ER	ER				ER	ER	
3			ER					ER			ER			ER	ER		ER			ER	ER		ER	ER	ER
4				ER					ER			ER		ER		ER		ER		ER		ER	ER		ER
5					ER					ER			ER		ER	ER			ER		ER	ER		ER	ER
6						NER																			
12	ER	ER					ER	ER	ER	ER	ER	ER	ER				ER	ER	ER	ER	ER	ER	ER	ER	
13	ER		ER				ER	ER	ER	ER	ER			ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER
14	ER			ER			ER	ER	ER	ER		ER		ER		ER	ER	ER	ER	ER	ER	ER	ER		ER
15	ER				ER		ER	ER	ER	ER			ER		ER	ER	ER	ER	ER	ER	ER	ER		ER	ER
23		ER	ER				ER	ER			ER	ER	ER	ER	ER		ER	ER	ER	ER	ER		ER	ER	ER
24		ER		ER			ER		ER		ER	ER	ER	ER		ER	ER	ER	ER	ER		ER	ER	ER	ER
25		ER			ER		ER			ER	ER	ER	ER		ER	ER	ER	ER	ER		ER	ER	ER	ER	ER
34			ER	ER				ER	ER		ER	ER		ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER
35			ER		ER			ER		ER	ER		ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER
45				ER	ER				ER	ER		ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER
123	ER	ER	ER				ER	ER	ER	ER	ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER
124	ER	ER		ER			ER	ER	ER	ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
125	ER	ER			ER		ER	ER	ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
134	ER		ER	ER			ER	ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
135	ER		ER		ER		ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
145	ER			ER	ER		ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
234		ER	ER	ER			ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
235		ER	ER		ER		ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
345			ER	ER	ER			ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER

Appendix IV. irr.py: functions for calculating inter-rater reliability (Python code)

```
#filename irr.py

def irr_kappa(master, second, part_agree=True, tolerance=1):


    Intervals=master.Interval
    n=len(Intervals)


    master=dict(zip(master.Interval, master.Code))
    second=dict(zip(second.Interval, second.Code))

    code_list=set.union(set(master.values()), set(second.values()))
    list_c=[0] * len(code_list)
    row_marginals=dict(zip(code_list, list_c))
    col_marginals=dict(zip(code_list, list_c))


    #initialise lists
    list_m=[0] * n
    matches=dict(zip(Intervals, list_m))


    #kappa
    #consider agreement for partial agreement (at least one code matches)
    #obtain the base rate for each code
    #calculate expected agreement

    if part_agree==False:
    #percentage agreement within 1s
        for t in Intervals:
            if t==Intervals[0]:
                if second[t] == master[t] or second[t] ==
master[t+tolerance]:
                    matches[t]=1

            elif t==Intervals[0] + (n-tolerance):
                if second[t] == master[t] or second[t] == master[t-
tolerance]:
                    matches[t]=1

            else:
                if second[t] == master[t] or second[t] ==
master[t+tolerance] or second[t] == master[t-tolerance]:
                    matches[t]=1

            #base rate of all codes for coder 1 and 2
            col_marginals[master[t]]=col_marginals[master[t]]+1
            row_marginals[second[t]]=row_marginals[second[t]]+1


    elif part_agree==True:
    #consider agreement for partial agreement (at least one code matches)
        for t in Intervals:
            if t==Intervals[0]:
```

```
                if second[t] in master[t] or second[t] in
master[t+tolerance] or master[t] in second[t] or master[t] in
second[t+tolerance]:

                    matches[t]=1

            elif t==Intervals[0] + (n-tolerance):
                if second[t] in master[t] or second[t] in master[t-
tolerance] or master[t] in second[t] or master[t] in second[t-tolerance]:

                    matches[t]=1

            else:
                if second[t] in master[t] or second[t] in
master[t+tolerance] or second[t] in master[t-tolerance] or master[t] in
second[t] or master[t] in second[t+tolerance] or master[t] in second[t-
tolerance]:

                    matches[t]=1


            #base rate of all codes for coder 1 and 2
            col_marginals[master[t]]=col_marginals[master[t]]+1
            row_marginals[second[t]]=row_marginals[second[t]]+1

    #expected agreement
    p_exp=0
    for code in code_list:
        p_exp_code=row_marginals[code]/n * col_marginals[code]/n
        p_exp=p_exp+p_exp_code

    #observed agreement
    total_matches=0
    for m in matches.values():
        if m ==1: total_matches=total_matches+1

    p_agree=total_matches/n

    #kappa
    kappa = (p_agree - p_exp) / (1 - p_exp)

    return kappa


def irr_agree(master, second, part_agree=True, tolerance=1):

    Intervals=master.Interval
    n=len(Intervals)

    master=dict(zip(master.Interval, master.Code))
    second=dict(zip(second.Interval, second.Code))

    #initialise lists
    list_m=[0] *  n
    matches=dict(zip(Intervals, list_m))

    if part_agree==False:
    #percentage agreement within 1s
        for t in Intervals:
            if t==Intervals[0]:
                if second[t] == master[t] or second[t] ==
master[t+tolerance]:
                    matches[t]=1
```

```
            elif t==Intervals[0] + (n-tolerance):
                if second[t] == master[t] or second[t] == master[t-
tolerance]:
                    matches[t]=1

            else:
                if second[t] == master[t] or second[t] ==
master[t+tolerance] or second[t] == master[t-tolerance]:
                    matches[t]=1


    elif part_agree==True:
    #consider agreement for partial agreement (at least one code matches)
        for t in Intervals:
            if t==Intervals[0]:
                if second[t] in master[t] or second[t] in
master[t+tolerance] or master[t] in second[t] or master[t] in
second[t+tolerance]:

                    matches[t]=1

            elif t==Intervals[0] + (n-tolerance):
                if second[t] in master[t] or second[t] in master[t-
tolerance] or master[t] in second[t] or master[t] in second[t-tolerance]:

                    matches[t]=1

            else:
                if second[t] in master[t] or second[t] in
master[t+tolerance] or second[t] in master[t-tolerance] or master[t] in
second[t] or master[t] in second[t+tolerance] or master[t] in second[t-
tolerance]:

                    matches[t]=1

    #calculate percentage agreement
    #1. obtain total number of intervals

    total=len(matches.values())

    #2. count total number of 1s in matches
    total_matches=0
    for m in matches.values():
        if m ==1: total_matches=total_matches+1

    percent_agree=total_matches/total*100

    return percent_agree
```

Appendix V. chrRQA.R - functions for executing Chromatic Auto-RQA (R code)

```
#filename: chrRQA.R

#chrRQA function
#Computes chromatic recurrence quantification analysis for auto and cross
RQA analysis of time series containing categorical values.
#Produces recurrence rate and recurrence measures relevant to categorical
variable types (vertical structures and entropy of block structures)
#Dependent on ggplot2, tidyr (pivot_longer)
#Input variables:
#TS1 and TS2: the two timeseries to be analysed, input the same timeseries
for auto RQA
#SS_chr: The chromatic state space matrix as a dataframe or datafile (.csv
filetype)
#Vmin: The shortest vertical structure to be considered.
#Outputs: chromatic recurrence matrix, recurrence plot, recurrence measures
for each chromatic (RR, LAM, Vmax, TT, ENTb)

library(ggplot2)
library(tidyr)

chrRQA<-function(TS1, TS2, SS_chr, Vmin=1, outputRecMat=0){

  #Check that state space matrix is in matrix form
  #Executing function to load the datafile with row and column headings if
SS_chr is a .csv filename
  #Then check if data provided for SS_chr variable is already in a matrix
form. If it is not, stop and return error message
  if (is.character(SS_chr)==TRUE) {
    SS_chr=ChrMatch(SS_chr)
  } else {
    if (is.data.frame(SS_chr)==FALSE) {
      stop('Input SS_chr as a dataframe or .csv file containing the state
space of chromatic matches')
    }
  }

  #Create recurrence matrix
  rec<-RecMat(TS1, TS2, SS_chr)

  #Then calculate variables for later use
  ## chromatics: a list of the chromatics states occurring in the
recurrence matrix, empty states labelled as Undefined
  ## rqatype: whether auto or cross recurrence analysis (affects
calculation of recurrence rate)
  chromatics<-unique(as.vector(rec))
  chromatics<-chromatics[! chromatics %in% ""]  #remove empty fields
  chromatics<-sort(chromatics)

  rec[rec==""]="Undefined" #rename blanks to undefined
  if ("Undefined" %in% rec) {
    chromatics=c("Undefined", chromatics) #append undefined state to first
location in the vector, useful for plotting white spaces later
  }

  if (identical(TS1, TS2) == TRUE) {
    rqatype="auto"
```

```
  } else {
    rqatype="cross"
  }

  #Generate recurrence plot
  RP<-plotRP(rec, chromatics)

  #Obtain recurrence measures for defined chromatic states
  output=c()
  for (c in chromatics) {
    if (c == "Undefined") { #skip calculation for undefined states
      next()
    }

    #Recurrence rate of each chromatic
    RR=calRR(rec, c, rqatype)
    #Recurrence measures related to vertical structures: Trapping time,
Laminarity, Vmax
    Vert=calVert(rec, c, Vmin)
    #calculate entropy of block structures
    ENTb=calENTb(rec, c)

    #append the output list to the previous list
    output=c(output, RR, Vert, ENTb)
  }

  #append the recurrence matrix and recurrence plot to the output list.
  #option to output recurrence matrix can be used to customise plots later
using plotRP function.
  output=c(list(RP=RP), output)

  if (outputRecMat=="1") {
    output=c(list(rec=rec), output)
  }

  return(output)
}

# R helper functions 1 - chromatic RQA
#
===========================================================================
==
#Function for loading state space matrix
#Input the filename of a .csv file containing data specifying chromatic
values of state space matrix
#Matches are defined in output dataframe SS_chr, based on row and column
name/number
ChrMatch<-function(filename){
  SS_chr<-read.csv(filename, row.names=1, check.names = FALSE, header=TRUE)
#load dataframe from csv file
  return(SS_chr)
}

#Function for creating chromatic recurrence plot
#Input timeseries and match matrix, for chromatic recurrence analysis.
Input same timeseries for TS1 and TS2 if conducting auto chromatic
recurrnece
RecMat<-function(TS1, TS2, SS_chr) {
  TS1=as.vector(as.matrix(TS1))
  TS2=as.vector(as.matrix(TS2))

  sample_num=length(TS1)        #TS1 and TS2 need to comprise the same
number of samples
```

```
  RecMat_chr<-matrix(0, sample_num, sample_num)
  #loop over TS1 and TS2 for each sample
  for (n1 in 1:sample_num) {
    for (n2 in 1:sample_num) {
      row=TS1[n1]            #TS1 values form row names
      col=TS2[n2]            #TS2 values form col names
      match_val=SS_chr[row, col] #output the match type based on the values
of SS_chr given row and col names
      RecMat_chr[n1, n2]=match_val
    }
  }
  return(RecMat_chr)
}


#Function for plotting chromatic recurrences
##Convert recurrence matrix into dataframe for plotting in ggplot2
##Plot recurrence plot
plotRP<-function(rec, chromatics, palette="") {
  #convert RecMat into a long dataframe containing recurrent states over
each value of time in TS1 and TS2
  mat_length=(length(rec))**(1/2)
  colnames=as.character(sequence(mat_length))
  rec=as.data.frame(rec)
  names(rec)=colnames
  rec$TS1=colnames
  relocate(rec, TS1)
  rec<-pivot_longer(rec, !TS1, names_to="TS2", values_to="State")
  rec$State<-factor(rec$State, levels=chromatics)
  rec$TS1<-as.numeric(rec$TS1)
  rec$TS2<-as.numeric(rec$TS2)

  cbp1<-c("white", "#E69F00", "#999999", "#56B4E9", "#009E73",
          "#F0E442", "#0072B2", "#D55E00", "#CC79A7")       #define
palette, white space as first value, reverse first two colours
  cbp1r<-c("white", "#999999", "#E69F00", "#56B4E9", "#009E73",
           "#F0E442", "#0072B2", "#D55E00", "#CC79A7")      #define
palette, white space as first value, reverse first two colours
  cbp2<-c("#E69F00", "#999999", "#56B4E9", "#009E73",
           "#F0E442", "#0072B2", "#D55E00", "#CC79A7")      #define
palette, no white

  if (palette=="no white") {
    cbp=cbp2
  } else if (palette=="reverse") {
    cbp=cbp1r
  } else {
    cbp=cbp1
  }

  RP<-ggplot(rec, aes(TS1, TS2)) + geom_point(aes(colour=State)) +
    scale_color_manual(values=cbp) +
    scale_x_continuous(breaks=seq(0, mat_length, 10), expand = c(0,0)) +
    scale_y_continuous(breaks=seq(0, mat_length, 10), expand = c(0,0)) +
    ggtitle("Recurrence Plot") +
    theme_bw(base_size = 14)+
    theme(panel.grid=element_blank())
  return(RP)
}

#Input variables: recurrence matrix, rqatype auto or cross
#Recurrence rate of each chromatic
#for auto-recurrence, calculate using Webber & Zbilut (2006) formula.
```

```
## 1. calculate recurrence of each chromatic on central diagnoal
## 2. obtain recurrence on symmetric half: calculate total recurrences of
each chromatic, subtract recurrence on central diagonal, and divide by two

calRR<-function(rec, c, rqatype){
  mat_length=(length(rec))**(1/2)
  if (rqatype=="auto") {
    rec_diag=0
    for (diag in 1:mat_length) {
      if(rec[diag, diag]==c) {
        rec_diag=rec_diag+1
      }
      rec_total=sum(rec==c)
      rec_symmetric_half=(rec_total-rec_diag)/2
      RR=rec_symmetric_half/((mat_length*(mat_length-1)/2))*100
    }
  } else {
    #for cross-recurrence, calculate using Cox et al (2016) formula. No
need (not applicable) to separate out recurrences in symmetric half of the
RP
    mat_size=length(rec)
    RR=sum(rec==c)/mat_size
  }
  varNameRR<-paste(c, "_", "RR", sep="")
  listc=list(RR)
  names(listc)=c(varNameRR)

  return(listc)
}

#Trapping time and Laminarity
#Input variables: recurrence matrix, vmin, length of shortest vertical line
considered
#Obtain distribution of lengths of all the vertical lines in the entire
matrix, based on Coco crqa tt function, adapted from matlab CRPtoolbox
function.
https://www.rdocumentation.org/packages/crqa/versions/1.0.9/source
#this method doesn't loop over each value of the matrix, so will be faster
# For each chromatic:
# 1. Replace values of the chromatic under consideration with 1, other
chromatics to 0.
# 2. Pad each matrix column (or row, since they are symmetric) with zeros,
this ends each col of the matrix with a 0 when converted to a vector, so
any recurring vertical structure is considered to end
# 3. Convert the matrix into a vector
# 4. Identify start of a sequence and end of a sequence using r "diff"
function
# 5. Obtain the start and end positions of vertical structures
# 6. Calculate trapping time, the mean length of vertical structures
# 7. Calculate laminarity, percent of recurring points in vertical
structures meeting min criteria out of total recurring points

#vertical structures in whole Recurrence Matrix
#outputs a list containing the recurrence measures of vertical structures
calVert<-function(rec, c, Vmin) {
  rec_c=rec #work with a duplicate of recurrence matrix
  rec_c[rec_c!=c] <-0 #convert non-matching values to 0
  rec_c[rec_c==c] <-1 #convert values in the recurrence matrix matching the
chromatic currently considered to 1
  rec_vector=as.vector(rbind(rec_c, rep(0, ncol(rec_c)), deparse.level =
0))
  rec_vector=as.numeric(rec_vector)
```

```
  rec_vector=c(0, rec_vector) #pad one zero to the top to allow start of
vertical structure to be detected from the first location
  rec_start_end=diff(rec_vector) #differentiate vector to obtain start and
end of vertical structures throughout the rec matrix
  start_positions=which(rec_start_end==1) #define positions where vertical
structures start
  end_positions=which(rec_start_end==-1) #define positions where vertical
structures end
  structures_length=end_positions-start_positions

  TT=mean(structures_length)

  Vmax=max(structures_length)

  rec_points=sum(rec_vector) #total number of recurring points
  structures_above_vmin=structures_length[which(structures_length>Vmin)]
#select structures greater than vmin only
  LAM=sum(structures_above_vmin)/rec_points*100 #percentage of recurring
points in vertical structures

  #create variable names for recurrence output measures for the chromatic
under consideration
  varNameTT<-paste(c, "_", "TT", sep="")
  varNameVmax<-paste( c, "_", "Vmax", sep="")
  varNameLAM<-paste(c,  "_", "LAM", sep="")

  #generate the output list
  listc=list(TT, Vmax, LAM)
  names(listc)=c(varNameTT, varNameVmax, varNameLAM)

  return(listc)
}

#Entropy of rectangular block structures
calENTb <- function(rec, c) {
  rec_c=rec #work with a duplicate of recurrence matrix
  rec_c[rec_c!=c] <-0 #convert non-matching values to 0
  rec_c[rec_c==c] <-1 #convert values in the recurrence matrix matching the
chromatic currently considered to 1
  rec_c=apply(rec_c, 2, as.numeric) #convert characters to numeric values
within recurrence matrix

  ind = which(rec_c > 0, arr.ind = TRUE) #obtain indices where recurrence
occurred. produces [Nrec_c by 2] matrix specifying row indices and column
indices, where Nrec_c is the total number of recurrences
  mat_dimensions = dim(rec_c) #obtain dimensions of recurrence matrix

  ENTb=catEnt(ind, dim(rec_c)) #calculate entropy of block structures using
code by G.Leonardi, modified by M.Coco

  varNameENTb<-paste(c, "_", "ENTb", sep="")

  listc=list(ENTb)
  names(listc)=c(varNameENTb)

  return(listc)
}

# R helper functions 2 - from crqa package
#
=========================================================================
==
# catEnt = compute categorical entropy
```

```
# Standalone function we can use on the already extracted RP
# (a Sparse Matrix) in order to compute categorical entropy
# using the findBlocks() function.
#
# creator: Giuseppe Leonardi (giuleonardi@gmail.com)
# integrated and modified by Moreno I. Coco (moreno.cocoi@gmail.com)
#
===========================================================================
==
# ind  = the indices of the recurrence plot where recurrence is observed
# size = the dimension of the recurrence plot

catEnt <- function(ind_c, size){

  # print(dim(ind_c))
  points <- findBlocks(ind_c, size)

  nbk   <- length(unique(points$x))
  areas <- as.numeric(table(points[points$x%in%1:nbk, 3]))

  bkarea <- areas[areas > 1]
  if (length(bkarea) > 0) {
    tabarea <- as.data.frame(table(bkarea))
    parea <- tabarea$Freq / sum(tabarea$Freq)
    catentropy = -sum(parea * log(parea))
  } else { catentropy <- NA}

  return(catentropy)

}

# ===============================================================
# findBlocks
# Matrix transformation by @alexis_laz (Stackexchange)
# Assign to non-zero elements of a sparse Matrix
# (i.e. categorical recurrence plot) a numerical code identifying
# its block membership
# ===============================================================
# creator: Giuseppe Leonardi (giuleonardi@gmail.com)
# integrated and modified by Moreno I. Coco (moreno.cocoi@gmail.com)

findBlocks <- function(ind_c, size) {

  lt    = nrow(ind_c) ## the number of datapoints

  ind_c = as.list(as.data.frame(ind_c)) ## working with lists that consume
less memory
  # print(dim(ind_c))
  blocks = list(lastSeenRow = integer(size[1]),
                lastSeenCol = integer(size[2]),
                gr = integer(lt))

  # k = 1
  # i = 1
  ngr = 0 # initialize the counter of blocks

  for(k in 1:lt) {
    kr <- ind_c$row[k]
    kc <- ind_c$col[k]
    # print(c(k, kr, kc))
    i <- blocks$lastSeenRow[kr]
    j <- blocks$lastSeenCol[kc]
```

```
    if (i && (abs(kc - ind_c$col[i]) == 1))      blocks$gr[k] =
blocks$gr[i]
    else if (j && (abs(kr - ind_c$row[j]) == 1)) blocks$gr[k] =
blocks$gr[j]
    else {
      ngr <- ngr + 1L; blocks$gr[k] = ngr
    }

    blocks$lastSeenRow[kr] <- k
    blocks$lastSeenCol[kc] <- k
  }

  return(data.frame(i = ind_c$row, j = ind_c$col, x = blocks$gr))

}
```

Appendix VI. IMPE.py - Functions for implementing Improved Multiscale Permutation Entropy (Python code)

```
#filename: IMPE.py
###### IMPE
#Functions to calculate Improved Multiscale Permutation Entropy as
described in [1]
#
###### Inputs
#TS: timeseries
#m: embedding dimension
#tstep: time step - current code only implemented for tstep=1
#scale: timescale
#
###### Outputs
#pe: permutation entropy as described in [2]
#CoarseGrain: coarsegrained timeseries according to procedure described in
[3]
#impe: permutation entropy at the desired timescale as described in [1]
#(implements coarsegraining procedure described in [4])
#
###### References
#[1] H. Azami and J. Escudero, ìImproved Multiscale Permutation Entropy
#for Biomedical Signal Analysis: Interpretation and Application to
#Electroencephalogram Signalsî,  Biomedical Signal Processing and
#Control , 2015.
#[2] C. Bandt, and B. Pompe. "Permutation entropy: a natural complexity
#measure for time series." Physical review letters 88.17 (2002).
#[3] Costa
#[4] Wu
#####

from itertools import permutations
from math import log2
from math import factorial

def pe(TS, m, tstep=1):

    #List of all possible permutations
    m_list=[x for x in range(1, m+1)]
    l_perm=list(permutations(m_list))

    #Create dictionary of permutations (key) with number of matches
(values) initialised at 0
    max_perm=len(l_perm) #total number of permutations
    m_perm=dict(zip(l_perm, [0 for x in range(1, max_perm+1)]))

    #loop across each value of the timeseries to obtain the d-sized vectors
    for t in range(1, len(TS)+1-tstep*(m-1)):
        index_start=t-1
        index_end=t-1+m

        v=TS[index_start:index_end]
        v_sort=TS[index_start:index_end]
        v_sort.sort()

        equal=0
        elements=[]
        previous_element=0
```

```
        #check if any elements are equal
        if len(v_sort)!=len(set(v_sort)):
            for element in v_sort:
                if previous_element!=0:
                    if element==previous_element:
                        if equal==0:
                            elements=[element]
                            equal=equal+1

                        else:
                            elements=elements+[element]

                previous_element=element

            for e in elements:
                v_sort[v_sort.index(e)]=v_sort[v_sort.index(e)]-
0.0000000001
                v[v.index(e)]=v[v.index(e)]-0.0000000001

        #get permutations observed in v
        v_perm=dict(zip(v_sort, m_list))

        v_order=[v_perm[value] for value in v]

        #Look up and update dictionary with matches
        m_perm[tuple(v_order)]=m_perm[tuple(v_order)]+1

    #Calculate permutation entropy
    total=sum(m_perm.values())

    h_perm={x: -1* m_perm[x]/total * log2(m_perm[x]/total) for x in m_perm
if m_perm[x]!=0}
    H=sum(h_perm.values())

    #normalise permutation entropy
    #Hnorm=H/log2(factorial(m))

    return H


import numpy as np
def CoarseGrain(TS, scale):
    TS_coarse=[]
    N=len(TS)
    for i in list(range(1, int(N/scale)+1)):
        TS_coarse=TS_coarse+[np.mean(TS[(i-1)*scale:i*scale])]
    return TS_coarse


def impe(TS, m, tstep, scale, norm=False):

    if scale==1:
        #calculate and return pe of the original TS, no coarsegraining
required
        imPE=pe(TS, m, tstep)

        return imPE

    #Create temporary list to store pe values of s coarsegrain TSs
    PE_temp=[np.nan for x in range(1, scale+1)]

    #coarsegrain the signal, s coarsegrained TSs, calculate pe of each
```

```
    for i in list(range(0, scale)):
        TS_coarse=CoarseGrain(TS[i:], scale)

        #calculate pe for scale s for each coarsegrained TS
        H=pe(TS_coarse, m, tstep)

        #save value in temporary list
        PE_temp[i]=H

    #calculate impe for scale s, by taking mean of all pe values of each
coarsegrained TS
    imPE=np.mean(PE_temp) #produces nan if permutation entropy cannot be
obtained

    if norm==True:
        imPE=imPE/log2(factorial(m))

    return imPE
```

Appendix VII. Models fitted in Chapter 9

Beta coefficients (simple effects) of fitted model for MSE curve profile

	Permutation Entropy	
Predictors	*Beta (95% CI)*	*p*
Intercept	**0.73 *** (0.73 – 0.74)**	**<0.001**
Scale factor [Ref: Scale factor 1]		
Scale factor 4	**0.23 *** (0.22 – 0.24)**	**<0.001**
Scale factor 8	**0.24 *** (0.23 – 0.25)**	**<0.001**
Scale factor 13	**0.24 *** (0.23 – 0.25)**	**<0.001**
Scale factor 25	**0.22 *** (0.21 – 0.23)**	**<0.001**
Scale factor 50	**0.21 *** (0.20 – 0.22)**	**<0.001**
Prematurity [Ref: Term]		
Preterm	**0.03 *** (0.02 – 0.03)**	**<0.001**
Sensor location [Ref: Torso]		
Ankle-Left	**-0.08 *** (-0.09 – -0.07)**	**<0.001**
Ankle-Right	**-0.08 *** (-0.08 – -0.07)**	**<0.001**
Wrist-Left	**0.01 * (0.00 – 0.02)**	**0.011**
Wrist-Right	0.01 (-0.00 – 0.01)	0.271
Scale factor X Prematurity		
Scale factor 4 X Preterm	**-0.02 *** (-0.03 – -0.01)**	**<0.001**
Scale factor 8 X Preterm	**-0.03 *** (-0.04 – -0.02)**	**<0.001**
Scale factor 13 X Preterm	**-0.02 *** (-0.03 – -0.02)**	**<0.001**
Scale factor 25 X Preterm	**-0.02 *** (-0.02 – -0.01)**	**<0.001**
Scale factor 15 X Preterm	**-0.02 *** (-0.02 – -0.01)**	**<0.001**
Scale factor X Sensor location		
Scale factor 4 X Ankle-Left	**0.07 *** (0.05 – 0.08)**	**<0.001**
Scale factor 8 X Ankle-Left	**0.08 *** (0.07 – 0.10)**	**<0.001**
Scale factor 13 X Ankle-Left	**0.05 *** (0.04 – 0.07)**	**<0.001**

Scale factor 25 X Ankle-Left	**0.05 *** (0.04 – 0.07)**	**<0.001**
Scale factor 50 X Ankle-Left	**0.07 *** (0.06 – 0.08)**	**<0.001**
Scale factor 4 X Ankle-Right	**0.06 *** (0.05 – 0.07)**	**<0.001**
Scale factor 8 X Ankle-Right	**0.08 *** (0.06 – 0.09)**	**<0.001**
Scale factor 13 X Ankle-Right	**0.05 *** (0.03 – 0.06)**	**<0.001**
Scale factor 25 X Ankle-Right	**0.05 *** (0.04 – 0.06)**	**<0.001**
Scale factor 50 X Ankle-Right	**0.07 *** (0.05 – 0.08)**	**<0.001**
Scale factor 4 X Wrist-Left	-0.01 (-0.02 – 0.00)	0.138
Scale factor 8 X Wrist-Left	**-0.02 ** (-0.03 – -0.01)**	**0.001**
Scale factor 13 X Wrist-Left	**-0.02 *** (-0.04 – -0.01)**	**<0.001**
Scale factor 25 X Wrist-Left	**-0.02 * (-0.03 – -0.00)**	**0.022**
Scale factor 50 X Wrist-Left	-0.01 # (-0.03 – 0.00)	0.056
Scale factor 4 X Wrist-Right	-0.01 (-0.02 – 0.01)	0.336
Scale factor 8 X Wrist-Right	**-0.01 * (-0.03 – -0.00)**	**0.032**
Scale factor 13 X Wrist-Right	**-0.02 * (-0.03 – -0.00)**	**0.020**
Scale factor 25 X Wrist-Right	-0.00 (-0.02 – 0.01)	0.472
Scale factor 50 X Wrist-Right	-0.01 (-0.02 – 0.01)	0.407
Random Effects		
σ^2		2.29E-04
$\tau_{00\ ID}$		1.61E-05 $_{ID}$
ICC		0.07
N_{ID}		22
Observations		648
Marginal R^2 / Conditional R^2		0.971 / 0.973
AIC		-3181.585

* *p<0.05* ** *p<0.01* *** *p<0.001*

Beta coefficients (simple effects) of fitted model for Complexity index and mean acceleration

Fixed Effects	CI Beta (95% CI)	Acceleration Beta (95% CI)
SF Phase [Ref: Play]		
SF1	0.24 (-0.69 – 1.17)	-0.23 (-0.52 – 0.06)
R1	0.23 (-0.73 – 1.20)	**-0.31** * **(-0.61 – -0.00)**
SF2	-0.32 (-1.29 – 0.64)	-0.16 (-0.46 – 0.15)
R2	0.45 (-0.51 – 1.42)	-0.23 (-0.54 – 0.07)
Prematurity [Ref: Term]		
Preterm	**2.77** ** **(1.09 – 4.46)**	-0.40 (-1.00 – 0.21)
Sensor location [Ref: Torso]		
Wrist-Left	0.05 (-0.91 – 1.01)	**0.43** ** **(0.13 – 0.73)**
Wrist-Right	0.34 (-0.62 – 1.30)	**0.41** ** **(0.11 – 0.72)**
Ankle-Left	**-7.11** *** **(-8.07 – -6.15)**	**1.34** *** **(1.04 – 1.64)**
Ankle-Right	**-5.98** *** **(-6.94 – -5.02)**	**1.35** *** **(1.05 – 1.65)**

# *p<0.1* **p<0.05* ***p<0.01* ****p<0.001*

Fixed Effects	CI Beta (95% CI)	Acceleration Beta (95% CI)
Phase x Preterm		
SF1 x Preterm	-0.35 (-1.62 – 0.92)	0.27 (-0.13 – 0.67)
R1 x Preterm	-0.95 (-2.25 – 0.34)	**0.43** * **(0.02 – 0.84)**
SF2 x Preterm	0.04 (-1.28 – 1.35)	**0.43** * **(0.02 – 0.84)**

R2 x Preterm	-0.54 (-1.85 – 0.77)	0.41 (0.00 – 0.83)
Preterm x Sensor		
Preterm x Wrist-Left	**-1.44** * **(-2.75 – -0.13)**	-0.03 (-0.44 – 0.38)
Preterm x Wrist-Right	**-1.66** * **(-2.97 – -0.35)**	0.10 (-0.31 – 0.51)
Preterm x Ankle-Left	**1.32** * **(0.03 – 2.62)**	**-0.52** * **(-0.93 – -0.12)**
Preterm x Ankle-Right	0.39 (-0.90 – 1.68)	**-0.64** ** **(-1.04 – -0.23)**

# *p<0.1* * *p<0.05* ** *p<0.01* *** *p<0.001*

Random Effects (Var)	CI	Acceleration
σ^2	5.63	0.56
τ_{00}	1.94	0.31
ICC	0.26	0.36
N	22	22
Observations	515	515
Marginal R^2 / Conditional R^2	0.551 / 0.666	0.198 / 0.488

Beta coefficients (simple effects) of fitted model for Complexity index at five frequency bands

Fixed effects

Fixed Effects	CI Gamma Beta (95% CI)	CI Beta Beta (95% CI)	CI Alpha Beta (95% CI)	CI Delta Beta (95% CI)	CI Theta Beta (95% CI)
SF Phase [Ref: Play]					
SF1	**-0.18** ** **(-0.29 – -0.06)**	**-0.09** ** **(-0.14 – -0.03)**	**-0.06** * **(-0.12 – 0.00)**	0.57 (-0.11 – 1.24)	-0.01 (-0.25 – 0.23)
R1	**-0.15** * **(-0.28 – -0.03)**	-0.04 (-0.10 – 0.01)	0.05 (-0.01 – 0.12)	0.31 (-0.39 – 1.01)	0.07 (-0.18 – 0.32)
SF2	**-0.25** ** **(-0.37 – -0.13)**	**-0.10** ** **(-0.16 – -0.05)**	-0.04 (-0.11 – 0.02)	0.21 (-0.49 – 0.92)	-0.14 (-0.39 – 0.10)
R2	-0.11 # (-0.23 – 0.01)	-0.05 # (-0.10 – 0.01)	0.02 (-0.04 – 0.09)	0.66 # (-0.04 – 1.36)	-0.07 (-0.31 – 0.18)
Prematurity [Ref: Term]					
Preterm	0.09 (-0.12 – 0.31)	0.04 (-0.06 – 0.13)	0.01 (-0.09 – 0.11)	**2.25** ** **(0.97 – 3.53)**	**0.38** * **(0.01 – 0.76)**
Sensor location [Ref: Torso]					
Wrist-Left	0.02 (-0.10 – 0.14)	-0.04 (-0.10 – 0.01)	**-0.22** *** **(-0.28 – -0.15)**	0.57 (-0.13 – 1.27)	**-0.29** * **(-0.53 – -0.04)**
Wrist-Right	-0.06 (-0.18 – 0.06)	-0.03 (-0.09 – 0.02)	**-0.19** *** **(-0.25 – -0.12)**	**0.75** * **(0.05 – 1.44)**	-0.12 (-0.36 – 0.13)
Ankle-Left	**-1.15** *** **(-1.27 – -1.03)**	**-0.20** *** **(-0.26 – -0.15)**	**-0.25** *** **(-0.32 – -0.19)**	**-3.10** *** **(-3.80 – -2.41)**	**-2.40** *** **(-2.64 – -2.15)**
Ankle-Right	**-0.98** *** **(-1.10 – -0.86)**	**-0.09** ** **(-0.15 – -0.04)**	**-0.32** *** **(-0.39 – -0.26)**	**-2.41** *** **(-3.11 – -1.72)**	**-2.18** *** **(-2.42 – -1.93)**

# *p<0.1* * *p<0.05* ** *p<0.01* *** *p<0.001*

Fixed effects (interaction effects)

Fixed Effects	CI Gamma Beta (95% CI)	CI Beta Beta (95% CI)	CI Alpha Beta (95% CI)	CI Delta Beta (95% CI)	CI Theta Beta (95% CI)
Phase x Preterm					
SF1 x Preterm	0.15 (-0.01 – 0.31)	0.03 (-0.04 – 0.10)	0.00 (-0.09 – 0.09)	-0.55 (-1.47 – 0.37)	0.02 (-0.30 – 0.34)
R1 x Preterm	0.13 (-0.03 – 0.30)	0.05 (-0.02 – 0.13)	-0.08 (-0.16 – 0.01)	-0.82 (-1.76 – 0.12)	-0.24 (-0.57 – 0.09)
SF2 x Preterm	**0.17** * **(0.00 – 0.33)**	0.06 (-0.01 – 0.14)	0.01 (-0.08 – 0.10)	-0.31 (-1.26 – 0.64)	0.11 (-0.23 – 0.44)
R2 x Preterm	0.09 (-0.07 – 0.26)	0.03 (-0.05 – 0.10)	-0.05 (-0.14 – 0.04)	-0.56 (-1.51 – 0.39)	-0.05 (-0.39 – 0.28)
Preterm x Sensor					
Preterm x Wrist-Left	-0.04 (-0.20 – 0.13)	-0.03 (-0.10 – 0.05)	0.01 (-0.08 – 0.10)	**-1.21** * **(-2.16 – -0.26)**	-0.19 (-0.52 – 0.15)
Preterm x Wrist-Right	-0.03 (-0.19 – 0.14)	-0.06 # (-0.14 – 0.01)	0.03 (-0.06 – 0.12)	**-1.34** ** **(-2.29 – -0.39)**	-0.26 (-0.59 – 0.08)
Preterm x Ankle-Left	**0.26** * **(0.10 – 0.42)**	**0.12** ** **(0.05 – 0.19)**	-0.09 # (-0.18 – 0.00)	0.66 (-0.27 – 1.60)	**0.37** * **(0.04 – 0.70)**
Preterm x Ankle-Right	0.06 (-0.10 – 0.22)	-0.02 (-0.09 – 0.05)	0.05 (-0.04 – 0.14)	0.06 (-0.88 – 0.99)	0.24 (-0.09 – 0.57)

# *p<0.1* * *p<0.05* ** *p<0.01* *** *p<0.001*

Random effects

	CI Gamma	CI Beta	CI Alpha	CI Delta	CI Theta
Random Effects (Var)					
σ^2	0.09	0.02	0.03	2.97	0.37
τ_{00}	0.03 $_{ID}$	0.01 $_{ID}$	0.01 $_{ID}$	1.23 $_{ID}$	0.06 $_{ID}$
ICC	0.28	0.27	0.18	0.29	0.14
N	22	22	22	22	22
Observations	515	515	515	515	515
Marginal R^2 / Conditional R^2	0.664 / 0.759	0.179 / 0.397	0.300 / 0.425	0.351 / 0.542	0.689 / 0.733