Ageing and Communication: Understanding the roles of cognition, speech production and social participation

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Declaration

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Abstract

Typical ageing is accompanied by changes in cognitive and motor speech functioning. However, the relationship between these domains is underexplored, as is the extent to which they predict social participation, a lifestyle factor protective of brain health.

Using a survey, Study 1 investigated longitudinal relationships between subjective cognition and speech execution. Older adults ($N = 204$, $M = 70.58$, $SD = 6.65$) self-reported on cognitive abilities, speech execution and sociodemographic variables at two timepoints, 12 months apart. Attention/concentration, and language significantly predicted speech execution at baseline. Visual-perceptual ability at T1 predicted speech execution at T2, and speech execution at T1 predicted language at T2. Self-reported speech difficulty may provide an early marker of cognitive change in the absence of objective cognitive impairment.

Study 2 investigated relationships between fluid/crystallised cognition and speech execution subsystems (articulation and phonation). Older adults ($N = 87$, $M = 71.48$, $SD = 6.71$) completed the NIH toolbox cognition and sensation domains, two maximum performance tasks assessing articulation and phonation, two connected speech tasks, and self-reported sociodemographic and wellbeing measures. Fluid and crystallised cognition predicted articulation during a diadochokinetic (DDK) but not during connected speech, suggesting that everyday communication is relatively spared.

Study 3 investigated whether fluid cognition, crystallised cognition, and/or articulation predicted social participation, using Study 2 data. Participants self-reported their activity engagement, social network size and levels of communicative participation. There were no significant relationships amongst core predictors and social participation. Self-reported speech difficulty, a covariate, significantly predicted reduced communicative participation. Perceptions of speech may be a better indicator of communicative participation than objective measures.

Future research should consider whether self-reported cognition predicts social participation. The development of self-report questionnaires measuring speech in typical ageing is also a priority.

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1. Ageing, cognition and speech production

1.1 Chapter overview

This chapter is the first of two literature review chapters, in which the broad sociopolitical context for studying healthy ageing is introduced. Global demographic shifts in population ageing and the World Health Organisation's (WHO; 2020) Decade of Healthy Ageing 2021-30 are discussed, as both inform the rationale for this work. This is followed by introducing the first of our core variables for the present work, cognition. This is discussed in relation to theories of cognitive ageing, including the distinction between fluid and crystallised cognition (Horn & Cattell, 1966), and the common cause hypothesis (Baltes & Lindenberger, 1997). The second core variable, speech production, is then introduced and discussed in relation to models of speech production (e.g. Guenther & Hickok, 2015; Tourville & Guenther, 2011; Weerathunge et al., 2022). The chapter closes by discussing the limitations of existing evidence investigating relationships between cognition and speech production in typical ageing and how the current programme of research aims to address these issues.

1.2 Population Ageing

The world's population is ageing rapidly. It is predicted that, by 2050, people aged over 60 will outnumber children and young adults. Persons in the 'oldest-old' category, aged over 80, are expected to reach 434 million, tripling from 125 million in 2015 (United Nations, 2015). The immediate cause of the disproportionately large

population of over 65s is lower fertility rates coupled with increased life expectancy (Aitken, 2022; Christensen et al., 2009; Storey, 2018). However, there is an apparent paradox. While population ageing reflects societal progress, bringing with it a generation of healthier, more active older people, able to contribute to society for much longer (Healy & Healy, 2004), longevity is also associated with a number of physical health conditions including arthritis, hypertension, heart disease, obesity, diabetes and cancer (Christensen et al., 2009; Fried, 2000) with multimorbidity affecting over half of the older adult population (Marengoni et al., 2011). The prevalence of frailty and falls is also common in older age (Fried, 2000), as is cognitive impairment, with Alzheimer' Disease continuing to be the fifth leading cause of death in those aged over 65 in the United States (Alzheimer's Association, 2022). In the UK, there is estimated to be approximately 885, 000 people currently living with dementia, costing the government £34.7 billion (Wittenberg et al., 2019). This suggests that, despite the population living longer, a proportion of older adults are not necessarily ageing better (Kirkwood, 2017). Importantly, there is considerable variability in how people age, with individual ageing trajectories determined by the accumulation of risk and protective factors throughout the life course (Section 2.0). This includes genetic predisposition and environmental influences, especially socioeconomic status (McMaughan et al., 2020) and their interaction (Migliore & Coppedè, 2022). Evidence-based public health initiatives are required to better understand how all older adults can live longer, healthier and more fulfilling lives.

To tackle the increase in age-related health challenges brought about by population ageing, the United Nations (UN; 2015) declared the Decade of Healthy Ageing (2021 – 2030; Keating, 2022). This is a collaborative effort across all sectors

with the aim of fostering healthy ageing so that all older adults can maximise their potential, enjoy the latter stages of their lives and continue contributing to society. Individuals are, however, multifaceted and gaining an understanding of one's functioning requires a holistic assessment of the individual. The World Health Organisation (WHO, 2022) proposes that understanding the overall functional ability of an older adult requires assessment of physical health, levels of functioning and the ability to participate in daily activities.

1.3 Healthy Ageing

The World Report on Aging and Health, and the more recently published report on the Decade of Healthy Ageing (WHO, 2020, p. 15) define healthy ageing as "the process of developing and maintaining the functional ability that enables well-being in older age". Functional ability is described as an overarching concept, consisting of intrinsic capacity, and the environment. This framework progresses previous guidance from International Classification of Functioning, Disability and Health (ICF; https://www.asha.org/slp/icf/) by recognising that health should not be classified simply as the absence of disease. As the current research focuses on healthy ageing, application of the 'functional ability' framework is more appropriate than the International Classification of Functioning, Disability and Health (ICF; WHO, 2002), which focuses on the absence of disease and is often used in clinical practice (https://www.asha.org/slp/icf/) and research (e.g. Cerniauskaite et al., 2011; Pichora-Fuller, 2015).

Functional ability determines how well individuals engage with the things that they value. It allows people to meet their own basic needs and facilitates relationships and quality of life (WHO, 2022). Functional ability relies on intrinsic

capacity, which is the sum of a person's mental and physical abilities, including sensory functioning, vitality, cognition, and psychological capacity (Cesari et al., 2018). Environments also influence functional ability and include all extrinsic factors that shape what a person can do with their intrinsic capacity. Environments include a person's home, their community and/or society (WHO, 2015). Contrary to the ICF (2001) where a reactive approach to identification and diagnosis was adopted, the concepts of functional ability, intrinsic capacity and environments champion a preventative approach and suggest inherent wellness even if there are risk factors (Cesari et al., 2018). While these concepts have been developed to tackle population-level social issues such as ageism, the improvement of care facilities, and finding purpose in older age (WHO, 2021), the concept of functional ability is a useful theoretical framework for guiding empirical research into healthy ageing, which can in turn potentially inform policy.

Given that one goal of the Decade of Healthy Ageing is to foster healthy ageing by preventing or slowing down decline, this thesis aims to develop knowledge in this area by providing evidence to help achieve this aim. The programme of research presented in this thesis can be applied to the concept of functional ability. Firstly, the focus on cognition (Section 1.4) and motor speech production (Section 1.5) represents aspects of older adults' intrinsic capacity. The impact of these intrinsic capacities on older adults' everyday social engagement (Section 2.5) is also explored, reflecting functional ability. Moreover, across this programme of research, older adults' environment is considered by collecting demographic information such as socioeconomic status, living situation and occupation, while theoretically relevant confounding factors, such as years of education, and independence in daily living are

statistically controlled. In addition to developing scientific understanding of ageing, cognition and speech production, the evidence obtained from this programme of research may also be useful in policy decisions related to the Decade of Healthy Ageing.

1.4 Cognitive Ageing

Cognition or 'thinking skills' develop across the lifespan, generally following the pattern of an inverted u-shaped curve (Li et al., 2024). Cognitive development in infancy reflects maturation of brain processes such as growth of grey matter density, myelination, and white matter volume (Craik & Bialystok, 2006). While cognition develops globally throughout infancy and childhood, the development of specific brain regions follows a heterogenous pattern with prefrontal and lateral temporal areas developing last. These areas are associated with more sophisticated cognitive abilities such as control of thoughts and action (Casey et al., 2005). In older age, the trajectory of cognitive change is gradual global decline (Li et al., 2024). However, there is an asymmetrical pattern to this change, with some cognitive abilities being more susceptible to gradual declines, while others remain relatively stable and in some cases can even continue to show improvement (Salthouse, 2019; see Section 1.4.1 for detailed description). This asymmetric pattern is due to degradation of the structure and functioning of some brain areas more than others. For example, frontal areas, particularly the prefrontal cortex, shows the greatest decrease in volume relative to other areas such as the hippocampus and medial temporal lobes (Hedden & Gabrieli, 2004). This shows that typical age-related cognitive decline is a dynamic and multidirectional process (Loaiza, 2024). Understanding variability in the

typically ageing brain is important for distinguishing between normal ageing and pathological cognitive decline.

Alzheimer's Disease (AD) is the most commonly diagnosed type of dementia (Allwright et al., 2023) and is a progressive neurodegenerative disorder associated with increasing age, most commonly affecting older adults (Kamatham et al., 2024). It is characterised by memory impairment, communication difficulties and mood changes, leading to more widespread cognitive decline that eventually interferes with daily living (Kamatham et al., 2024). AD is typically identifiable only when the symptoms appear, and treatment is limited to managing these symptoms by using medication and/or therapies to adjust the environment. Pathological changes, such as atrophy in the entorhinal cortex and hippocampus, are believed to begin a decade or more before clinical diagnosis (Hedden & Gabrieli, 2004; Nelson et al., 2009) of AD or other dementias. As a result, the early stages of pathological decline can often go unnoticed, limiting the potential for preventative treatments to be optimised including modifiable lifestyle factors such as social participation (Livingston, 2024; see section 2.2.1). As mentioned, healthy ageing is also associated with gradual decline to some cognitive domains (section 1.3.1) and speech production (section 1.4) meaning it may be challenging, at times, to distinguish between symptoms that reflect typical versus pathological brain changes (Singh-Manoux & Kivimäki, 2010). As such, it is essential to continue research in healthy ageing to identify reliable markers of typical cognitive ageing to improve early detection of pathological decline and to contribute to preventing or delaying the onset of dementia.

1.4.1 Patterns of stability, growth, and decline

Typical cognitive ageing is associated with gradual declines to 'fluid' cognitive abilities as well as stability and growth to 'crystallised' cognitive abilities (Horn & Cattell, 1966; Figure 1). Fluid cognition encompasses skills such as reasoning, memory, spatial orientation, and perceptual speed, allowing individuals to generate, transform and manipulate information (Salthouse, 2019). These abilities are typically assessed through behavioural performance on tasks that measure speed, accuracy, or coordination of mental processing (Baltes et al., 1998). Fluid abilities generally begin to decline from around the third decade of life, with a steeper decline towards the 6th and 7th decades (Salthouse, 2012; Schaie, 2005) when cognitive difficulties may become more noticeable in everyday tasks (Logie & Maylor, 2009). These declines are associated with degradation of anatomical, chemical, and functional brain changes (Cabeza, 2002; Cabeza et al., 2018). However, the rate and extent of decline varies depending on the specific cognitive ability (Jenkins et al., 2000; Figure 1).

Figure 1

Cross-sectional ageing data
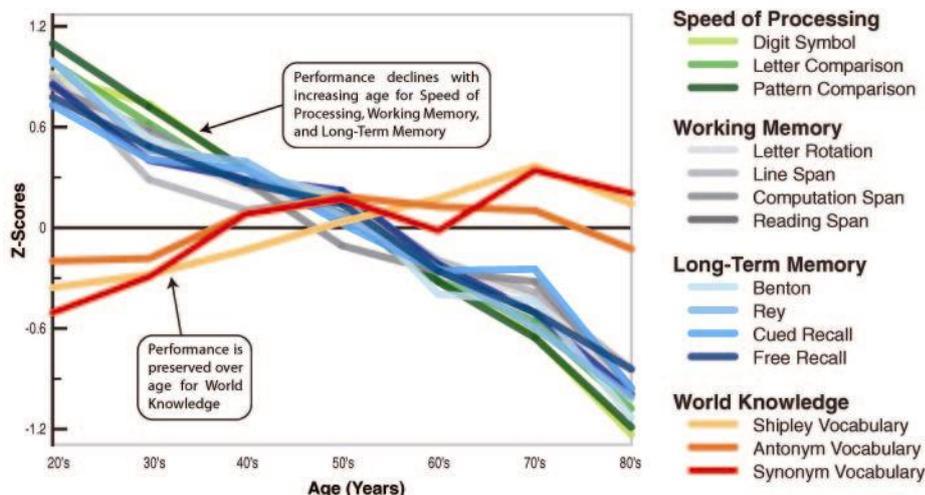
Park DC, Reuter-Lorenz P. 2009.
Annu. Rev. Psychol. 60:173–96

Note: Figure reproduced from Park & Reuter-Lorenz (2009) with permission from Copyright Clearance Centre Inc

On the other hand, crystallised abilities are learned skills, such as verbal or numerical knowledge, which are accumulated through learning and experience (Cianciolo et al., 2004; Cianciolo & Sternberg, 2004) and may contribute to maintenance of reading and writing skills, academic and professional qualifications, and self-knowledge (Baltes et al., 2006). Contrary to fluid abilities, crystallised abilities tend to remain stable or even show continued improvement across the lifespan, often only slightly declining in very late life (Salthouse, 2010) and may serve as a compensatory function in the face of declining fluid abilities. This may be because brain areas associated with crystallised abilities, such as vocabulary, are less vulnerable to healthy age-related decline due to continuous use and growth across the lifespan (Park & Reuter-Lorenz, 2009).

These multidirectional patterns of growth, stability, and decline (Loaiza, 2024) are highly replicated in cross-sectional and longitudinal research (Salthouse, 2019; Schaie, 2005; Schaie & Willis, 1993; Singer et al., 2003), suggesting that ageing trends are generally consistent at the population level, despite individual differences in rates of decline (Ghisletta et al., 2012). However, evidence also suggests there is an association between the rate of change in fluid and crystallised abilities. Over two longitudinal studies, Tuker-Drob et al. (2022) found that those who showed greater losses in fluid cognition showed smaller gains in crystallised abilities, while those with minimal declines in fluid abilities showed the greatest gains in crystallised abilities. This suggests that fluid and crystallised abilities may not be entirely independent of one another. Considering both fluid and crystallised cognition contributes to understanding how each set of processes perform in older age, and how they might differently influence performance in other tasks or real-world outcomes.

1.4.2 Cognitive and sensory decline: one common factor

As well as cognitive change, older age is associated with sensory losses, particularly to hearing and vision (Cruickshanks et al., 1998; Houde & Huff, 2003; Lin, 2012; Tam & Koppel, 2021), which can significantly impact older people's lives in terms of communication difficulties, social isolation and reduced quality of life (Hill et al., 2017). Changes to cognitive and sensory functioning may not be separate health concerns as research shows that there are strong links between these two domains (Baltes & Lindenberger, 1997; Dawes et al., 2015; Maharani et al., 2020). For example, older adults with visual and hearing impairments are at greater risk of

developing dementia (Dawes et al., 2015; Pichora-Fuller, 2015; Wayne & Johnsrude, 2015). In healthy ageing, visual and auditory ability accounts for a larger proportion of the variance in fluid cognitive abilities in older than in younger adults (Baltes and Lindenberger, 1997), indicating that cognitive and sensory domains become more interrelated with increasing age. A similar pattern of relationships have been shown between cognitive (e.g., memory) and sensorimotor abilities such as walking (e.g., Li et al., 2001) and grip strength (Christensen et al., 2001). These, and subsequent authors, have reviewed evidence on the interdependence of sensory/sensorimotor and cognitive abilities in ageing, concluding that one common factor explains the increasing interdependence between cognitive and sensory/sensorimotor abilities (Li et al., 2001; Lindenberger et al., 2000; Wayne & Johnsrude, 2015).

While the common cause hypothesis (Baltes et al., 1999; Baltes & Lindenberger, 1997) has been influential in explaining that covariation across declining functions is the result of the same global ageing factor, the exact common factor remains speculative. For example, volumetric data shows age-related cortical thinning in frontal and occipital brain regions (Salat et al., 2004) possibly acting as the neurobiological link between visual and cognitive declines (Park & Reuter-Lorenz, 2009). Neural degeneration in the prefrontal cortex (Cabeza et al., 2018) has also been described as the 'seat' of the common cause (Hirst et al., 2022) as it is responsible for multisensory integration and executive 'fluid' abilities (Knight et al., 1999). Given the complex pattern of cognitive changes with age, it is unlikely any one mechanism can explain cognitive and sensory deficits in all individuals. Park and Reuter-Lorenz (2009) stated that it is the combined influence of cognitive decline and compensatory mechanisms that predict behavioural performance. As such, it is

necessary to consider additional theoretical models to more comprehensively understand the interplay between sensory, sensorimotor and cognitive changes in ageing (note, Section 2.2 introduces relevant compensation models).

1.5 The ageing of speech production

As mentioned in section 1.4.2, the common cause hypothesis has been applied to a variety of sensory and sensorimotor abilities in ageing including vision, hearing, walking and grip strength (Baltes and Lindenberger, 1997; Christensen et al., 2001; Li et al., 2001; Wayne & Johnsrude, 2015). Motor speech production is an additional sensorimotor process (Behroozmand et al., 2015; Miller & Guenther, 2021; Tourville & Guenther, 2011; Tremblay et al., 2015, 2018, 2019; Weerathunge, et al., 2022) that shows age-related changes (section 1.6). However, thus far, there is very little research investigating the relationship between cognition and motor speech production in ageing.

The following sections provide an overview of theoretical models of speech production, including relevant psycholinguistic models and computational models of speech motor control.

1.5.1 Speech production models

Successful speech production begins with the intention to communicate a message and ends in articulation (Tremblay et al., 2019a). Therefore, speech production can be viewed from a cognitive and a motor perspective resulting in different but complementary models (Ivanova et al., 2023). Although there are several models of speech production, few offer a higher-level perspective on the

overarching process of speech production, which involves linguistic processing, speech motor planning or programming, response selection, sequencing, timing, execution and sensorimotor integration (Tremblay et al., 2019a). Given this complexity, models of speech production either focus on language production (i.e. involving linguistic processing; section 1.5.2) or motor speech production (section 1.5.3).

One model that offers a simple visual representation is that of Parrell et al. (2019), who conceptualise speech production as a multistage process in a four-tiered hierarchical model (Figure 2). According to this model, speech production begins with higher-level linguistic processes, including the semantic, syntactic, prosodic, and phonological properties of speech (i.e. language production). The next layer is the 'planner', referring to speech motor planning, which deals with the sequencing of motor programmes. This is followed by the 'controller' layer which bridges the gap between the planner and the plan. Finally, the plant is the layer that deals with speech execution and includes articulation. The term 'speech production' is an umbrella term that can be used to describe any of these subprocesses. While the current research primarily focuses on the final stage of the model, the 'plant', representing motor speech execution, it is essential to discuss higher-level linguistic processing as much research has focused on ageing effects in this domain.

Figure 2

Levels of speech production
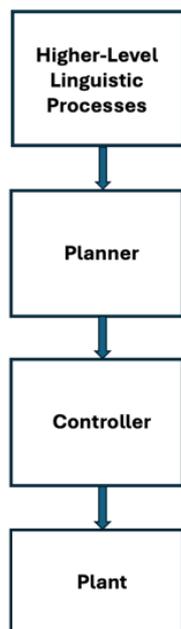
Note: Model recreated based on Parrell et al. (2019).

1.5.2 Language production

      Levelt et al.'s (1999) influential psycholinguistic model outlines the process of single-word production from early lexical selection to articulatory output. According to this model, words are formulated through a feedforward process involving conceptual preparation, lexical selection and morphological and phonological encoding. While the model is successful in explaining the stages of word production, it is limited in its application to connected speech and provides minimal explanation of the articulatory mechanisms involved in speech motor control (Miller & Guenther, 2021). Although articulation is acknowledged in the model as the final stage of speech production, it is not specified in detail. Indeed,

Levelt et al. (1999) stated that a thorough exploration of the articulatory process is beyond the scope of the theory, recognising the complexity of motor speech processes. Linguistic processing is typically aligned with cognitive processing as both reside in the mental system, whereas motor speech processes are neuromuscular in nature (Redford, 2015). As a result, ageing research has focused primarily on the cognitive processes underlying language production (Arbuckle & Gold, 1993; Kemper et al., 2009; Kemper & Herman, 2006; Shafto et al., 2007; Wright, 2016).

Empirical investigation into the linguistic stages of speech production has relied on speech errors, such as word finding failures and phonological substitutions (e.g. a sound error that deviates from the speaker's intention such as "fleaky squoor" instead of "squeaky floor"; Meyer, 1992). One of the most researched examples is the tip-of-the-tongue (TOT) phenomenon, first described by James (1890; in Burke et al., 1991), which refers to the temporary inability to retrieve and produce a known word (Shafto et al., 2007). Experimental inductions of TOT states in young adults, prompted by providing definitions of infrequent words, show that retrieval of certain characteristics are more likely to result in eventual success, for example, the beginning or end of a word (Brown & McNeill, 1966). TOTs provide a window into the language production system because they represent an issue with phonological retrieval when semantic and lexical information is intact (Kohn et al., 1987), consistent with hierarchical models of word production (e.g. Levelt et al., 1999) in which phonological encoding is a discrete stage that follows semantic retrieval. TOTs occur when semantic and lexical information has been encoded but phonological access is impaired, or slower, resulting in a feeling of 'knowing' alongside the inability to produce the correct word (Shafto et al., 2007). Importantly, TOTs become

more frequent with typical ageing (Burke & Shafto, 2004a; Lovelace & Twohig, 1990), and are one way in which older adults experience and perceive changes in communicative abilities (Lovelace & Twohig, 1990).

1.5.3 Theories of speech motor control

Research also shows that there are age-related differences in speech motor control (section 1.4.4). Declines in sensory functioning (Section 1.4.2) may be partly responsible for increased difficulty with the execution of speech with age (Goozée et al., 2005). The Direction into Velocities of Articulators (DIVA) model (Guenther & Hickok, 2015; Tourville & Guenther, 2011) is a computational model that accounts for the neural control of articulatory movements during the production of single speech utterances. Crucially, the model highlights the reliance on sensory information, particularly auditory and somatosensory processes, to guide feedforward and feedback commands.

The role of auditory information can be demonstrated in natural environments, where speakers increase loudness to overcome auditory feedback being masked by noise in the environment (Stathopoulos et al., 2014). Experimental manipulations also demonstrate that delaying auditory feedback disrupts speech fluency, and speakers rapidly adjust their pitch in response to unexpected vocal perturbations (Guo et al., 2017; Liu et al., 2018; Yates, 1963). Auditory input also supports feedforward control, whereby learned auditory programs are used to produce subsequent speech. This, for instance, helps post-lingually deafened speakers retain intelligible speech despite rapid declines to the control of pitch and loudness (Lane et al., 1997).

Somatosensory information is similarly used to guide articulatory speech movements. Golfinopoulos et al. (2011) found that perturbing somatosensory feedback using a balloon protrusion in the mouth resulted in activation of brain regions not typically recruited during unimpeded speech. This suggests that stored somatosensory information is used in feedforward control of speech, when somatosensory feedback is not available. This demonstrates that physical alterations to the vocal tract, such as dental or orthodontic changes, can disrupt the speech motor system until it has learned the new starting point of the articulators (Postma et al., 2000). Given the central role of sensory information in the execution of speech motor control, age-related declines in sensory functioning may contribute to difficulties in speech execution. In addition, cognitive functioning may also be associated with motor speech execution, due to the established links between cognition and sensory functioning (section 1.4.2). However, other than acknowledging that speech motor control is preceded by linguistic input, DIVA does not define the role of other cognitive processes in speech motor control.

An additional limitation of DIVA is that it does not distinguish between clinically defined speech subsystems. In the clinical management of motor speech disorders, speech execution relies on the physiological processes of respiration, phonation, articulation and resonance (Lee et al., 2014; Rong et al., 2015a). Respiration refers to breath support for speech while phonation is the process of generating voice through vocal fold vibration. The resulting sound wave comprises a range of properties including pitch, loudness and voice quality. Resonance involves the sound made from producing oral or nasal air flow and articulation involves moving the tongue, lips and jaw to produce speech sounds (Yorkston et al., 2010).

Phonation and respiration are closely linked and often considered together, as air flow is required for vocal fold vibration (Dedry et al., 2022).

The Laryngeal Directions into Velocities of Articulators (LaDIVA) is an extension of the DIVA model, which begins to decouple the laryngeal (phonation) and articulatory subsystems (Weerathunge, et al., 2022a). In their study, Weerathunge et al. (2022b) applied auditory and physical perturbations to 20 young adult speakers' sustained phonation of the vowel /a/ to assess how the laryngeal and articulatory subsystems respond to altered feedback. Physical perturbations were applied to the jaw and larynx to inhibit somatosensory feedback. Auditory feedback was perturbed to assess the laryngeal subsystem by shifting the fundamental frequency, and the first formant to assess the articulatory subsystem. There were no significant relationships observed between responses to auditory and somatosensory feedback, nor was there a relationship between auditory-motor features (i.e. responses to auditory perturbations of F0 and F1) in the laryngeal and articulatory subsystems. This suggests that pitch and articulatory feedback may be controlled separately and that these subsystems rely on partially distinct neural mechanisms.

While both DIVA and LaDIVA demonstrate the crucial role of sensory processing in speech motor control, they are based on data from typical young adult speakers. Therefore, their applicability to older adults who are likely to experience sensory and cognitive changes, is unclear. Nevertheless, both theories provide a framework for understanding the neural basis of speech motor control. Decoupling of the laryngeal and articulatory subsystems is particularly relevant for this programme of research which focuses specifically on the subsystems of phonation and articulation. This raises the possibility that ageing may affect these two subsystems

differently. Indeed, evidence shows that there are differences in the speech execution of older adults compared to younger adults (section 1.4.4), highlighting the need to consider age as a factor in models of speech motor control.

1.5.4 Age related changes to speech execution

Older adults can be differentiated from younger adults based on respiratory (Huber & Darling-White, 2017), phonatory (Rojas et al., 2020) and articulatory measures (Ben-David & Icht, 2018; Kuruvilla-Dugdale et al., 2020; Tucker et al., 2021). The subsystems of respiration and phonation have been investigated most extensively in relation to ageing (Kuruvilla-Dugdale et al., 2020) and represent the most noticeable age-related changes, relative to articulation or language production (Caruso & Mueller, 1997).

Pitch, loudness and vocal effort are the most commonly reported differences (Rojas et al., 2020). For example, speaking fundamental frequency (F0), which is perceived as pitch, generally lowers with age (Awan, 2006; Hollien & Shipp, 1972). However, there is disagreement with regards to the degree of change in F0 and how this differs in males and females. For example, Goy et al. (2013) reported in their normative data sample of younger and older adults that F0 was lower in older females than in younger females. However, there were no differences in F0 between young or older males. Other research shows small gradual decreases in F0 for males from age 20 with a rise in level from age 60 (Hollien & Shipp) or 70 (Nishio & Niimi, 2008). These changes to vocal quality are caused by structural and physiological changes in the speech system including reduced muscular control in the larynx, vocal fold atrophy and vocal fold bowing (Caruso & Mueller, 1997; Rojas

et al., 2020). This physiological degeneration also affects lung pressure and volume

(Zraick et al., 2006), which impacts breath support for phonation. Maximum

phonation time is a clinical measurement of breath support for phonation (section

3.4.2). A limited number of studies have assessed maximum phonation time in older

adults, and the findings are mixed. Some evidence suggests considerably lower

normative values in older adults than in younger adults, while some researchers

report no effects of age (Kent et al., 1987; Maslan et al., 2011). For instance, Goy et

al. (2013) reported, surprisingly, that older females produced significantly longer

maximum phonation times ($M = 18.9$ s, $SD = 7.3$ s) than younger females ($M = 15.1$

s, $SD = 4.4$s) when producing an /a/ sound for as long as possible. There was no

significant difference between older ($M = 18.6$ s, $SD = 8.0$) and younger males ($M =$

20.2 s, $SD = 8.1$s), which contradicts other perceptual evaluations showing that older

adults have poorer voice quality (e.g. higher dysphonia and roughness, breathiness,

strain and instability) than younger adults (Meyerson, 1976; Rojas et al., 2020).

Although the authors make no attempt to explain the counterintuitive findings, it is

noted that 8.3% of the younger adults in Goy et al. reported having chronic

bronchitis, relative to none of the older adults, which could explain why the older

females outperformed younger. This shows that there is a need for more normative

data on older adults' phonation. In addition, it is important to collect additional

information about the sample, such as smoking status, medication, history of chronic

respiratory disorders and use of dentures.

The articulatory subsystem also undergoes age-related changes. Older adults

produce slower speech and articulation rates than younger adults and fewer

accurate/stable articulatory movements in syllable and sentence repetition and

connected speech tasks (Ben-David & Icht, 2018; Bilodeau-Mercure & Tremblay, 2016; Duchin & Mysak, 1987; Goozée et al., 2005; MacPherson, 2019, Sadagopan & Smith, 2013; Smith et al., 1987). A large-scale review by Kent et al. (2022) looking into syllable repetition rates across the lifespan revealed decreasing rate with advancing age, particularly when the repetitions are trisyllabic (e.g. /pataka/). However, unlike phonation, the reasons underlying the age-related decline in articulation are unclear. Several studies have found that physiological factors including tongue weakness do not explain reduced articulation rates in healthy older adults (Goozée et al., 2005; Kuruvilla-Dugdale et al., 2020; Mefferd & Corder, 2014; Neel & Palmer, 2012). For instance, Neel and Palmer (2012) found no significant correlation between maximum tongue pressure and articulation rate in reading passages. This suggests that physiological degeneration may play only a small role in articulation rates, at best. It has been suggested that older adults adopt a slower speaking rate as a compensatory strategy to account for neuromuscular changes, hence, introducing a role for cognition (Goozée et al., 2005; Mefferd & Corder, 2014; Neel & Palmer, 2012). Despite this suggestion, limited research has investigated the relationship between cognitive decline and speech execution in typically ageing older adults. To test the theory posited in LaDIVA (Weerathunge et al., 2022a), that phonation and articulation rely on partially distinct neural mechanisms, both subsystems are examined in this thesis. It is predicted that phonation, being driven primarily by physiological processes, will show little or no association with cognition, whereas articulation will be related to cognitive performance (section 5.2.6).

1.6 The relationship between cognition and motor speech production in other populations

While research in healthy ageing is limited (although see Section 1.6), there is evidence of a relationship between cognition and motor speech execution in other populations. For example, in infants, cognitive development appears to aid the development of articulatory control. In a longitudinal study of children aged 9 to 21 months, Nip et al. (2011) measured articulatory kinematic characteristics, language and cognitive development. Orofacial behaviours were captured for the upper and lower lip and jaw movements using motion capture. It was found that cognitive ability, specifically attention and memory, and language test scores were positively associated with orofacial movement speed over the course of a year. The authors suggest that the development of the phonological loop in working memory (Gathercole & Baddeley, 1990) may facilitate faster speech motor planning and articulatory execution.

Research in typical young adult speakers has used dual-task paradigms to examine the effect of dividing attention on speech motor control (Dromey & Bates, 2005; Dromey & Benson, 2003). For example, Dromey and Bates (2005) investigated how performance on different secondary tasks - linguistic, cognitive and visuomotor -interacted with speech production. It was found that intensity and speech kinematics decreased under dual-task conditions, depending on the type of concurrent task. Lower lip and jaw displacement significantly decreased when the secondary task was a visuomotor task. Articulatory variability (spatiotemporal index) significantly increased only during the linguistic task. Loudness (sound pressure level) significantly increased across all dual-task conditions (linguistic, cognitive and

visuo-motor). These findings show that increased cognitive complexity during dual-tasking affects speech motor control, even in young adults. In addition, the findings suggest that certain tasks interfere differently with speech motor control, resulting in qualitatively different motor speech outcomes. The authors suggest that different attentional resources are required for linguistic versus manual motor tasks, and that there may be shared or overlapping neural substrates involved in both speech and language.

More recently, Whitfield et al. (2021) identified potential strategies that can mitigate cognitive interference by investigating varying speaking conditions. Young adult participants were asked to repeat a sentence while performing a digital tracking task, using the mouse to follow a moving target around a circular path. The dual-task paradigm was performed under three speaking conditions in which participants were asked to speak in their habitual speaking style, to speak loudly and to overenunciate (clear speaking condition). In the habitual speaking condition, it was found that kinematic characteristics (lip aperture and range velocity) and loudness were compromised under dual-task conditions, while tracking performance was preserved. In the loud and clear speaking conditions, no significant speech changes were observed from single to dual-task conditions, but there were losses in tracking accuracy. The authors conclude that a more effortful style of speech reduces the effect of dual-task interference because modifications to speech style demands attentional resources as it becomes less habitual. These attentional resources are subsequently diverted away from tracking, resulting in poorer performance. This shows that speech motor control contains an attentional component during habitual speech. Together, these findings highlight that there are relationships between

cognition, especially attention, and speech execution in earlier life. However, there is a gap in the literature researching healthy ageing, which limits understanding from a lifespan perspective. It may be that speech motor control in older adults is particularly vulnerable to the effects of increasing cognitive complexity due to age-related cognitive decline.

In older adult clinical populations, there is clear evidence of a relationship between cognition and motor speech execution. For example, individuals with Parkinson's disease or Multiple Sclerosis (MS), who exhibit greater cognitive impairments, particularly in attention, memory or processing speed, are more likely to have a motor speech disorder (Liu et al., 2018; Rodgers et al., 2013). Furthermore, a meta-analysis by Doneva (2020) found that individuals who stutter performed more poorly on tests of selective and divided attention compared to typical speakers. In Rodgers et al., no relationships were observed between cognition and articulation rate in healthy middle-aged adults during an expository speaking task, suggesting that the relationship between cognition and speech execution may emerge with increasing age. Furthermore, in patients with MS, when syllable repetition performance ('pataka') was included as a covariate, both cognitive composites became non-significant in predicting articulation rate. This suggests that the association between cognition and speech execution was being driven by physiological articulatory ability. Therefore, it is important to consider physiological speech functioning when examining relationships between cognition and speech execution (section 3.4.3).

1.7 A systematic review of relationships between older adult's cognitive and motor speech abilities

Based on the theoretical and empirical evidence outlined above, and considering the gap in the literature regarding clear evidence of a link between cognition and speech execution in healthy older adults, we carried out a systematic review to identify and evaluate the available evidence (Manderson et al., 2025). The review identified 22 studies that had investigated relationship between cognition and motor speech execution in healthy older adults aged over 60. Broadening the scope of the review, studies that had included patients diagnosed with Mild Cognitive Impairment (MCI) were also included, to contribute towards understanding the motor speech abilities in groups with varying cognitive profiles.

The reviewed studies varied with respect to the cognitive and motor speech characteristics that were included, and different relationships emerged depending on how cognition and speech execution were measured. The cognitive measures included global cognitive functioning, speed of processing, attention/executive functioning, working memory, long-term memory and verbal knowledge/ability. The motor speech characteristics included articulatory measures (e.g. articulation rate, speech/speaking rate, articulatory control, accuracy) and phonatory measures (e.g. pausing, fundamental frequency 'F0', intensity).

Most of the included evidence had investigated the link between attention/executive abilities and articulatory control, either experimentally using dual-task paradigms or by correlation. Mirroring the literature in young adults (Section 1.5), the correlational and experimental evidence suggested that increasing task complexity interferes with articulatory ability in older adults, particularly under

conditions demanding attentional and/or executive abilities. Another recent systematic review focusing only on the dual-task literature assessing language production reported a similar trend, showing that speech fluency in discourse was more vulnerable under dual-task conditions in older than in younger adults. Together, these reviews suggests that age effects are present in speech and language production under more challenging conditions (Salis et al., 2025). However, both reviews highlight that the overall evidence base is of poor quality.

In our review (Manderson et al., 2025), the evidence was disproportionately focused on a potential relationship between attention/executive abilities and speech execution, with few studies investigating other cognitive domains. Many included studies contained small sample sizes because healthy older adults were often selected as age-matched controls in clinical studies. Adequate power analyses were not performed, and sample sizes did not meet the requirements for the selected statistical analyses. In addition, studies failed to administer cognitive screening assessments. Therefore, it was not certain that the healthy participants adequately represented the older adult population. Finally, there was limited inclusion of relevant covariates (e.g. age, education, mood, lifestyle) in analyses that could have had influenced the findings. The methodological gaps and limitations identified in our systematic review therefore made it difficult to draw firm conclusions about the relationship between cognition and motor speech production in typical ageing. This thesis now addresses some of these limitations.

1.8 Investigating cognition and speech execution in healthy older adults

The first aim of the present research was to establish whether a relationship exists between cognition and speech execution in healthy older adults by addressing the limitations of the current evidence base, using a well-powered design, with clear inclusion/exclusion criteria and cognitive status confirmed through cognitive screening. In addition, a range of cognitive and speech tasks were used to explore associations across multiple cognitive domains, and to differentiate between phonatory and articulatory aspects of speech execution. This aim was addressed through two complementary studies: a 12-month longitudinal survey of healthy older adults (N = 204) capturing subjective reports of functioning (Study 1), and controlled laboratory-based study providing objective evidence of functioning (Study 2) using a separate sample of healthy older adults (N = 87). A third study (Study 3) which draws on the same set of collected data as Study 2 is introduced at the end of the next chapter (Section 2.6). Study 3 addressed the second aim of this programme of research, which focuses on the role of lifestyle factors in cognition and speech execution in ageing. A unified rationale for the present work, integrating these perspectives, is provided at the end of chapter 2 (section 2.6)

1.9 Chapter Summary

This chapter first introduced the background and context for studying healthy ageing including global ageing trends and the Decade of Healthy Ageing 2021-30 (World Health Organization, 2020) which provides the broad theoretical framework for this programme of research. The hallmarks of typical cognitive ageing were discussed such as the distinction between fluid and crystallised cognition (Horn &

Cattell, 1966) and the link between cognition and sensory decline in ageing (Baltes & Lindenberger, 1997). Theoretically, it has been proposed that one common underlying factor may be responsible for age-related increases in the association between cognition and sensory/sensorimotor functioning. Relevant theories highlight the central role of sensory functioning in speech motor control. The intersection of cognitive ageing theories and speech motor control theories lays the foundation for investigating relationships between cognition and speech execution in healthy ageing. This rationale was further justified through literature demonstrating that there are age differences in speech execution. The final section of this chapter discussed prior work of our group (Manderson et al., 2025), a systematic review. This identified relationships between cognition and speech execution in older adults, highlighting important limitations in the field, which this programme of research aims to address. This chapter closed by presenting the first aim of this thesis which is the intention to establish firmer conclusions as to whether there is a relationship between cognition and speech execution in healthy older adults. The next chapter continues the literature review by introducing individual differences in ageing trajectories and examining the potential role of lifestyle factors, while also presenting our second key research aim.

2. Variability in ageing trajectories and engagement in lifestyle activities

2.1 Chapter overview

The previous chapter outlined general trends in population ageing and introduced the core variables of this thesis: cognition and speech execution, along with the rationale for investigating their relationship in typically ageing older adults. However, assessing this relationship requires the understanding that older adults are a highly heterogenous group. Individual differences in cognitive ageing trajectories can be partly explained by cognitive reserve theory (Stern, 2002), compensation at the behavioural and neural levels (e.g. Baltes et al.,1999; Cabeza, 2002), and lifestyle factors (Park & Reuter-Lorenz, 2009, Reuter-Lorenz & Park, 2024). The Scaffolding Theory of Ageing and Cognition- Revised (STAC-R; Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Park, 2024) is a core theory that can account for potential associations amongst cognitive functioning, speech execution, and lifestyle factors, and a role for social participation. Despite social participation being recognised as vital for maintaining brain health and wellbeing in ageing (e.g. Oh et al., 2021; Small et al., 2012), relatively little research has investigating potential predictors of social participation in healthy ageing. The present chapter closes by outlining the second aim of this thesis: to investigate the extent to which measures of cognition and speech execution predict social participation.

2.2 Cognitive resilience

In terms of cognitive functioning, older adults are a highly heterogenous group. Despite general population ageing trends (section 1.3.1), there are individual

differences in the rate at which individuals cognitively age, with chronological age being a poor predictor of true mechanistic change (MacDonald et al., 2011). Although older age is associated with deterioration to underlying neuropathology (Hedden & Gabrieli, 2004), some older adults show greater resilience than others (Stern et al., 2019), and this can manifest behaviourally as better-preserved cognitive ability. The following section describes behavioural theories that contribute to cognitive resilience including cognitive reserve theory (Stern, 2002, 2003; Stern et al., 2019) and Selection, Optimisation, and Compensation (SOC) theory (Baltes et al., 2006).

Cognitive resilience refers to an individual's ability to retain the functional cognitive performance at a level comparable to someone younger and is an overarching definition that includes the subcomponents of brain maintenance, brain reserve and cognitive reserve (Stern et al., 2019). Brain reserve describes the neurological condition of the brain at any given time (Stern et al., 2019). Brain maintenance refers to the relative absence of neurological decline, supporting preserved cognition. Cognitive reserve is a function of brain reserve that reflects the brain's ability to optimise and compensate, allowing individuals to perform better than expected in cognitive tasks, despite age-related brain changes. These three concepts are intricately linked. However, given the data presented in this thesis are cognitive-behavioural in nature, the following section focuses on cognitive reserve, while acknowledging the inseparable influence of underlying brain reserve and brain maintenance.

2.2.1 Cognitive reserve

Cognitive reserve is one factor that contributes to variation in ageing trajectories with some older adults displaying better performance in cognitive tasks than others, despite evidence of age-related neural changes (Hedden & Gabrieli, 2004; Mazzonna & Peracchi, 2012). The concept of cognitive reserve was first introduced by Stern (2002) to explain the observation that, in some individuals, there appears to be no relationship between degree of brain damage and clinical manifestation of pathology. For example, the symptom severity of Alzheimer's Disease (AD) can vary from person to person despite existence of common underlying pathology, showing that some individuals' cognitive functioning is more negatively affected than others.

The concept of cognitive reserve can also be applied to typical cognitive ageing, demonstrating that some older adults are more able to offset the effects of age-related neuropathological changes. For instance, there are documented cases of older adults who exhibited no outward symptoms of cognitive impairment yet were discovered to show signs of advanced AD pathology upon post-mortem examination (Katzman et al., 1989; Stern, 2002). This highlights that cognitive reserve can delay or mask the clinical manifestation of underlying pathology by allowing individuals to maintain cognitive function despite brain changes, whether in typical ageing or preclinical AD (Parra et al., 2019). Lövdén et al. (2020) state that it is individual differences in how people process cognitive tasks that influences their vulnerability to adverse brain changes. Differences in cognitive processing stem from early life experiences, particularly educational attainment, which develops skills and knowledge that facilitate healthy cognitive functioning. Individuals with higher

levels of cognitive reserve also tend to experience healthier ageing and longer lifespans. However, once brain reserve - brain volume or synaptic density - drops below a critical threshold (Stern, 2003), a steeper decline in cognitive and functional capacity is observed (Parra et al., 2019).

Cognitive reserve is now generally understood as the accumulation of neural resources that can attenuate the effects of age-related cognitive decline in later life (Cabeza, 2002; Cabeza et al., 2018). As cognitive reserve is not directly observable, several variables have been used as proxy measures of it. The most common variables are intelligence, educational and occupational attainment, and engagement in cognitively stimulating activities (e.g. Mazzonna & Peracchi, 2012; Pettigrew et al., 2023; Stern, 2002, 2003). For example, lack of education in early life has been identified as a risk factor for developing dementia in later life (Basu, 2013; Bickel & Kurz, 2009). Furthermore, educational, occupational attainment and involvement in leisure activities across the lifespan are predictive of later dementia diagnosis (Stern, 2002; Yates et al., 2016). In the most recent Lancet commission on dementia prevention, Livingston et al. (2024) report 14 modifiable risk factors that could half the prevalence of dementia. These include early life education, continuing to be intellectually, physically and socially active in midlife (i.e. 18 – 65 years) and in late life (i.e. > 65 years), treating high blood pressure and high cholesterol from midlife, treating hearing and vision loss, and reducing social isolation in late life. Modifiable lifestyle factors therefore clearly contribute to higher levels of cognitive reserve, which serves as a protective factor to cognitive impairment (Legdeur et al., 2018). Furthermore, higher levels of cognitive reserve can, to an extent, attenuate genetic

risk for cognitive decline in some cognitive domains, including global cognitive functioning and memory (Livingston et al., 2024; Pettigrew et al., 2023).

Cognitive reserve is a useful concept for understanding individual differences in ageing trajectories. Yet, indirect measurements, such as educational attainment, come with limitations, as they do not always reflect the quality of educational experiences. Mazzonna and Peracci (2012) showed that individuals with higher levels of education exhibited better cognitive performance (particularly recall, fluency and numeracy) in late life. However, their education variable contained broad categories, grouping high school and college graduates together, which lacks specificity relative to, for example, total number of years of education. Evidence from the Lothian Birth Cohorts (Deary et al., 2000; Deary et al., 2012) demonstrate that childhood intelligence is also strongly predictive of later-life cognitive functioning, meaning it can be difficult to disentangle the independent contribution of education. Importantly, years of education shows modest but independent associations with cognitive outcomes across the lifespan, even when prior ability is controlled (Ritchie & Tucker-Drob, 2018). Therefore, in the absence of childhood IQ data, years of education can be interpreted as a proxy measure of cognitive reserve, while also partly reflecting prior ability.

Furthermore, research focused on education or occupational attainment neglects consideration of other important life-course factors, such as physical health/activity (Clouston et al., 2013; Kumar et al., 2022) and late life educational attainment (Peeters et al., 2020). Peeters et al. (2020) found that older adults with little or no early life education significantly improved their cognitive performance after a four-year intervention in later life. Similarly, in a longitudinal study of

individuals aged 90 years or over with no dementia at baseline, it was found that

reading significantly reduced the risk of dementia at 36-month follow-up (Ledgeur et

al., 2018). These findings suggests that cognitive reserve can be strengthened, even

in later life, supporting brain maintenance and potentially attenuating the effects of

age-related cognitive decline (Stern et al., 2019). Therefore, inclusion of several

lifestyle indicators may provide a more accurate description of cognitive reserve.

Although cognitive reserve is not the primary focus of this thesis, it is a

valuable theoretical framework for interpreting individual differences in cognitive

and speech execution abilities in older age. Therefore, the studies included in this

programme of research include several proxy indicators of cognitive reserve such as

years of education and activity engagement that are included as covariates across all

three studies. In addition, sample characteristics are described using information such

as socioeconomic status (SES) and general health (section 4.3.1), which may also

indirectly support cognitive reserve.

2.2.2 Selection optimisation and compensation (SOC) theory

While brain reserve is considered a passive model that reflects anatomical

status of the brain (e.g. brain volume, synapse count; Stern, 2002), cognitive reserve

is considered an active model. It describes how the brain adapts to brain changes or

damage by drawing on efficient cognitive processing strategies or by recruiting

compensatory mechanisms (Stern, 2002). The following section therefore introduces

Selection, Optimisation and Compensation (SOC) theory (Baltes et al., 2006). SOC

theory offers a cognitive-behavioural perspective on how older adults with greater

cognitive reserve use compensatory mechanisms in everyday functioning. It

illustrates that individuals use a range of information processing resources (Stern, 2002) to perform well on cognitive tasks, despite age-related cognitive decline.

SOC theory (Baltes et al., 1999) is a lifespan developmental theory that describes how older adults can adapt to functional changes by using behavioural strategies to maintain high levels of functioning in everyday life. The theory can be illustrated by 80-year-old concert pianist, Arthur Rubenstein (AR), who described using three strategies to maintain his musical ability. First, AR played fewer pieces overall (selection), focusing on specific goals and outcomes to maximise gains and minimise losses. Second, he played his selected piano pieces more frequently (optimisation) to enhance desirable outcomes, and to avoid placing resources on strategies that do not produce desirable outcomes. Finally, AR changed the tempo of his playing to compensate for reduced speed (compensation), for example, playing a segment more slowly to give the impression that the following segment was played faster. Therefore, SOC theory describes an adaptive process that is applicable across the lifespan but is particularly applicable in older age when individuals typically must adapt to increasing functional limitations.

SOC theory can be used to predict how older adults maintain functional ability in the face of biological losses. Rather than supporting developmental growth as in childhood, available reserves are redirected towards resilience and maintenance. Evidence comes from research including dual-task paradigms, which examine how individuals allocate attentional resources when performing two tasks simultaneously (e.g. Li et al., 2001; Lindenberger et al., 2000). These studies consistently show that older adults experience greater dual-task costs, indicating that reduced cognitive resources affect everyday abilities including walking, memory and speech execution

(Section 1.5). For example, Lindenberger et al. (2000) administered a concurrent walking and memory task with middle-aged and older adults. Dual-task costs to both functional domains were greater in older than in younger adults, indicating that reduced cognitive resources in older adults interfere with functional ability/performance in everyday tasks. Similarly, Li et al. (2001) investigated whether compensation strategies differed between younger and older adults. Extensive training was provided on the memory task beforehand to minimise the effects of task difficulty. This study revealed higher dual-task costs to the memory task in older than in younger adults, but dual-task costs in the walking condition were similar across groups. This shows that older adults diverted more attentional resources to one task, and selected walking, presumably to minimise falls. Moreover, when given the option to select a compensatory aid, older adults selected use of the handrail, to optimise walking, whereas the younger adults opted to use a memory aid (Li et al., 2001). This suggests that, when a risk to physical health or injury is perceived, older adults allocate a larger share of attentional resources to protecting physiological characteristics.

At the neural level, older adults recruit additional or bilateral brain regions to maintain performance (Cabeza, 2002; Reuter-Lorenz & Cappell, 2008). The Hemispheric Asymmetry Reduction in Older Adults (HAROLD) model (Cabeza, 2002) proposes that older adults recruit additional neural networks spread across both hemispheres when compared to younger adults carrying out the same cognitive task. The compensation-related utilisation of neural circuits hypothesis (CRUNCH; Reuter-Lorenz & Cappell, 2008) predicts that compensatory recruitment in both hemispheres has an upper limit and when task difficulty reaches a critical threshold,

performance drops to lower than that of younger adults (i.e. it reaches the CRUNCH point). SOC and neural compensation theories suggest that behavioural and neural adaptations help maintain functioning in later life. However, there appears to be individual differences in the extent to which individuals can select, optimise and compensate with superior performance associated with the ability to generate new and more efficient developmental resources to navigate everyday life (Baltes et al., 2006). In one cross-sectional study, young, middle-aged, and older adults were asked to self-report their use of SOC strategies. In middle age, there was an increase in the use of SOC resources, and the most convergence between all three components, suggesting that the SOC system is in optimal use in middle age. In older adults, there was a decline in all three strategies (Freund & Baltes, 2002) illustrating that age-related cognitive decline could influence the extent to which an individual is able to implement these strategies. Successfully adapting therefore depends on individual differences in cognitive reserve and the availability of resources. However, SOC and neural compensation theories do not fully account for how lifestyle factors are associated with compensatory behaviours across the lifespan.

2.3 Scaffolding Theory of Ageing and Cognition

One of the most prominent theories of compensation that addresses this gap by enabling testing of modifiable lifestyle factors is the Scaffolding Theory of Ageing and Cognition (STAC/STAC-R; Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Park, 2014, 2024). STAC-R (Figure 3) is a life course model that enables assessment of lifestyle factors including social and intellectual activity as interventions to improve cognitive ability and/or change (Reuter-Lorenz & Park,

2014). According to STAC-R, an individual's overall level of functioning and rate of

cognitive change is a consequence of the following: life course experiences that lead

either to neural resource enrichment (e.g. multilingualism, education) or depletion

(e.g. brain injury, APOE genotype); the negative effects of biological ageing on brain

structure and function – together "brain health" (Reuter-Lorenz & Park, 2024; e.g.

white matter deterioration, atrophy, weakened neuronal connectivity); and the

beneficial process of 'compensatory scaffolding'. At the behavioural level,

compensatory scaffolding can be stimulated in later life through intervention such as

engaging in new learning, exercise, meditation, intellectual and social engagement,

which importantly relies on successful communication (Meeker et al., 2021). At the

neural level, scaffolding refers to alternative or supplementary neural circuit

recruitment, for example increased prefrontal or bilateral activation (Cabeza, 2002;

Gutchess, 2014) to compensate for neurofunctional decline to more specialised areas

(Section 2.3).

Figure 3

The Scaffolding Theory of Ageing and Cognition

A Life Course Model of The Scaffolding Theory of Aging and Cognition (STAC-R)
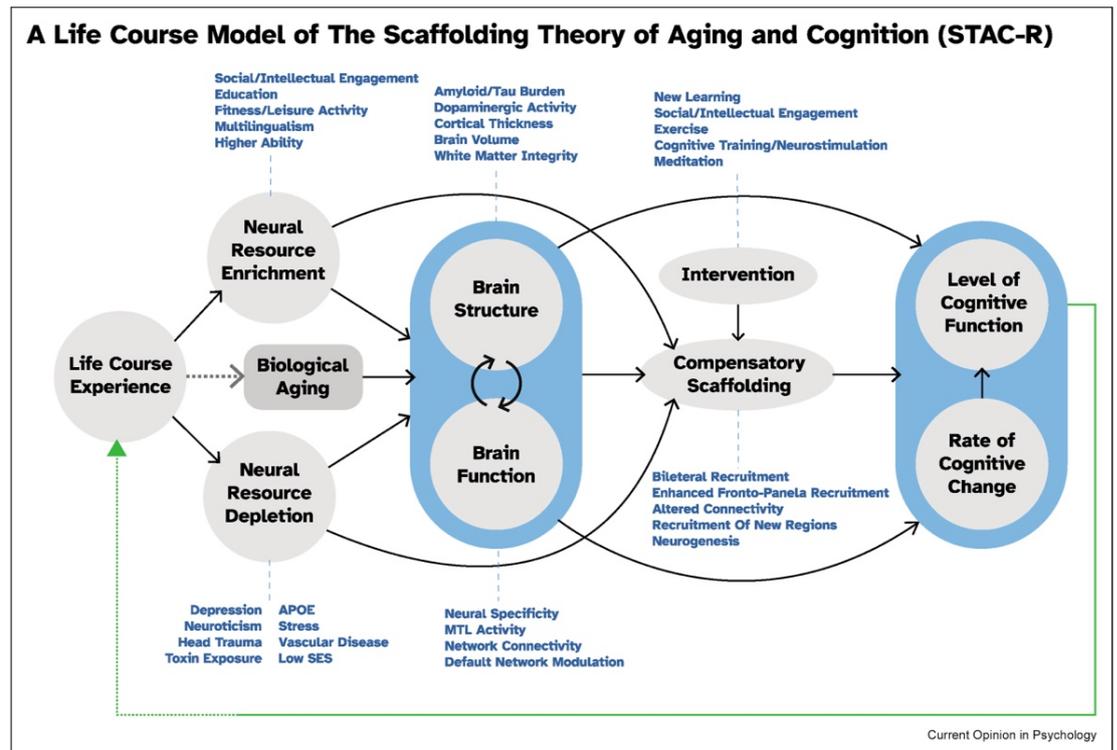
Note: Reproduced from Reuter-Lorenz & Park (2024) with permission under the Creative Commons CC BY license.

While cognitive reserve primarily focuses on the protective role of intellectual stimulation in mitigating cognitive decline (Stern, 2002), STAC-R extends this framework by incorporating a wider variety of lifestyle factors as protective mechanisms. STAC is supported by evidence showing that higher levels of intellectual (Peeters et al., 2020; Stern, 2002), physical (Kramer & Erickson, 2007) and social (Oh et al., 2021; Small et al., 2012) engagement have separate beneficial effects on cognitive functioning. In terms of intellectual engagement, as mentioned in Section 2.2.1, educational enrichment is beneficial for reducing the risk of dementia

pathology (Stern, 2002) and educational and occupational attainment are predictive of higher levels of cognitive reserve (Basu, 2013; Bickel & Kurz, 2009; Cabeza et al., 2018; Pettigrew et al., 2023; Stern, 2003). In relation to physical engagement, aerobic fitness in particular enhances brain structure and functioning in middle aged, healthy older adults, and older adults at risk of cognitive decline due to improved cardiovascular functioning (Kramer & Erikson, 2007). Aerobic fitness training interventions appear to be most beneficial across a variety of cognitive and perceptual skills, with particular gains in executive control processes that are especially vulnerable to ageing (e.g. planning, shifting, inhibition). The influence of physical activity on the ageing brain is complex and non-specific but, generally, exercise influences cognition at the cellular and molecular level, structural and functional level, and at the behavioural and socioemotional level (Erickson et al., 2022). Evidence in support of social engagement includes longitudinal population-based studies showing that consistent social participation protects against age-related cognitive decline (Kelly et al., 2017; Small et al., 2012), even at moderate levels of engagement (Kim & Yoon, 2022; Oh et al., 2021). More recently, the implications of wider lifestyle activities, such as intergenerational engagement (Krzeczkowska et al., 2021), grandparenting, volunteering, and caring responsibilities have been considered (Henning et al., 2023). However, despite observing positive cross-sectional associations between volunteering and cognition, measured by speed of processing, Henning et al. (2023) reported no consistent longitudinal associations. Therefore, intellectual, physical and social engagement appear to be the most robust pathways to protecting cognitive health (Livingston et al., 2024).

While studies have often examined these domains in isolation, this approach has been criticised for oversimplifying the complexity of real-world activities (Marr et al., 2021). Many activities are multidimensional containing physical, social, or intellectual components. For example, Kramer and Erickson (2007) note that the cognitive benefits of physical activity may be strengthened by a social component. Similarly, Ihle et al. (2021) found that the association between having close friends and subsequent decline in executive functioning was mediated by cognitive reserve accumulated by activity participation. Therefore, it is challenging to isolate the aspect of engagement most beneficial for cognitive functioning. Moreover, it is likely that there are both direct and indirect relationships between activity engagement and cognitive health. For example, an active lifestyle may enhance emotional wellbeing, protecting against depression, which is a risk factor for cognitive decline in older adulthood (Lichtenberg et al., 1995). Therefore, 'holistic' or multidimensional engagement may be the most promising avenue of exploration, due to the synergistic effects of different forms of engagement (Park et al., 2025).

2.3.1 Bidirectional relationship between cognition and engagement

Importantly, STAC-R provides a theoretical basis for assessing the extent to which individual differences in cognition and speech execution may predict social participation. In the most recent iteration of STAC-R (Reuter-Lorenz & Park, 2024) the relationship between life course experience and level of cognitive functioning in later life is depicted as bidirectional (Figure 2.1). This version of the model acknowledges that, as well as lifestyle factors influencing later cognitive levels, there are individual differences from birth which may dictate maximum potential for

cognitive levels in later life. For example, an individual with superior cognitive abilities may benefit more from the education they receive. Likewise, age-related cognitive decline may increase social withdrawal. However, this direction is explored less in research. The possibility of reverse causality between cognition and engagement has been explored in the literature (e.g. Gow et al., 2012) with some research investigating bidirectional relationships between cognition and activity engagement. For example, Small et al. (2012) found that, over a 12 year period, reduced lifestyle engagement was associated with declines to cognition (verbal speed, episodic memory, and semantic memory). While poorer cognitive abilities were not always associated with less frequent engagement in general, all three cognitive domains predicted the social activity domain. Conversely, Lövdén et al. (2005) found that reduced social participation predicted lower perceptual speed over a two-year period, but perceptual speed did not predict social participation. Finally, Casey et al. (2021) found a reciprocal relationship between cognition and social network size over six years. The cognitive battery included measures of global cognition, attention/processing speed, language, executive functioning, visuo-spatial abilities, memory, and verbal memory. Only the language domain predicted subsequent social network size, whereas initial social network size predicted executive function six years later. Taken together, these findings present a complex picture regarding the bidirectional relationship between cognition and engagement. However, social participation (relative to intellectual or physical) appears to be the strongest candidate outcome when measuring this direction of the relationship, suggesting that poorer cognitive ability in older age may reduce social participation.

Likewise, poorer speech production may limit social participation due to reduced quality of interactions (Meeker et al., 2021; Page & Yorkston, 2022).

2.4 Social Participation

Social participation is crucial for maintaining brain health, reducing the risk of dementia and improving quality of life in older adults (Bielak et al., 2007; Fratiglioni et al., 2004, 2020; Livingstone, 2023; Small et al., 2012; Sommerlad et al., 2023; Tomaz et al., 2021). Social participation also relies on verbal communication (Meeker et al., 2021) including successful speech execution. Therefore, this programme of research focuses predictors of social participation, relative to alternative 'interventions' highlighted in STAC-R such as exercise or meditation (Figure 2.1). The following section focuses on defining social participation.

Social participation is a key indicator of successful ageing (Douglas et al., 2017). However, a diverse array of indicators have been implemented in research to measure the concept of social participation which has complicated comparisons across studies (Hertzog et al., 2008). 'Social participation' has been used interchangeably with terms such as social support, social engagement, social integration, and social relations (Fuller-Iglesias & Rajbhandari, 2016). Previous research has conceptualised the social aspect of people's lives by measuring the size of social networks, types of social support, closeness of social relations, and frequency of social activities (Cruice et al., 2005; Fuller-Iglesias & Rajbhandari, 2016; Nagayoshi et al., 2017; Palmer et al., 2019; Small et al., 2012). As it stands, no one measure adequately captures the multifaceted nature of social participation

(Douglas et al., 2017). In this programme of research, social participation is used as an umbrella term encompassing three indices selected to reflect its complexity. These indices are activity engagement, social network size and communicative participation. The rationale for selecting each of these indices as measures of social participation is detailed in Section 2.5. Importantly, most of the evidence included above linking social participation to cognitive benefits is observational and correlational, despite being collected longitudinally. Therefore, the possibility of reverse causality cannot be ruled out and cognitive and/or speech execution abilities may also be acting as barriers, reducing overall social participation. The next section first discusses the theoretical background and existing evidence on age-related differences and/or changes in social participation.

2.4.1 Barriers to social participation

Historically, older age was considered as a period of social isolation. The social disengagement hypothesis (Cumming & Henry, 1961) proposed that older people start to withdraw from their social networks as a 'symbolic death'. Challenging this negative stereotype of ageing, Socioemotional Selectivity Theory (Charles & Carstensen, 2010) conversely predicts that older adults are in control of their social worlds, and prioritise emotional wellbeing by selecting a smaller network of more meaningful relationships. Research shows that older adults with smaller networks report better wellbeing due to the perceived quality of relationships (Bruine de Bruin, 2020). Yet, the World Health Organisation (WHO; 2021) report that social isolation is increasing globally amongst older populations, with 20 to 34% of older people in China, Europe, Latin America, and the United States reporting feeling

lonely. In 2018, the UK government appointed a 'loneliness minister' to tackle social isolation in general (WHO, 2021), with specific guidance for reducing social isolation in older adults, for example, through programmes focused on physical activity and sport for older adults (Her Majesty's Government, 2018). In addition, the Lancet report (Livingston et al., 2024) specifically highlights tackling social isolation as one key action point in reducing dementia risk. There appears to be a conflict between theory, which states older adults have improved wellbeing, and global data showing high levels of social isolation and loneliness. Therefore, there is a need for more research that aims to address the gap between theory and data. One way to address this gap is by examining potential predictors of social participation in older adults (Section 6.0).

Older age is associated with many positive gains including emotion regulation, and increased knowledge and experience (Carstensen et al., 2000; Charles & Carstensen, 2010; Charles & Luong, 2013) that can offset some of the difficulties associated with age-related cognitive declines. For example, Badham et al. (2015) reported that prior knowledge disproportionately benefits older adults during memory retrieval, compensating for age-related declines in episodic memory. This supports the more positive view that ageing follows a multidirectional trajectory (Loaiza, 2024) characterised by gradual cognitive declines, some of which can be ameliorated by the many benefits of ageing.

However, older adults can also experience specific challenges as they navigate lifestyle changes including retirement, bereavement and increased reliance on healthcare (Yorkston et al., 2010). These changing circumstances may influence the extent to which an individual wishes, or is able, to engage socially. Therefore,

there may be barriers to social participation in ageing. A systematic review by Townsend et al. (2021) reported that, although most research focuses on logistical barriers to social participation in ageing, such as transport and accessibility, emerging evidence identifies health factors such as cognitive impairment, vision loss, speech impairment and mobility difficulties, as amongst the most common barriers to social participation. These findings suggest that cognitive and speech changes are candidate barriers to social participation. Indeed, several studies have found that self-reported communication difficulties can lead to a reduction in social network size and activities in older adults with and without speech impairment (Cruice et al., 2005; Lovelace & Twohig, 1990; Palmer et al., 2016, 2019). This suggests that individuals' perceptions of their speech abilities may also be an important predictor of social participation. However, very limited research has examined whether objective measures of cognition and/or speech execution predict social participation in typically ageing older adults.

2.5 Indices of social participation

As mentioned in section 2.4, social participation is used here as an umbrella term, due to the varying measures implemented in research to reflect the construct (Fuller-Iglesias & Rajbhandari, 2016). As a result, three social measures are used in this programme of research to represent the multifaceted nature of social participation. The first is a general measure of activity engagement which was selected due to the robust relationships between frequency of activity engagement and cognition (section 2.3.3). The second measure is social network size due to the literature reporting links between cognition, communication and social network size

(Casey et al., 2021; Cruice et al., 2005; Lovelace & Twohig, 1990; Palmer et al., 2016, 2019). The third measure is communicative participation, which is distinct from other social participatory activities (Page & Yorkston, 2022). It is defined as involvement in life situations through verbal communication (section 3.5) and is typically assessed in clinical populations to determine the impact of an individual's speech disorder on everyday participation (Eadie et al., 2006). Limited communicative participation can affect daily experiences and quality of life (Sauder et al., 2021; Ter Wal et al., 2023), with lower levels of communicative participation potentially leading to social withdrawal, loneliness and, in turn, accelerated cognitive decline. However, there is very limited evidence assessing communicative participation in typical ageing. In one study, Meeker et al. (2021) found that communicative participation was predicted by cognition, education, living setting and quality of communication life. However, these authors measure communicative participation using social network size, which does not acknowledge communicative participation as a distinct construct (Page & Yorkston, 2022). Therefore, the present programme of research considers social participation to contain activity engagement, social network size and communicative participation. The selection of these measures is discussed in more detail in Section 3.5.

2.6 Cognition and speech execution as potential predictors of social participation

The first aim of this thesis is presented in Section 1.6, Given that social participation is crucial for maintaining brain health and wellbeing in ageing (Oh et al., 2021; Small et al., 2012; Livingston et al., 2024) and global data reveal

increasing social isolation and loneliness in older adults, it is important to determine whether there are any unrecognised barriers to social participation in older adults. Some research has revealed clinical health factors such as cognitive impairment and stuttering lead to social withdrawal in older adults (e.g. Townsend et al., 2021). However, it is unclear whether individual differences in cognition and speech execution similarly affect social participation in healthy older adults. Therefore, a second aim of this thesis is to examine the extent to which measures of cognition and speech execution predict social participation, including measures of activity engagement, social network size and communicative participation. This aim will be addressed in Study 3 (Section 6.0).

Taken together, the arguments made in Chapters 1 and 2 form the overall rationale for studying relationships between cognition, motor speech execution and social participation in healthy ageing. Chapter 1 identified a clear gap in the literature regarding the potential relationship between cognition and motor speech execution in typical adult ageing, as existing research has primarily focused on clinical ageing populations (section 1.7). The common cause hypothesis (Baltes & Lindenberger, 1994) offers a theoretical framework through which cognitive ageing theories (e.g. Salthouse, 2019) and models of speech motor control (Miller & Guenther, 2021; Weerathunge et al., 2022) can be integrated. In this thesis, it is proposed, for the first time, that motor speech execution may represent an additional sensorimotor process that is associated with cognitive function in older adults. Chapter 2 extended the research gap by demonstrating that there is limited understanding of health-based predictors of social participation in ageing. Cognition and speech execution were presented as candidate variables that warrant investigation as being potential barriers

to social participation (section 2.4.1). Beyond the theoretical and empirical contributions outlined above, examining cognitive-speech relationships in typical ageing also has diagnostic value by providing normed baseline data that can be compared with data from clinical populations. Similarly, the existence of such relationships has the potential to aid the development of non-invasive screening tools to identify early signs of cognitive impairment via assessing speech, either objectively and/or subjectively.

2.7 Chapter Summary

This chapter continued the literature review which commenced in chapter 1. The first half of the present chapter explored the mechanisms underlying individual differences in cognitive ageing and how these are considered within this programme of research. Cognitive reserve theory (Stern, 2002), and behavioural and neural compensation theories (e.g. Cabeza, 2002; Reuter-Lorenz & Cappell, 2008) informs understanding of the core theory underpinning this work, the Scaffolding Theory of Ageing and Cognition – Revised (STAC-R; Reuter Lorenz & Park, 2008, 2024). Importantly, STAC-R provides a lifespan perspective on ageing, integrating across the above theories while benefitting from being able to assess the role of modifiable lifestyle factors. Amongst these, social participation is a modifiable lifestyle factor that relies on communication (Meeker et al., 2021) and is believed to be beneficial for reducing the risk of cognitive impairment in older age (e.g. Fratiglioni et al., 2004, 2020; Livingston et al., 2024). The second half of this chapter defined social participation as an umbrella term encompassing activity engagement, social network size and communicative participation. Potential barriers to social participation were

discussed, identifying a gap in the literature investigating whether individual differences in cognition and speech execution in older adults predict social participation. The second aim of this thesis was outlined: to investigate whether cognition and/or speech execution predict social participation in healthy older adults. The present chapter closed by presenting a unified justification for the work presented in this thesis. The following chapter outlines the general methodology for this programme of research.

3. Methodology for investigating relationships amongst cognition, speech production and social participation in older adults

3.1 Chapter overview

The previous chapter discussed individual differences in ageing trajectories and introduced cognition and speech execution as potential predictors of social participation. The present chapter provides a conceptual overview of the key methodological considerations and decisions involved in designing this programme of research. It begins with a discussion of the broader methodological challenges related to ageing research, including recruitment of representative samples and the limitations of cross-sectional and longitudinal research. This is followed by an evaluation of the methods chosen to study the core variables of cognition, speech production and social participation. Relevant covariates, including mental wellbeing and activity engagement, are also considered. Finally, the rationale for inclusion of specific subjective and objective measures is outlined.

3.2 Challenges in ageing research

This section outlines two key challenges that are inherent in ageing research. The first is defining and obtaining a representative sample of healthy older adults. The second is the importance of study design, for example cross-sectional or longitudinal. These issues were considered in detail when designing this programme of research, as outlined below.

3.2.1 Representativeness in ageing research

One of the key challenges in research is recruiting a sample that is representative of the target population (Banack et al., 2019). Recruiting older adults for research may be particularly problematic because older age is associated with higher prevalence of disability, hospitalisation, care home admission (Han et al., 2016) and increased time spent on formal or unpaid caring roles for other family members (Wittenberg et al., 2020). These factors may exclude older adults from participating or limit their availability. Longitudinal research can also be impacted due to large attrition rates, as older people who have worsening illness, cognition or frailty are more likely to drop out (Chatfield et al., 2005). Additionally, caring responsibilities may have a significant impact on individuals' mental health, with research showing that individuals with poorer physical and/or mental health are less likely to take part in research (der Wiel et al., 2002). As a result, such lifestyle and health-related barriers might limit recruitment (Harada et al., 2013), potentially leading to a sample that does not fully represent the older adult population.

These barriers can lead to survivor-bias, referring to research involving only the healthiest individuals (Banack et al., 2019). This results in samples that do not capture the naturally occurring variation seen in the general population. Indeed, a sub-group of older adults, referred to as 'super agers', show exceptional cognitive and physical ability akin to midlife functioning (Powell, 2006). Super agers may be more likely to volunteer in research with one example being large-scale epidemiological research studies that typically comprise white women, who are well-educated, and from better socioeconomic backgrounds (Brayne & Moffitt, 2022). Although an ongoing issue in ageing research, specific efforts to achieve

representativeness should be implemented into the study design process (section 3.2.3).

Another barrier to participation among older adults is digital exclusion, which can further compromise sample representativeness. Older adults are more digitally connected than ever before (Anderson & Perrin, 2017) increasing the accessibility of research to those who may have physical disabilities or live in rural areas. Despite this, uptake of technology is still slower than in younger populations and is particularly limited in those aged over 75. As of 2022, in the United Kingdom, it was reported that 34% of people aged 75 and over do not use the internet. Moreover, 69% of those who do use the internet are not able to complete fundamental tasks required to use the internet successfully and safely. This includes, for example, turning on the device, adjusting settings, and connecting to Wi-Fi (Age UK, 2023). Although most older people now own a mobile phone, many do not have a smartphone. Barriers to using the internet include lack of IT skills, limited access to equipment, and health factors (Age UK, 2023). In the United States, Pew Research Centre similarly cited lack of confidence in the ability of older adults to learn new technology as a primary barrier to internet use. As well as those who are older, those from less privileged backgrounds and/or with lower levels of education were also less likely to use the internet (Anderson & Perrin, 2017). Therefore, efforts to minimise digital exclusion should also be incorporated into the study design (section 3.2.3).

3.2.2 Study design: cross-sectional and longitudinal

A concern often cited in the cognitive ageing literature is the dominance of cross-sectional relative to longitudinal research (e.g. Harada et al., 2013; Hofer et al.,

2002). This is particularly problematic in ageing research because age cannot be manipulated experimentally. This limits the ability to determine the specific effects of age on an outcome. In cross-sectional ageing research, older adults are typically compared to younger adults on performance measures at a single point in time, concluding that any differences found are due to age (e.g. Abou-Dest et al., 2012). However, cohort effects may be prevalent in cross-sectional research due to varying lifestyle, educational and cultural factors in the groups being studied (Harada et al., 2013). Comparing younger and older adults may be problematic because different life experiences could impact outcomes, for example, the public health context or accessibility to higher education.

Longitudinal research that tracks within-person change over time is an alternative study design. For example, The English Longitudinal Study of Ageing (ESLA) has collected data on cognitive, health, economic and social factors since 2002 (Steptoe et al., 2013). However, it is possible that the outcomes are confounded by practice effects, as the same cognitive tasks are undertaken multiple times. Although there is normally several years between each testing phase and/or parallel versions of the same tasks, participants may be able to maintain their test scores through practice. Attrition may also be higher in longitudinal studies of ageing due to increased age being associated with poor health outcomes, thus resulting in higher drop-out rates (Chatfield et al., 2005) and a bias towards those that remain healthier (Banack et al., 2019). Nevertheless, statistical procedures can help to mitigate these effects (section 3.2.3).

Importantly, choice of research design, be it cross-sectional or longitudinal, can influence the results of ageing research. For example, Schaie (2005) investigated

patterns of cognitive ageing using both a cross-sectional and longitudinal design in several birth cohorts, some of whom were followed longitudinally. The cross-sectional analysis revealed the typical patterns of growth, stability and decline (section 1.4.1). However, the longitudinal analysis did not reveal the same pattern. Instead, all cognitive domains appeared to decline, but changes were less pronounced than in the cross-sectional studies. As the measures and participants were stable across the two studies, this demonstrates that research outcomes can depend on the type of design and analysis.

To investigate this further, Salthouse (2019) introduced a novel quasi-longitudinal condition. This design involves recruiting participants from the same birth cohort (i.e. all are born in 1960) but assesses cognitive measures at different time points, when participants are different ages. For example, half of the participants born in 1960 were tested in 2000, at age 50, and half were tested in 2010, at age 60. This eliminated cohort effects and practice effects as all participants were from the same cohort, and no participant completed the same task twice. Interestingly, the findings from Salthouse's quasi-longitudinal study were more aligned to the pattern of cognitive abilities found in cross-sectional studies. This could suggest that practice effects in longitudinal studies lead researchers to underestimate the age effects on cognition (Loaiza, 2024). Recognising the strengths and weaknesses of both methods, the optimal approach may be to use converging evidence from cross-sectional and longitudinal designs (section 4.0).

3.2.3 Addressing key challenges in ageing research

These challenges related to representativeness and study design were considered in the design of this programme of research. The solutions implemented to address these issues are discussed in the following section.

To achieve representativeness and minimise digital exclusion, this research applied multiple strategies. In Study 1, a longitudinal online survey (section 4.0), study materials were made accessible by offering both online and paper-based questionnaires, allowing participants to complete surveys at home or return them by post, reducing the barrier of digital access and increasing accessibility. In Study 2 and 3, the lab-based objective measures (section 5.3.3.2) required computerised responses which was made more user-friendly by using an iPad rather than a mouse and keyboard. Participants were also reassured that no specific, prior experience was required before inclusion and that the researcher would be on hand to provide help should difficulties arise.

Health-related data, such as general health, hearing and vision were collected and were particularly useful in monitoring attrition in Study 1. This helped understand differences in sample characteristics between those who completed the study versus those who dropped out (section 4.6.1.1). Eligibility was determined via self-report in Study 1, whereby participants confirmed that they met the inclusion criteria by reporting no known cognitive impairment, neurological disorder, or speech and/or language difficulties.

In Studies 2 and 3, The Mini-Cog (Borson et al., 2000) was administered to screen for potential cognitive impairment. This is a brief, validated instrument in which participants are asked to immediately repeat a list of three words, then to complete a clock drawing task, followed by attempted recall of the words (Borson et

al., 2000). The maximum score is 5 (3 points for 3 words remembered correctly, and 2 points for drawing the clock correctly) and the cut-off for dementia screening is < 3. This test was chosen relative to other screening tools, such as the Mini-Mental State Examination (MMSE; Folstein et al., 1975) and the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005). Such tests take slightly longer, approximately 10-15 minutes. Yet, despite the Mini-Cog taking just three minutes to administer, it has been found to be more sensitive and accurate in detecting Mild Cognitive Impairment (MCI) in a range of ethnicities (Borson et al., 2005). Furthermore, the Mini-Cog is less affected by language, education and literacy than the MMSE (Borson et al., 2005; Li et al., 2018). The Mini-Cog is therefore more efficient and easier to administer while offering excellent validity (Borson et al., 2005).

Although it was considered important to adhere to strict exclusion criteria, avoiding over-exclusion was necessary to limit filtering out natural variation in functioning (section 3.2.1). As it is common for older adults to experience some degree of vision and hearing difficulties, participants were not excluded on this basis, despite both hearing and vision being associated with cognition (Christensen et al., 2001; Dawes et al., 2015; Lin, 2012; Hirst et al., 2022) and hearing playing a prominent role in speech execution (Behroozmand et al., 2015; Jarick & Jones, 2009; Parrell & Houde, 2019; Weerathunge et al., 2022). In all studies, participants were eligible provided they had normal or corrected-to-normal vision and hearing.

Importantly, vision and hearing were measured separately and included as covariates in the analyses. This enabled a wider range of participants with varying degrees of sensory abilities to take part, which is reflective of the heterogeneity in the

older adult population. Depending on the specific study, vision and hearing were measured using self-report (Bailey & Dromey, 2015; Whitfield et al., 2021) and objective methods, which are generally positively correlated in older populations (Whillans & Nazroo, 2014; Hämäläinen et al., 2021) indicating that self-report is a valid indicator of sensory ability when objective testing is not feasible. In Study 1, vision and hearing were measured subjectively using a five-point Likert scale, rating sensory functioning from very good to very poor. In Studies 2 and 3, hearing was measured using a words-in-noise test (section 5.3.3.1), relative to the more commonly used pure tone audiometry test (Zecker et al., 2013), due to better ecological validity. In addition, the words-in-noise test provided continuous data which was appropriate for regression analysis (section 5.3.5). Vision was also measured objectively in Studies 2 and 3 using a visual acuity task (section 5.3.3.1). A visual acuity task was chosen because this form of visual impairment is the most common and valid predictor of difficulties with everyday activities such as driving, reading and social interaction (Varma et al., 2013).

Last, to address the issue of results differing depending on study design, both a cross-sectional and longitudinal component was included in Study 1. The cross-sectional component also minimised the possibility of cohort effects as the investigation focused on within-group variability in older adults, as opposed to comparing older adults with younger adults at a single time point. Furthermore, the longitudinal component contributed to understanding within-person change over time, while acknowledging the possibility of reverse causality when assessing relationships within and between variables.

In summary, this programme of research was designed with careful consideration of key methodological challenges in ageing research related to representativeness and study design. Strategies used to address these challenges included offering accessible participation options where possible, defining clear and inclusive eligibility criteria and incorporating both subjective and objective measures of sensory functioning. This aimed to capture the heterogeneity of the older adult population while maintaining methodological rigour.

The following section outlines the decision-making process when selecting the measurement tasks and tools used in this programme of research. First, our core variables of cognition and speech execution are discussed with reference to subjective and objective measurements. This is followed by justification for selecting self-report instruments to measure key covariates including activity engagement and emotional wellbeing.

3.3 Measuring cognition

Cognition can be measured in a variety of ways (e.g. Fastame, 2022; Henning et al., 2023; MacPherson, 2019; Montejo et al., 2011; Rotenberg et al., 2020; Tulsky et al., 2014), each with their own benefits. In this programme of research cognition is measured using two complementary methods: subjectively, using self-report methods, and objectively, by assessing performance on cognitive tasks.

3.3.1 Measuring cognition subjectively

Self-report methods are widely used across a range of disciplines (Fausto et al., 2018). However, they are often criticised due to their subjective nature, for being less accurate or reliable than objective methods (Choi et al., 2016) and because of

limited predictive validity (e.g. Johnco et al., 2014). For example, older adults may self-report cognitive difficulties but demonstrate no objective cognitive difficulties in the lab (Fastame, 2022). Likewise, older adults with cognitive impairment may lack the awareness to provide accurate self-reports of their cognitive difficulties (Cacciamani et al., 2021). Although there is some evidence that self-reported cognition does predict lab-based memory performance (Fausto et al., 2018; Van bergen et al., 2009) the effects are small (Crumley et al., 2014). Therefore, perceptions of cognitive ability often differ from objective measures of cognitive performance.

Objective cognitive assessments also have limitations, with laboratory-based tasks often lacking ecological validity (Chaytor & Schmitter-Edgecombe, 2003), with observed deficits not necessarily applicable to real-world functioning. For example, Phillips et al. (2006) found that increasing age was associated with poorer performance on the Tower of London (TOL) task, a task typically used to measure planning and/or executive functioning. However, age effects were not observed on a more ecologically valid everyday planning task. This suggests that age effects observed in the lab may overestimate the impact of any deficits in real-world functioning. While it is important to acknowledge the limitations of both types of measurement, both were selected for inclusion in this programme of research for their individual strengths.

One primary strength of measuring cognition subjectively is that it provides a unique insight into individuals' perceptions of their cognitive functioning which in turn predicts day-to-day experiences and wellbeing. For example, an individual's perception of their cognitive ability may influence the extent to which an individual

chooses to socially engage or even withdraw (Rotenberg et al., 2020) which has important implications for brain health and mental wellbeing (section 2.4). Furthermore, subjective cognitive decline is associated with reduced independence, as older adults who report more cognitive difficulties are also more likely to develop difficulties with basic and instrumental activities than those who do not report cognitive difficulties (Liu et al., 2022). Research also shows that subjective cognitive complaints predict later dementia diagnosis (Jessen et al., 2020), mental wellbeing (Brück et al., 2019) and have been described as a pre-clinical behavioural marker of cognitive impairment (Fastame, 2022). Therefore, perceptions of cognitive abilities, whether accurate or not, are independent and meaningful predictors of real-world outcomes.

There are a range of tools available to measure cognition subjectively (e.g. Burmester et al., 2016; Jessen et al., 2020; Montejo et al., 2011; Rotenberg et al., 2020) and several were considered when designing this programme of research. As discussed in Section 1.3.1, healthy cognitive ageing is multidirectional (Loaiza, 2024) with some cognitive abilities showing decline and others showing stability or improvement (Salthouse et al., 2019). Therefore, it was important to select a self-report tool that incorporated multiple cognitive domains. However, many instruments, one example being the Multifactorial Memory Questionnaire (MMQ) – Ability Subscale (Troyer & Rich, 2002), focus only on subjective memory complaints (e.g. "Do you have memory problems? Yes/No"; Montejo et al., 2011). This approach does not acknowledge the existence of multiple cognitive domains (e.g. attention, language). Furthermore, the binary question does not enable the data to capture variation in memory ability that occurs naturally in the population. An

alternative instrument is the Cognitive Failures Questionnaire (CFQ; Broadbent et al., 1982; Fastame, 2022) which targets a range of everyday cognitive failures (e.g. "Do you find you forget appointments?"). However, due to the inability to assess subdomains of cognition, an alternative instrument was sought.

In the current programme of research, the Multiple Ability Self-Report Questionnaire (MASQ; Seidenberg et al., 1994) was used. The MASQ is a 38-item scale measuring subjective cognitive ability across five cognitive domains including language (e.g. "I find myself searching for the right word to express my thoughts"), verbal memory (e.g. "I forget to give phone call messages"), visual-perceptual ability (e.g. "I get lost when travelling around"), visual-spatial memory ("I can easily pick my coat out from among others") and attention/concentration (e.g. "I am alert to things going on around me"). The scale is scored using a 5-point Likert scale from 1 (never) to 5 (always). The visual-perceptual subscale contains six items, while the others contain eight. Therefore, to make each subscale comparable, the mean score from each subscale is taken, with higher scores representing greater cognitive difficulty. The MASQ has the additional benefit of some items within each subscale being reverse scored, to reduce the likelihood of biased responding. The MASQ shows acceptable internal reliability across all subscales ($\alpha = .97$; $> .70$ for each subscale; Seidenberg et al., 1994) and has been used widely in research with healthy older adults (Spalding et al., 2021, 2025; Nicholls et al., 2021; Williams & Arnold, 2011).

Although there is some inconsistency in the recommended cut-offs for Cronbach's alpha (Tavakol & Dennick, 2011), values of 0.70 are generally considered acceptable for established scales (Streiner, 2003) with values of 0.80

being described as good and values of up to 0.90 described as excellent. Values in the region of 0.60 may be acceptable for instruments in the early stages of development (Nunnally, 1967; in Streiner, 2003). In the current sample, the MASQ showed acceptable to good internal reliability. Specific reliability scores can be found in Section 4.3.3.2. Note that previous studies that have measured relationships between subjective cognition and activity participation have only considered memory (Liu et al., 2022; Rotenberg et al., 2020; Rotenberg & Dawson, 2022) as opposed to a wider range of cognitive abilities (Newson & Kemps, 2006). Therefore, inclusion of the MASQ addresses this gap in the literature (section 4.5).

3.3.2 Measuring cognition objectively

Considering the limitations of self-reported cognition (section 3.3.1) with research demonstrating that people can have limited insight into their own cognition (e.g. Newson & Kemps, 2006), objective methods were also included in the current research. The objective measures were selected primarily based on the gap in the existing literature investigating multiple cognitive abilities and their relationship with motor speech execution (Manderson et al., 2025). Our systematic review identified cross-sectional research that was focused on cognitive domains such as working memory (e.g. Kemper et al., 2009, 2011; Morris, 1987), processing speed, inhibition (e.g. Kemper et al., 2009, 2011), executive functioning (Yu et al., 2014), and global cognitive functioning (e.g. Kim et al., 2019; Kim et al., 2021). Similar to the critique of self-reported cognition (section 3.3.1), objective measures focusing on isolated cognitive skills limits understanding of the interaction between a range of important cognitive abilities. The experimental research identified through our systematic

review was predominantly in the form of dual-task studies, where concurrent task performance was considered to reflect divided attention. However, dual-task paradigms limit the ability to identify more specifically which cognitive abilities are being taxed, as it is likely that other cognitive abilities, beyond divided attention, are also involved (Dromey & Bates, 2005), depending on the complexity of the two concurrent tasks (Whitfield et al., 2021). Indeed, MacPherson (2019) acknowledged that overlapping cognitive abilities, such as response inhibition, selective attention and working memory were involved in their high cognitive demand condition, which involved a 'stroop' segment embedded within a sentence repetition task. Therefore, the cognitive abilities taxed depends on the demands of each task. The current programme of research adopts a cross-sectional, correlational approach to enable inclusion of multiple cognitive domains. This may contribute towards greater understanding of specific cognitive-motor speech relationships that could be particularly vulnerable to ageing.

A further gap in the literature is regarding investigation of cognition and speech execution using composite indexes. Compared to single test scores, cognitive composites are better placed to measure an underlying ability as opposed to specific task performance, which may less reliably predict everyday functioning (e.g. Phillips et al., 2006). Composite measures also have reduced measurement error and allow the researcher to restrict the number of comparisons (Amaefule et al., 2021; Clark et al., 2016; Wolfsgruber et al., 2017). One study included in our systematic review (de Looze et al., 2018) created composite subscales from a cognitive battery, including an attention/working memory subdomain, and a language subdomain. However, no studies have incorporated cognitive composite measures from the perspective of fluid

and crystallised abilities (section 1.3.1) in relation to motor speech performance (although see Borgeest et al., 2020). Most research has relied on performance on single cognitive tasks when assessing relationships with motor speech execution (Manderson et al., 2025). Incorporating cognitive composites of fluid and crystallised cognition (section 1.3.1) enables direct assessment of how cognitive ageing theory impacts on motor speech performance.

To address this, the current programme of research utilises The National Institute for Health (NIH) Toolbox version 2.0 (www.NIHToolbox.org). This resource contains a wide variety of performance-based tasks in the domains of cognition, motor and sensory functioning, and emotion, appropriate for use across the lifespan. The cognitive domain contains seven performance-based tasks covering attention, executive functioning, episodic memory, working memory, processing speed, receptive vocabulary and reading decoding (section 5.3.3.2). Importantly, the NIH toolbox combines these tasks to provide composite scores for fluid (attention, executive functioning, episodic memory, working memory, processing speed) and crystallised (receptive vocabulary, reading decoding) cognition. Vision and hearing were also measured objectively using the NIH toolbox sensation domain (section 3.2.3). Further benefits of measuring cognition and sensory functioning via the NIH toolbox include the tasks being suitable for up to ages 85+ (Nolin et al., 2023) and administered via an iPad, ensuring that instruction and administration is identical across participants. Use of the iPad addresses some of the challenges with digital access described above in Section 3.2.3, due to being more user-friendly than a standard computer set-up and requiring minimal computer proficiency.

3.4 Measuring speech execution

When assessing speech execution, it is important to carefully consider both the task and the outcome. Tasks that measure speech execution can be described as maximum performance tasks (MPTs) such as vowel prolongation (e.g. Dedry et al., 2022) or diadochokinetic (DDK) performance (e.g. Karlsson & Hartelius, 2019; section 3.4.2). In addition, speech can be executed through connected speech tasks such as passage reading and free speech (Cay et al., 2024; Maryn et al., 2010). More detailed discussion about each type of speaking task can be found below in Section 3.4.2.

There are also a variety of ways to measure the outcomes of the speaking tasks such as perceptual evaluation (Gorham-Rowan & Laures-Gore, 2006; Harnsberger et al., 2008), for example, expert ratings of an individual's breathiness, intelligibility and/or articulatory precision (Kim et al., 2024; Schultz et al., 2023). Speech execution can also be measured objectively by extracting acoustic and/or kinematic features from speech samples, for example, articulation rate (syllables per second), fundamental frequency (F0; perceived as pitch) or articulatory movements (e.g. lip aperture variability; Friedova et al., 2019; Iwarsson et al., 2020; Neel & Palmer, 2012; Van Brenk et al., 2014). Speech execution can also be assessed using self-report methods (section 3.4.1).

3.4.1 Measuring speech execution subjectively

Prior research has measured speech execution by using self-reports to determine patient perceptions of speech impairment (Baylor et al., 2013; Donovan et

al., 2008; Eadie et al., 2006; McAuliffe et al., 2017) and how it affects daily living (Baylor et al., 2008). For example, 'speech severity' has been measured clinically using the Amytrophic Lateral Sclerosis - Functional Rating Scale (ALS-FRS; Cedarbaum et al., 1999; McAuliffe et al., 2017) from "normal speech processes" through to "not understandable". 'Communication effectiveness' (e.g. "having a conversation with a stranger over the telephone"; Donovan et al., 2008) has also been assessed in patients with Parkinson's disease. In addition, 'speech usage' has been measured in patients with spasmodic dysphonia (e.g. undemanding, routine, extensive; Baylor et al., 2008). Therefore, most prior research measuring speech execution by self-report has done so in clinical populations. As a result, there are no validated instruments for assessing speech execution in healthy ageing.

Due to the lack of appropriate scales, in this programme of research, it was decided to adapt an existing scale created for clinical research. The original scale, 'Living with Neurologically Based Speech Difficulties' (LwD; Hartelius et al., 2008), includes 50 items categorised into 10 subscales covering general communication problems (e.g. related to speech, language, fatigue, emotions), rated on a six-point Likert scale from 1 (definitely false) to six (definitely true). The first subscale, communication problems related primarily to speech, was selected for use in the current research.

The speech subscale contains five items corresponding to the speech subsystems of phonation/respiration and articulation (section 1.4.4; Lee et al., 2014; Rong et al., 2015) as well as intelligibility. For example, the items relating to phonation/respiration are: "I often run out of air when I talk"; "I often sound hoarse", the items relating to articulation are: "My speech is slow"; "My speech is slurred"

and the item relating to intelligibility is: "I often need to repeat what I've said because people don't understand me". Therefore, the items are appropriately worded to capture variation in speech execution ability in healthy older adults. One issue regarding the validity of these items is that it remains unclear whether community-dwelling older adult participants can successfully discriminate between speech subsystems via self-report, and whether their perceptions accurately reflect the speech subsystems or instead reflect their concept of language processes. To aid interpretation and to help participants answer the questions, a description of speech was provided (appendix 1) at the beginning of the questionnaire. The six-point scale was modified to align with the MASQ (Seidenberg et al., 1994; section 3.3.1), which is measured on a five-point scale, and the number of response options was reduced from six to five (i.e. 1 = never, 2 = seldom, 3 = sometimes, 4 = frequently, 5 = always). Scores were summed with higher scores reflecting greater difficulty with speech execution. We also removed the word "often" from the three items listed above that contained this word as the response options adequately cover frequency. The remaining subscales from LwD were excluded due to being considered inappropriate for the typical speakers in our sample (e.g. "my communication changes have affected my ability to…") or due to being too distant from capturing speech ability (e.g. the impact of fatigue and emotions on communication). Furthermore, the language subsection was removed due to duplication with the language subsection of the MASQ. The full scale, which contains the speech execution subscale along with nine other subscales (e.g. language, fatigue, emotions) has been validated in patients with dysarthria (The Communication Profile; Yorkston & Bombardier, 1993) showing significant correlations between items in LwD and

The Communication Profile ($r = 0.47$ to 0.69). No reliability metrics were reported in Hartelius et al. (2008), where LwD was first published. Internal reliability in the present samples ranged from relatively poor, but not unacceptable (Menon et al., 2025), to acceptable. Specific reliability estimates for the samples contained here can be found in Section 4.3.3.2 and in Section 5.3.3.1.

3.4.2 Measuring speech execution objectively

Theoretical and clinical evidence demonstrate that speech execution involves phonation and articulation (section 1.4.4; Lee et al., 2014; Rong et al., 2015). Therefore, this programme of research prioritised implementation of speaking tasks and measures examining both subsystems (section 3.4.2). Furthermore, as ageing is associated with changes in both the speech motor and cognitive-linguistic systems (Mefferd & Corder, 2014) it was important to carefully control for the influence of language production. For example, slower speech rates (syllables per second including pauses) in older compared to younger adults (Burke et al., 2000; Burke & Shafto, 2004; Duchin & Mysak, 1987) could reflect lexical retrieval difficulties, articulatory difficulties (Mefferd & Corder, 2014) or both. To test predictions of theories proposing that phonation and articulation may rely on distinct neural processes (Weerathunge et al., 2022a, b), it was essential to control for linguistic processing when examining whether cognition predicts speech execution in isolation (Karlsson & Hartelius, 2019). At the same time, it was important to incorporate tasks that were ecologically valid (Maryn et al., 2010) to accurately understand the potential impact of such relationships. The following section will outline the selection of speaking tasks, followed by the selection of acoustic measures.

3.4.3 Speaking tasks: maximum performance and connected speech

To balance the need for a controlled investigation to benefit theory development with ecological validity to reflect older adults' every day speaking skills, a combination of maximum performance tasks (MPTs) and connected speech tasks were selected for inclusion. MPTs measure the upper limit of a speaker's ability on a certain speech characteristic such as maximum phonation time or maximum repetition rate. These tests are physiological in nature reflecting strength, range or speed (Kent et al., 1987) in phonation or articulation, requiring minimal linguistic input. Inclusion of MPTs assessing phonation and articulation enables assessment of each subsystem without the confounding influence of the other (Karlsson & Hartelius, 2021), as well as reducing the influence of linguistic processing as they do not contain a communicative component. Therefore, two MPTs were included in the current programme of research to benefit theory development.

The MPT chosen to assess phonation was a vowel prolongation task using the vowel /a/ (section 5.3.3.3) with maximum phonation times reflecting the upper limits of breath support for phonation. The vowel /a/ is typically used to measure maximum phonation time, although /i/ and /u/ are also sometimes used (Kent, 1987; Rusz et al., 2021). To minimise the risk of vocal fatigue due to repeated administrations only /a/ was used here.

The MPT selected to measure articulation was a diadochokinetic (DDK) task, which involves rapid repetition of syllables straining the articulatory subsystem to provide information about the speed and regularity of articulation (section 5.3.3.3). Age effects are more robust for alternating syllable strings (/pataka/) as opposed to

single syllables (/pa/, /ta/, /ka/), suggesting that trisyllabic repetition is the more challenging, sensitive task (Mousavi et al., 2020; Pierce et al., 2013). Due to this, and to further minimise the risk of vocal fatigue, the DDK task focused only on trisyllabic repetitions.

It was also acknowledged that MPTs lack ecological and predictive validity (Maas, 2017), as performance does not reflect everyday speech nor does it necessarily correlate with speech execution outcomes in connected speech. For example, Ziegler (2002) found that DDK rate (number of syllables divided by total time in seconds) was not correlated with articulation rate in a sentence production task involving the same syllables in patients with ataxic dysarthria. This suggests performance on MPTs may be task specific and raises the question of whether age-related difficulties with articulation and/or phonation identified by MPTs would emerge in connected speech tasks, and vice versa. Maas et al. (2017) suggest integrating both MPTs and connected speech tasks into study designs to better understand overlapping and distinct speech processes. Such integration may clarify the extent to which MPT performance is reflected in general speech execution abilities versus being task-specific. In addition to the two MPTs, the current programme of research also included two connected speech tasks: passage reading and a monologue (section 5.3.3.3).

3.4.4 Speech execution measures in connected speech

Unlike in MPTs, producing speech through connected speech does involve many linguistic processes. For example, reading a passage of text aloud requires orthographic processing, phonological encoding, morphological and lexical

processing and syntactic parsing (Coltheart, 2005). Producing a spontaneous monologue additionally requires message conceptualisation and formulation into linguistic structures (Levelt et al., 1999). Therefore, targeting the speech-motor system relative to the linguistic system requires careful consideration of the measures.

Some measures, such as speech or speaking rate, have been used to measure both language (e.g. Kemper et al., 2009, 2011) and motor speech production in ageing (Duchin & Mysak, 1987; Harnsberger et al., 2008) leading to inconsistencies in how speech rate is interpreted. Some studies calculate speech rate as words per minute (Duchin & Mysak, 1987; Kemper et al., 2009, 2011), while others use syllables per second (Iwarsson et al., 2020) or sentence, word and segment duration (Harnsberger et al., 2008). These temporal measures, that include pauses, make it difficult to determine whether the age-related slowing of speech is due to the functioning of the speech motor system, or slower linguistic processing (Mefferd & Corder, 2014). This issue is particularly evident when the speaking task is unconstrained such as during spontaneous speech, where both speech motor and linguistic processes are involved. While connected speech tasks are more ecologically valid than MPTs, they introduce variability in pausing. For example, longer pauses during spontaneous speech are common in individuals with MCI which may reflect memory or overall cognitive impairment (Cay et al., 2024), as patients take longer to formulate and plan their utterances (Pistono et al., 2016; 2019). Therefore, measures that include pausing make it difficult to distinguish language production from motor speech production. An alternative measure is articulation rate which directly measures the agility of the articulators (Iwarsson et

al., 2020) and is calculated using syllables per second after excluding pauses (Iwarsson et al., 2020). This offers a more sensitive index of the speech motor system than speech rate. As such, articulation rate was used as a measure of the articulatory subsystem in the objective portion of this thesis (section 5.3.3.3).

Phonation occurs when subglottal (beneath the vocal folds) air pressure from the lungs causes the vocal folds to vibrate (Scherer, 2014). Fundamental frequency (F0) is physical measure of the frequency of vocal fold vibration (Lee & Humes, 2012), expressed in Hertz (Hz). F0 corresponds to the perception of pitch, with higher F0 values representing higher pitch due to elongation and tension in the vocal folds (Scherer, 2014). Given that F0 is an absolute value and is affected by gender, the standard deviation (F0SD) was used to reflect variability in pitch. However, similar to rate measures, F0SD could be interpreted differently depending on the type of speaking task. The accuracy of F0SD is limited in a passage reading task as individuals may implement an exaggerated reading style, leading to falsely inflated F0SD values that do not reflect phonatory control. Due to this, F0SD was not measured in the passage reading task. F0SD may be more accurate in spontaneous speech, which is unrehearsed and more naturalistic, and may provide a more representative indicator of phonatory control (Wang et al., 2010). Therefore, F0SD was measured in both the sustained phonation and monologue tasks. This enabled investigation of whether the relationship between phonatory control and cognitive measures differed depending on the task.

Overall, successfully interpretating relationships between cognition and speech execution required careful consideration of the type of speaking task and the specific speech execution measures. This resulted in selecting a range of maximum

performance tasks and connected speech tasks to balance ecological validity with measurement accuracy.

3.5. Measuring social participation

As mentioned in Section 2.4, a range of measures were included to capture social participation more broadly than has been done previously in studies that have focused on a single measure of social participation, namely social network size, or frequency of activity engagement (e.g. Fuller-Iglesias & Rajbhandari, 2016; Nagayoshi et al., 2017; Small et al., 2012) or have conflated communicative participation and social participation (Cruice et al., 2005; Palmer et al., 2019).

The first measure of social participation was activity engagement using the short-form version of the Victoria Longitudinal Survey – Activity Lifestyle Questionnaire (VLS-ALQ; Jopp & Hertzog, 2010; Marr et al., 2021; Small et al., 2012). The original scale contained 70 items (Hultsch et al., 1999), which was too lengthy for the current research given the number of variables included. The short-form version, adapted by Marr and colleagues, contains 22 items that load on to one of six factors: manual skills (e.g. household repairs such as painting); intellectual skills (e.g. creative writing); games (e.g. card games, board games); religious (e.g. attend church); exercise (e.g. aerobics); and social (e.g. talk on the phone to friends or relatives, go out with friends). Items are summed (Hultsch et al., 1999) to give a total score out of a possible 176. Higher scores indicate greater involvement in everyday activities. Internal reliability coefficients for the individual subscales ranged from 0.65 to 0.85 (Marr et al., 2021). Although there has been no validation of this scale in other samples as yet, there is evidence of construct validity in the

exercise domain ($r = 0.26$, $p < 0.001$) with the International Physical Activity Questionnaire (IPAQ; Hagströmer et al., 2006). Given this is a recently developed scale, internal reliabilities in the current samples were acceptable (Streiner, 2003). Specific reliability estimates can be found in Sections 4.3.3.2 and 5.3.3.1.

The second measure of social participation was social network size (Casey et al., 2021; Cruice et al., 2005; Meeker et al., 2021; Oh et al., 2021), measured using the Lubben Social Network Scale (LSNS; Lubben et al., 2006), which assesses social integration. The six item scale has been validated cross-culturally (Chang et al., 2018; Kuru Alici & Kalanlar, 2021; Myagmarjav et al., 2019) and in community-dwelling older adults (Lubben et al., 2006). Three items are used to evaluate kinship (family) ties with the same three items evaluating non-kinship (friendship) ties ("How many relatives/friends do you see or hear from at least once a month?", "How many relatives/friends do you feel close to such that you could call on them for help?", "How many relatives/friends do you feel at ease with that you can talk to about private matters?"). Scores were summed to give an overall score out of a possible 30 (Lubben et al., 2006). Cross-cultural reliability has been established for both kinship and non-kinship subscales with coefficients ranging from $\alpha = 0.84$ to 0.89 for kinship ties and $\alpha = 0.80$ to 0.82 for non-kinship. Internal reliability in the current sample was acceptable to good (Menon et al., 2025; Streiner, 2003; Tavakol & Dennick, 2011). See Section 6.3.3 for specific reliability scores.

The third measure included was communicative participation (section 2.4). Similar to self-reported speech execution (section 3.4), a review of the literature revealed no existing instruments measuring communicative participation in non-disordered populations (Eadie et al., 2006). The Communicative Participation Item

Bank (Baylor et al., 2009) is the most commonly used validated instrument that measures communicative participation in disorder-generic clinical samples (Baylor et al., 2013). Each question begins with "does your condition interfere with". The ten items that follow include "talking with people you know" and "communicating in a small group of people". Communicative participation was measured using a modified version of the Communicative Participation Item Bank (C-PIB; Baylor et al., 2013). The adapted scale can be found in Appendix 2. The instruction in Baylor et al. asks participants to mark how much their condition interferes with participation various communicative situations. For this scale to be appropriate for use in healthy older adults, the stem of each item was altered from asking "does your condition interfere with your ability…", to "does your age affect your ability to…". Examples include "talk with people you know" to more complex contexts such as "get your turn in a fast-moving conversation" (appendix 2). The scale is scored on a four-point Likert scale (3 - "Not at all"; 2 - "A little"; 1 - "Quite a bit"; 0 - "Very much") with items summed to give an overall score out of a possible 30 with high scores indicating less disruption to participation. The scoring method was retained with the exception of reverse-scoring the items so that higher scores reflecting greater difficulty with participation, in line with our other self-report measures. As reliability and validity have not yet been established in typically ageing older adults, this research provides an opportunity to assess the potential to develop the CPIB for use in typically ageing populations. Internal reliability in the current sample was good (Streiner, 2003) and specific scores can be found in Section 6.3.3.

3.6 Controlling for emotional wellbeing

One of the limitations of the research identified by our systematic review was the limited inclusion of relevant covariates that could potentially influence observed relationships between cognition and speech execution. Therefore, the present programme of research includes a range of sociodemographic (e.g. age, gender, years of education, independence in daily living) and health (sensory functioning, general health) variables as covariates in our analyses (sections 4.5, 5.3.5 & 6.3.5).

Notably, emotional wellbeing can impact performance in cognitive and speech tasks. For example, incidence of depression is associated with poorer cognitive performance in ageing (Lichtenberg et al., 1995), while anxiety is associated with poor speech fluency (Iverach & Rapee, 2014). Links between subjective cognition and psychological wellbeing are consistently found (Brück et al., 2019; Goodman et al., 2022). Indeed, Spalding et al. (2021) reported that greater trait anxiety was associated with greater self-reported cognitive difficulties when using the MASQ (Seidenberg et al., 1994). The effect also increased across the adult lifespan, with the largest effect occurring in older adults aged over 60. Furthermore, depression interferes with objective cognitive task performance, which can worsen with age (Albert et al., 2018). Given that mental health and wellbeing affect subjective cognition and objective performance in cognition and speech production tasks, emotional wellbeing was included as a covariate in all studies in this programme of research.

It is common to account for depression in ageing research as it is recognised as being associated with cognitive decline or cognitive failures (Beck & Steer, 1987, Brown et al., 2014; Lichtenberg et al., 1995). However, a range of emotions including anxiety and stress are also likely to impact cognitive performance, and are

also associated with poor speech performance (Del Brutto et al., 2015; Smith & Weber, 2017). Based on this, we chose to include a scale that concisely covers these core aspects of mental well-being. Levels of depression, anxiety and stress were measured using the Depression Anxiety Stress Scales (DASS-21; Henry & Crawford, 2005; Lovibond & Lovibond, 1995; Osman et al., 2012). The original DASS contains 42 items while the short form contains 21 items across three independent scales relating to depression (e.g. "I couldn't seem to experience any positive feeling at all"), anxiety (e.g. "I was close to panic") and stress (e.g. "I found it difficult to relax"). The DASS-21 benefits from all subscales being scored on the same four-point Likert scale with participants indicating how much each statement applied to them over the past week (0 = "Did not apply to me at all", 1 = "Applied to me to some degree", 2 = "Applied to me a considerable degree or a good part of the time", 3 = "Applied to me very much, or most of the time"). Scores on the DASS-21 are summed and multiplied by two to align with the original 42-item version (Lovibond & Lovibond, 1993). Higher scores indicate greater prevalence of depression, anxiety and/or stress. The psychometric properties of the DASS-21 have been established in non-clinical samples (e.g. Sinclair et al., 2012) with each of the subscales showing good internal reliabilities ($\alpha > .90$). In addition, the DASS-21 has been used in previous cognition and emotion research with healthy older adults (e.g. Spalding et al., 2021; 2025). Internal reliabilities in the current samples ranged from just below acceptable to good and can be found in Sections 4.3.3.2 and 5.3.3.1.

3.7 Statement on open science practices and ethics

This work was committed to open science practices to contribute towards improving the replicability, robustness and reproducibility of data (Nosek et al., 2022). As such, all studies included in this programme of research followed gold standard open science practices and were pre-registered on Open Science Framework (OSF) prior to data collection. The pre-registrations can be found at https://osf.io/ktxg4/. For all three studies, Ethical approval was granted by the University of Strathclyde, Department of Psychological Sciences and Health Ethics Committee prior to commencement.

3.8 Chapter Summary

This chapter discussed the pertinent methodological considerations and decisions that were made when designing this programme of research including gaining a representative sample and the adoption of a relatively unique approach to addressing the issue of cross-sectional versus longitudinal study design. The justification for including subjective and objective measures was presented. The Multiple Ability Self Report Questionnaire (MASQ; Siedenberg et al., 1999) was selected to measure subjective cognition because it comprehensively measures several cognitive domains. Considering speech execution and communicative participation, we adapted existing scales that were initially developed to investigate communication in people with speech disorders due to lack of available scales. Similarly, objective measures were selected due to being more comprehensive than in previous research. The NIH toolbox has the added benefit of calculating composite cognitive scores. Finally, this chapter discussed inclusion of relevant covariates giving particular attention to emotional wellbeing measured using the Depression,

Anxiety and Stress Scale (DASS-21; (DASS-21; Henry & Crawford, 2005; Lovibond & Lovibond, 1995; Osman et al., 2012). The chapter closed with acknowledgement of the ethics processes involved in the work and commitment to open science practices. The following chapter presents the first study in this programme of research.

4. Study 1 – Cross-sectional and longitudinal investigations of the relationships between subjective cognitive abilities and speech execution in healthy ageing

4.1 Chapter overview

In the previous chapter, the methodological decisions made when designing this programme of research were discussed. The current chapter presents Study 1, the first of three studies in this thesis. Study 1 investigates cross-sectional and longitudinal relationships between self-reported cognition and speech execution in older adults. This chapter provides relevant background literature and the rationale for using self-report measures and a longitudinal design. The specific methods implemented in this study are then presented, followed by the results from timepoint 1 (T1), the cross-sectional data collected at baseline. Next, the longitudinal data, collected at timepoint 2 (T2), 12 months later, are explored and presented in relation to the baseline data. This chapter closes by discussing the key findings in the context of the common cause hypothesis (Baltes & Lindenberger, 1994), a core theory underpinning this work. The study limitations and suggestions for future research are also discussed.

4.2 Introduction
4.2.1 Background

Communication is fundamental to successfully adapting to changing life circumstances (Yorkston et al., 2010), maintaining independence in daily living (Miura et al., 2004) and enjoying engagement in lifestyle activities (Meeker et al., 2021), which ultimately contribute to overall quality of life. Adults typically experience age-related declines in cognitive (Harada et al., 2013; Salthouse, 2019), sensory (Baltes & Lindenberger, 1997; Pichora-Fuller, 2015), linguistic (Burke et al., 2012; Burke & Shafto, 2004) and speech motor domains (Amerman & Parnell, 1992, 1992; Hooper & Cralidis, 2009), which potentially contribute to poorer overall speech production abilities. In the context of typical ageing, previous research has established sensory-cognitive (Baltes & Lindenberger, 1997; Hämäläinen et al., 2019) and cognitive-linguistic (Burke et al., 2012; Burke & Shafto, 2004; Perlovsky & Sakai, 2014) connections (section 1.4). However, very little research (Manderson et al., 2025) has investigated the potential relationship between cognitive and speech motor processes in typical adult ageing, despite known connections between cognition and motor speech characteristics in clinical populations (Cay et al., 2024; Doneva, 2020; Thies et al., 2020; Watts, 2001; section 1.6.1). In addition, no research to date has investigated the ageing of motor speech production through the lens of cognitive ageing theory (section 4.2.2).

4.2.2 Adult ageing and the common cause hypothesis

As detailed in Section 1.4, typical ageing is associated with gradual declines to 'fluid' cognitive abilities including reasoning, memory, and speed of information processing (Salthouse et al., 2019). 'Crystallised' abilities such as verbal and semantic knowledge remain relatively stable and can even show some improvement

over the adult lifespan (Salthouse, 2019). Furthermore, older adults experience

sensory declines, particularly to vision and hearing (Cruickshanks et al., 1998;

Curhan et al., 2020; Houde & Huff, 2003; Pichora-Fuller, 2015). Importantly, there

appears to be an association between cognitive and sensory declines (Baltes et al.,

1998; Baltes & Lindenberger, 1997; Pichora-Fuller, 2015). Research suggests that

age-related changes to cognitive and sensory/sensorimotor abilities are not entirely

independent but correlated, because they share an underlying common cause.

Crucially, sensory and sensorimotor abilities, including visual and auditory acuity

and walking, have been found to predict more of the variance in fluid cognitive

abilities in older than in younger adults (Baltes & Lindenberger, 1997; Li &

Lindenberger, 1999). The common cause hypothesis (Baltes & Lindenberger, 1994)

proposes that one common factor, for example neurodegeneration in prefrontal brain

regions (Baltes & Lindenberger, 1994), is responsible for simultaneous declines in

cognitive and sensory domains. This explains why increasing interdependence

between cognitive and sensory/sensorimotor abilities is observed with age (Baltes &

Lindenberger, 1997; see Section 1.4.2). While the common cause hypothesis has

focused on peripheral sensory processes (e.g. vision, hearing), sensorimotor

functions (e.g. walking, grip strength) and fluid cognitive abilities (e.g. reasoning,

processing speed), it is possible that the same common factor could also explain

changes in aspects of motor speech production, a sensorimotor process (Tremblay et

al., 2015). However, there is a lack of high quality evidence investigating

relationships between cognition and motor speech production processes (i.e. speech

planning, control and execution; Manderson et al., 2025). Understanding specific

relationships between cognitive and speech motor domains in healthy ageing may

contribute to understanding typical motor speech changes with age. In turn, this could help identify early markers of pathological ageing through motor speech characteristics.

4.2.3 Lifestyle engagement in adult ageing

There is large heterogeneity in the functional ability of older adults with both genetic and environmental factors influencing individual ageing trajectories (Section 1.2). One environmental factor that has been widely identified as being beneficial for cognitive function in older age is activity engagement (Bielak et al., 2007; Fratiglioni et al., 2004; Lourida et al., 2019; Small et al., 2012). Activities can be grouped into either physical (e.g. cardiovascular exercise), mental (e.g. educational attainment), or social (e.g. social network size) categories (Marr et al., 2021), with each type of engagement showing independent beneficial effects on cognition (Borgeest et al., 2020; Kelly et al., 2017; Kramer & Erickson, 2007; Small et al., 2012; Zhang et al., 2022). The Scaffolding Theory of Aging and Cognition-Revised (STAC-R; Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Park, 2010, 2014, 2024) predicts that engagement in modifiable lifestyle factors can influence the extent to which older adults are able to compensate for reduced cognitive resources (see Section 2.3.3). STAC-R crucially demonstrates that there are individual differences in the trajectory of cognitive decline, that depends on life course experience, possibly from birth.

As well as cognitive abilities, these lifestyle activities may also affect motor speech production in older adults. Xue and Muelle (1997) reported that the voice quality of sedentary older adults (males and females) could be discriminated from active older adults when asked to produce and sustain the vowel /a/. The active older

adults were judged as sounding younger, and acoustically presented as showing smaller jitter percentage (frequency variation; Teixeira et al., 2013) and less variability in fundamental frequency (F0; number of repetitions of sound wave produced by vocal cords; Teixeira et al., 2013). In addition, Nagayoshi et al. (2017) reported that social networks and involvement in leisure activities were associated with increased tongue pressure in participants aged over 40. This suggests that those who participated more frequently in leisure pursuits had better oral motor skills, possibly due to more frequent conversation (Kleim & Jones, 2008). Therefore, it is important to consider individual differences in lifestyle factors when investigating levels of functional ability in cognition and/or motor speech production.

4.2.4 Isolating speech execution

Motor speech production is a complex process that relies on a series of subprocesses including speech motor planning, control and execution (Tremblay et al., 2019a). This study focuses on speech execution, as age-related differences are observed across the speech execution subsystems of articulation and phonation (Awan, 2006; Goy et al., 2013; Hollien & Shipp, 1972; Huber & Darling-White, 2017; Huber & Spurill, 2008; Huber & Stathopoulos, 2015; Kuruvilla-Dugdale et al., 2020; Nishio & Niimi, 2008; Tucker et al., 2021). This has been shown using a variety of methods including auditory and perceptual measures showing that the ageing voice becomes less stable, with more vocal tremors, vocal fatigue, hoarseness, reduced speech rate and increased breathiness (Martins et al., 2014). Acoustic analysis of speech has also demonstrated that older adults have slower speech and articulation rates and reduced articulatory accuracy and stability than younger adults

(Bilodeau-Mercure & Tremblay, 2016; MacPherson, 2019; Sadagopan & Smith, 2013). Therefore, speech execution is clearly vulnerable to age-related changes.

However, the cause of age differences in speech execution is unclear. Physiological degeneration in the speech system has previously been thought to be responsible for age differences in phonation (e.g. Meyerson et al., 1976; Rojas et al., 2020; Zraick et al., 2006). For example, muscular degeneration in ageing diminishes lung pressure and volume, therefore affecting the respiratory system. Likewise, stiffness and atrophy of muscle tissue reduces vocal fold vibrations as well as range, speed, and accuracy of articulatory movement, affecting both the phonatory and articulatory subsystems (Zraick et al., 2006). The reasons for age-related differences in articulation are less clear with studies reporting that physiological factors only partially explain reduced articulation rates (Goozée et al., 2005; Kuruvilla-Dugdale et al., 2020; Mefferd & Corder, 2014; Neel & Palmer, 2012). While age-related cognitive decline is understood to influence language production in ageing (Meyerson et al., 1976), limited research has investigated whether cognition relates to speech execution in healthy ageing, despite speech motor control being described as a "cognitive-motor accomplishment" (Kent, 2004; p.3). Therefore, it is important to more fully understand the mechanisms associated with speech execution subsystems.

It is also methodologically difficult to tease apart motor speech production processes. Isolating speech motor planning from phonological planning and language planning requires a detailed experimental manipulation such as varying both the sequential and phonological complexity of syllable repetitions (e.g. Tremblay et al., 2019). This issue was highlighted in Manderson et al., (2025) who were unable to

reliably categorise the motor speech data into the subprocesses of speech motor planning or speech motor control due to these methodological challenges. As a result, the data were classified as measuring either articulation or phonation. To reduce potential confounding, and to contribute towards understanding specific motor speech subprocesses in isolation, the current study builds upon the findings of Manderson et al. (2025) by similarly focusing on speech execution.

Finally, because speech execution is the last stage of motor speech production, it is possibly experienced most by speakers themselves. Typically, speech execution is measured through perceptual observation by others (e.g. Harnsberger et al., 2008), objectively in experimental settings (e.g. Bilodeau-Mercure & Tremblay, 2016) or via self-report most commonly in clinical samples (e.g. McAuliffe et al., 2017; McKinstry & Perry, 2003). Therefore, it is also prudent to focus on speech execution because it is directly measurable.

4.2.5 Measuring speech execution and cognition subjectively

Self-report measures are valuable metrics for understanding individuals' perceptions and experiences of their speech and cognitive abilities which may, in turn, influence the extent to which they participate in lifestyle activities (Baylor et al., 2009). Older adults' perceptions of their speech abilities may particularly influence the extent to which they participate in activities involving communication (Section 6.0). However, there is very limited research investigating self-reported speech execution in healthy older adults, which limits general understanding of people's perceptions of their speech in older age. Likewise, measuring self-reported cognition is useful in understanding older adults perceived cognitive functioning,

which has been linked to independence in daily living (Liu et al., 2022), social engagement and withdrawal (Rotenberg et al., 2020), and is a predictor of later dementia diagnosis (Jessen et al., 2020). Our systematic review found no studies investigating relationships between self-reported cognition and speech execution in older adults (Manderson et al., 2025). Therefore, to our knowledge, this is the first study to investigate such a potential relationship using subjective measures.

4.2.6 Potential longitudinal bidirectional relationships

Most existing studies measuring cognitive-motor speech relationships are cross-sectional and correlational in nature (Manderson et al., 2025), limiting the ability to determine direction or causality (Henning et al., 2023). While it is possible that cognitive decline affects speech execution in ageing, age-related changes to speech execution may also affect cognition, or indeed both directions of the relationship may exist. Theoretically, age-related decline to fluid cognitive abilities, such as attention, executive functioning or working memory may disrupt aspects of motor speech production, such as speech monitoring, which becomes increasingly important in compensating for reduced support from anatomical and physiological processes (Goozée et al., 2005). At the same time, increasing perceived speech difficulty may reduce older adults' willingness or frequency of engagement in cognitively or socially stimulating activities, in turn accelerating cognitive decline.

Although no prior research has investigated bidirectional relationships between cognition and speech execution, other literature has identified bidirectional relationships between cognition and activity engagement (e.g. Casey et al., 2021; Lövdén et al., 2005; Small et al., 2012) using cross-lagged structural equation

modelling. Small et al. (2012) used the Dual Change Score Model (DCSM; McArdle, 2001) to examine bidirectional relationships in which prior levels of cognition and engagement predicted later change in the other. It was found that reduced lifestyle engagement was associated with declines to cognition (verbal ability/speed, episodic memory, and semantic memory) over a 12-year period. Conversely, all three cognitive domains were longitudinally associated only with frequency of social engagement, but not other lifestyle activities (physical, intellectual). Using a similar method, Casey et al. (2021) found reciprocal relationships between cognitive domains and social networks over six years. Language ability at baseline predicted later social network size, whereas social network size at baseline predicted executive function six years later. Lövdén et al. (2005) used random intercepts cross-lagged panel modelling (RI-CLPM; Selig & Little, 2012) which does not predict change per say, but rather whether one variable predicts later levels of another, and vice versa. It was found that reduced social participation predicted slower perceptual speed over a two-year period, but perceptual speed did not predict social participation. The above findings highlight the value of longitudinal designs and the types of analyses that can uncover potential bidirectional relationships. Although these studies had three or more timepoints, their design informed the longitudinal component of the current study and the intention to assess bidirectional relationships between cognition and speech execution. Given the current study contained two timepoints, a different form of cross-lagged panel modelling was chosen (see section 4.6.3.2 for details).

4.2.7 Aims, objectives and research question

To our knowledge, no prior research has investigated potential relationships between self-reported cognitive and speech abilities in typical populations. Therefore, this study aims to determine the existence of such relationships in healthy older adults when controlling for levels of activity engagement and other relevant health, mental well-being, and daily living covariates. In addition, this study aims to explore potential longitudinal bidirectional relationships between cognition and speech execution. These aims will be addressed using a cross-sectional and longitudinal design to answer the following research question: to what extent do self-reported cognitive abilities predict self-reported speech execution ability in healthy older adults?

4.2.8 Hypothesis

The link to the pre-registered hypothesis can be found here: https://osf.io/brje5. It was hypothesised that, cross-sectionally, one or more domains of subjective cognition would significantly predict speech execution, over and above relevant covariates. The longitudinal component of the study was exploratory in nature. Therefore, no specific hypotheses were proposed regarding the direction of longitudinal relationships.

4.3 Method

4.3.1 Participants

Participants who completed the survey at baseline were 204 healthy older adults (146 Female, 58 Male; Table 1) aged 60 or over ($M = 70.58$, $SD = 6.65$; Table 1) based in the United Kingdom (UK). The mean years of education of the sample

was 16.20 (*SD* = 3.46; Table 1). Participants were recruited through older adult

participant panels at the University of Strathclyde, and general advertising/word of

mouth around the University campus, via collaborating partners and in local

communities (health centres, libraries, supermarkets etc). Participants confirmed that

they had not been diagnosed with any cognitive impairments (e.g. Alzheimer's

Disease, Mild Cognitive Impairment), neurological condition (e.g. brain injury,

Parkinson's Disease, stroke) or learning difficulties (e.g. dyslexia). Participants also

confirmed that they had no known and/or diagnosed speech, language and/or voice

disorders (e.g. aphasia, apraxia of speech, dysarthria, stutter). The follow-up

questionnaire was completed by 158 of the same participants, 12 months later.

Potential differences between the final sample and those who dropped out were

explored and are reported below in section 4.6.1.

Table 1

Sociodemographic characteristics of the Study 1 sample at baseline

Variable	Missing		Mean (*SD*) / Frequency (%)
Age (N = 203)	1	Min = 60 Max = 92	*M* = 70.58 (6.65)
Years of education (N = 186)	18	Min = 6 Max = 28	*M* = 16.20 (3.46)
Gender (N = 204)	0	Female	146 (71.6%)
		Male	58 (28.4%)
		Non-binary	0 (0%)
		Prefer not to say	0 (0%)
Ethnicity (N = 204)	0	White	201 (98.5%)
		Mixed or Multiple ethnic groups	1 (0.5%)
		Caribbean or Black	1 (0.5%)
		Other (Chinese)	1 (0.5%)
Employment status (N = 204)	0	Full-time employment	7 (3.4%)
		Part-time employment	8 (3.9%)
		Unemployed	1 (0.5%)
		Self-employed	6 (2.9%)
		Student	1 (0.5%)
		Retired	180 (88.2%)
		Prefer not to say	1 (0.5%)
Living Situation (N=203)	1	Living alone	81 (39.7%)
		Living with other/s	120 (58.8%)
		Prefer not to say	2 (1.0%)
Relationship status (N = 204)	0	Single (never married)	15 (7.4%)
		Married/cohabiting	115 (56.4%)
		In a partnership	4 (2.0%)
		Separated/divorced	39 (19.1%)
		Widowed	31 (15.2%)
Education level (N = 204)	0	Secondary/high school	21 (10.3%)
		Further education/college	45 (22.1%)
		University undergraduate	45 (22.1%)
		University Postgraduate	80 (39.2%)
		Doctorate	13 (6.4%)
Deprivation index (N = 199)	5	1	4 (2.0%)
		2	7 (3.4%)
		3	10 (4.9%)
		4	13 (6.4%)
		5	19 (9.3%)
		6	23 (11.3%)
		7	30 (14.7%)
		8	38 (18.6%)
		9	23 (11.3%)
		10	32 (15.7%)
Smoking status (N = 204)	0	Never smoked (less than 100 cigarettes in lifetime)	126 (61.8%)
		Former smoker (quit 5 or more years ago)	69 (33.8%)
		Former smoker (quit in the past 5 years)	5 (2.5%)
		Current smoker	4 (2.0%)

Note. Frequency percentages exclude missing data. Deprivation Index (1 = most deprived area, 10 = least deprived area). 192 were Scottish postcodes, 7 were English postcodes. The Scottish Index of Multiple Deprivation (SIMD; 2020) was used to transform Scottish postcodes, and the English Indices of Deprivation (IMD, 2019) was used to transform English postcodes.

The percentage of missing data at baseline was low (see section 4.5 below), and there were no participant exclusions. Therefore, it was possible to retain complete outcome data for the cross-sectional analysis for all 204 participants. An a-priori G*Power (Faul et al., 2009) power analysis was carried out to determine the required sample size to detect a medium effect ($f^2 = 0.15$) with alpha set at 0.05 and power at 0.90 for the 16 predictor variables used in the regression analysis (See Section 4.3.2 for list of predictors and outcome). The minimum number of participants required was N = 175. Therefore, the study was sufficiently powered.

4.3.2 Design

The study design was cross-sectional and correlational with a longitudinal follow-up 12 months later. Both the cross-sectional and longitudinal data were analysed in separate models and are therefore reported here in turn. The 16 predictor variables included in the cross-sectional analysis were: age, gender (1 = female, 2 = male), years of education, vision, hearing, general health, depression, anxiety, stress, activity engagement, independence in daily living, language, visual-perceptual ability, verbal memory, visual-spatial memory and attention/concentration. The outcome was speech execution, with higher scores indicating greater difficulty with speech execution. The longitudinal predictors and outcomes are detailed below in Section 4.6.2.

4.3.3 Materials

4.3.3.1 Demographic and health characteristics

Participants provided demographic information on age, gender, years of education, ethnicity, employment status, relationship status, living situation, education (highest level) and socioeconomic status (SES). These sample characteristics are reported descriptively above in Table 1.

Health characteristics (general health, vision and hearing) were self-reported and included as covariates in our core analyses. Participants rated their general health (1 = very good to 5 = very poor), vision and hearing ability (1 = very good to 5 = very poor). These three variables were not reverse scored to maintain consistency with the core variables of cognition and speech execution, in which higher scores reflect greater difficulty. However, all three variables were recoded from ordinal categorical into binary variables to be suitable for correlation and regression analyses (Field, 2024). Participants who reported their abilities as 'very good' or 'good' were coded as 0 and those who reported their abilities as 'fair', 'quite poor' or 'very poor' were coded as 1. Smoking status was also measured (never smoked, former smoker who quit 5 + years ago, former smoker who quit < 5 years ago, current smoker) but was not included in the core analyses (Table 1).

The following section lists each of the standardised or adapted questionnaires that were administered. Other than the Instrumental Activities of Daily Living questionnaire (IADL; Lawton & Brody, 1969), the measures are described in detail in Sections 3.3 to 3.6.

4.3.3.2 Measured variables

Instrumental Activities of Daily Living (IADL). Independence in daily functioning was measured using the Instrumental Activities of Daily Living questionnaire (IADL; Lawton & Brody, 1969). This questionnaire contains eight items reflecting everyday tasks (e.g. using the telephone, shopping, food preparation) with three to five associated descriptions that represent varying capabilities. Participants respond by selecting which description best matches their current level of ability. For example, participants can respond to item five 'Laundry' by selecting 1. "Does personal laundry completely", 2. "Launders small items – rinses socks, stockings, etc", or 3. "All laundry must be done by others". Each item is scored as either zero or one, with one reflecting independence in that task and zero indicating partial or complete inability to carry out that task (Lawton & Brody, 1969). Scores are summed to create a total score out of a possible eight.

The psychometric properties of the IADL have not been examined in great detail other than in one study in which the interrater reliability was tested (Graf, 2008) and reliability was established at 0.85. In the current sample of participants, the internal reliability of the scale was weak (α = 0.38). Nevertheless, the IADL has been validated cross-culturally (e.g. Ng et al., 2006) and is extensively used in ageing research (e.g. Facal et al., 2023; Nicholls et al., 2021). IADL score shows consistent associations with subjective cognitive decline (Liu et al., 2022), language difficulties (Wolff & Benge, 2019) and sensory impairments (Lin et al., 2019). Therefore, it was selected to include as a covariate in the core analyses.

Activity engagement. Activity engagement was measured using a short-form version of the Victoria Longitudinal Survey - Activity Lifestyle Questionnaire (VLS-

ALQ; Jopp & Hertzog, 2010; Marr et al., 2021; Small et al., 2012). In the current

sample of participants, the internal reliability for the overall scale was moderate but

not unacceptable (Menon et al., 2025; Table 2), especially given this version of the

scale was recently developed (Streiner, 2003).

Table 2

Reliability estimates for measured variables

Scale	Subscale	N items	Cronbach's alpha
IADL	-	8	0.38
VLS-ALQ	-	22	0.67
DASS-21Depression	-	7	0.87
DASS-21 Anxiety	-	7	0.69
DASS-21 Stress	-	7	0.81
MASQ	Language	8	0.77
	Visual-perceptual ability	6	0.70
	Verbal memory	8	0.84
	Visual-spatial memory	8	0.73
	Attention/concentration	8	0.77
LwD	Speech execution	5	0.59

Note. Instrumental Activities in Daily Living (IADL), Victoria Longitudinal Survey –

Activity Lifestyle Questionnaire (VLS-ALQ), Depression, anxiety and stress scale

(DASS – 21), Multiple Abilities Self-Report Questionnaire (MASQ), Living with

Neurological Difficulties (LwD).

Emotional wellbeing. Levels of depression, anxiety and stress were measured

using the Depression, Anxiety, Stress Scales – Short Form (DASS – 21; Lovibond &

Lovibond, 1995; Henry & Crawford, 2005). In the current research, the internal

reliability for each of the subscales ranged from acceptable ($\alpha = 0.70$) to good to ($\alpha =$

0.87; Table 2; Streiner, 2003).

Subjective cognition. Cognitive difficulty was measured using The Multiple

Ability Self – Report Questionnaire (MASQ; Seidenberg et al., 1994). In the current

sample, all scales showed acceptable to good internal reliabilities ($\alpha \geq 0.70$; Table 2).

Subjective speech execution. Subjective speech difficulty was measured using

an adapted version of Living with Neurological Difficulties (LwD; Hartelius et al.,

2008). In the current sample of healthy older adults, the internal reliability of the five items was $\alpha = 0.59$, reflecting relatively poor, but not unacceptable, internal reliability (Streiner, 2003).

Because speech execution is the primary outcome in this work, and due to the paucity of existing relevant scales (Section 3.4.1), 15 additional questions were developed for use in this study (appendix 3). These items were created based on speech subsystems theory (Lee et al., 2014), had been used in prior unpublished research and did not duplicate any items already covered in LwD. The items tapped into specific aspects of respiration (e.g. "I struggle to say more than a few words in one breath"), phonation (e.g. "My voice is quiet"), articulation (e.g. "I find myself mumbling") and intelligibility (e.g. "Most of my speech sounds are clear"). The questions were also scored on a five-point Likert scale (1 = never to 5 = always) to enable comparisons with LwD. The data obtained from these additional questions are reported descriptively in Appendix 3 to supplement the limited LwD speech execution subscale. Using the data from the current sample of participants, the Cronbach's alpha for these items showed good internal reliability at T1 ($n = 190$, $\alpha = 0.81$) and T2 ($n = 140$, $\alpha = .83$), one reason being because there are a higher number of items than the five included in LwD. In addition, there was good test-retest reliability in our sample of older adults with a significant correlation of 0.74 ($p < .001$). Responses from the 15 items were not included in the core analyses because further work is initially required to validate the items as a standardised scale. However, the descriptive data are drawn upon in the interpretation of the overall results. With further validation in other samples, these items could potentially be used in future research to measure speech execution.

4.3.4 Procedure

The first wave of data were collected between September and December 2022 using an online 'e-survey' on Qualtrics (https://www.qualtrics.com/) and a postal survey. Prior to data collection, the survey was piloted with staff and postgraduate students at the University of Strathclyde to determine usability and functionality of the e-survey. The link was found on study advertising materials which could be easily typed into a web browser or clicked on directly if the advert was viewed online via social media.

To reduce the risk of digital exclusion (section 3.2.1), paper copies of the survey were available upon request, which were returned via post using pre-paid return envelopes that were included with the survey materials. A total of 16 participants completed the Time point 1 (T1) survey via post (vs 188 e-survey responders). There were no differences between the e-survey and postal responders with regards to gender, ethnicity, general health, or independence in daily living (all $p > 0.1$). However, an independent samples t-test showed that participants who completed the postal survey were significantly older ($M = 75.07$, $SD = 6.80$) than the e-survey responders ($M = 70.22$, $SD = 6.52$, $p = 0.01$, two-tailed).

Participation was voluntary and no incentives or participation fees were offered. The survey took approximately 20 minutes to complete, and participants did so in the comfort of their own home, or any other location of their choosing. Participants were instructed that they could pause and return to the survey within 48 hours using the same device.

Participants who consented to being contacted again were invited to take part in the one-year follow-up. The survey was re-administered with these participants approximately 12 months later, with this second wave of data collection taking place between October 2023 and January 2024.

4.4 Data Analysis

The T1 dataset contained data that were missing completely at random (MCAR), confirmed by Little's Missing Completely at Random (MCAR) test (Little, 1988), $X^2 = 5024.41$, $df = 6358$, $p = 1.00$. Overall, there were less than 1% missing values (99.38% complete, 0.62% incomplete) in the raw data. According to Newman (2014), if there is item level missingness, data are MCAR, and constructs are being analysed (i.e. as opposed to item level analysis), then the participant's mean for that scale should be used. Further, this can be calculated from the available items, even if there is as little as one item available (Newman, 2014). Given there were very little missing data, data from the available items were therefore combined to create the variables (i.e. scales/subscales) needed to conduct the core cross-sectional analysis.

The timepoint two (T2) dataset also contained data that were MCAR, $X^2 = 4384.28$, $df = 4412$, $p = .61$. Not including attrition (which will be discussed below in section 4.8), there were even fewer missing values in the T2 dataset, with less than 1% of the raw data containing missing values (99.58% complete, 0.42% incomplete). Therefore, in accordance with Newman (2014), data from the available items were combined to create the variables needed to conduct the core longitudinal analysis. Measurement invariance (Putnick & Bornstein, 2016) was established prior to conducting any longitudinal analyses. This is discussed in more detail in section 4.6.

4.5 Cross-sectional results

Data analyses were carried out using IBM SPSS statistics version 27.0 (2020). First, assumptions of linearity, homoscedasticity and collinearity were assessed. Descriptive statistics were then calculated, and a correlation matrix was constructed to examine relationships amongst core variables (Table 4). Core data were then analysed using a hierarchical multiple linear regression, with speech execution (higher scores reflecting greater speech difficulty) as the outcome variable. Missing data were dealt with by selecting 'replace with mean' rather than listwise deletion to avoid losing data unnecessarily (Newman, 2014). The following covariates were entered into the model at step one: age, gender, years of education, general health, hearing, vision, depression, anxiety, stress, and IADL. At step two, activity engagement measured by the VLS-ALQ was entered to assess the relationship with speech difficulty, over and above the covariates entered at step one. Finally, all five cognitive subscales from the MASQ were entered into the model at step three (language, visual-perceptual ability, verbal memory, visual-spatial memory, attention/concentration) to determine the extent to which cognitive difficulties predict speech difficulty, over and above the covariates. Assumptions of normality, linearity, collinearity and homoscedasticity were checked using simple slopes, scatterplots, variance inflation factors (VIF) and a correlation matrix (Tabachnick, 2014). There was no evidence of violation of these assumptions (all VIF < 5; Thompson et al., 2017). Outliers were retained at this stage but will be discussed in more detail below.

4.5.2 Descriptive statistics

Descriptive data including age, gender, years of education, and smoking status can be found above in Table 1. Means and standard deviations of the responses to the 15 additional speech execution questions are presented in Appendix 2. The 15 items are grouped by speech subsystem: respiration, phonation, and articulation. The mean scores for each subsystem show that, numerically, older adults reported greater difficulty with phonation ($M = 12.05$, $SD = 3.33$) than with respiration ($M = 6.47$, $SD = 2.05$) and articulation ($M = 4.29$, $SD = 1.57$). Within the phonation subscale, the mean values for items six ("My voice is loud") and seven ("My voice is quiet") are notably higher than the other items (Appendix 3). Indeed, a frequency-based analysis showed that these items contained the greatest variation in responses with 37.7% of the sample reporting that their voice is sometimes loud, and 32.8% of the sample reporting that their voice is sometimes quiet. This suggests that older adults may have the most difficulty with controlling the volume of their voice when speaking, at least when measured via self-report.

Table 3 contains the means and standard deviations for core variables included in the analysis. For general health, hearing and vision the mean score is based on the original Likert scale data. However, these variables were re-coded into binary variables to be suitable for regression analysis.

Table 3

Sample means and standard deviations for core variables at baseline

Core variables	N	Mean	SD	mix-max
General Health	204	0.03	0.18	0 - 1
Hearing	204	0.09	0.27	0 - 1
Vision	204	0.02	0.14	0 - 1
Depression	204	5.80	6.15	0 - 26
Anxiety	204	3.17	3.84	0 - 22
Stress	204	7.44	5.67	0 - 30
IADL	204	7.93	0.33	5 - 8
VLS ALQ	204	65.30	18.37	28 - 137
MASQ language	204	1.72	0.45	1 – 3.13
MASQ visual-perceptual ability	204	1.68	0.50	1 – 3.17
MASQ verbal memory	204	1.95	0.52	1 – 3.75
MASQ visual-spatial memory	204	1.74	0.43	1 – 3.13
MASQ attention/concentration	204	1.83	0.43	1 – 2.88
Speech difficulty	204	6.97	1.93	5 - 14

Note. General health, hearing and vision were recoded into binary variables (0 = good, very good, 1 = fair, poor, very poor). Higher IADL scores represent greater independence. Higher VLS-ALQ scores represent greater activity engagement.

A correlation matrix containing predictor, control and outcome variables is presented in Table 4. Self-reported hearing, depression, anxiety, stress and all five MASQ subscales were significantly associated with speech difficulty. All correlations were positive, meaning that higher scores indicate more difficulties.

Table 4:

Mean values (with SDs) and Pearson correlations amongst predictor, control and outcome variables

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Age	-															
2. Gender	.094	-														
3. Years of education	-.240 ***	-.096	-													
4. General Health	.077	.060	-.089	-												
5. Hearing	.097	.139*	-.011	.345***	-											
6. Vision	-.05	.068	.024	-.027	.090	-										
7. Depression	-.005	-.076	-0.13	.129 *	.152 *	.166 **	-									
8. Anxiety	-.036	-.033	.064	.111	.263 ***	.105	.436 ***	-								
9. Stress	-.071	.001	.103	.028	.184 **	.089	.607 ***	.452 ***	-							
10. IADL	-.098	-.157*	-.036	-.122 *	-.213**	-.184 **	-.144 *	-.158 **	-.059	-						
11. VLS ALQ	.007	.045	.126*	-.161 *	-.046	.002	-.092	-.079	.043	.133 *	-					
12. MASQ language	-.033	-.050	.066	.082	.227 **	.148 *	.337 ***	.312 ***	.359 ***	-.096	-.094	-				
13. MASQ visual perceptual ability	.017	-.091	.015	.186 **	.154 *	.092	.307 ***	.311 ***	.297 ***	-.095	-.091	.514 ***	-			
14. MASQ verbal memory	.009	.041	.083	.063	.130 *	.201 **	.340 ***	.320 ***	.321 ***	-.081	-.100	.579 ***	.583 ***	-		
15. MASQ visual-spatial memory	.017	.071	.061	.052	.122 *	.096	.296 ***	.289 ***	.270 ***	-.071	-.111	.506 ***	.640 ***	.686 ***	-	
16. MASQ attention/concentration	-.050	-.028	.126 *	.066	.174 **	.034	.390 ***	.336 ***	.456 ***	-.051	-.020	.607 ***	.571 ***	.721 ***	.668 ***	-
17. Speech difficulty	.010	.015	.008	.003	.147 *	.112	.259 ***	.452 ***	.308 ***	-.011	-.041	.458 ***	.386 ***	.440 ***	.449 ***	.511 ***

Note. * < 0.05;   ** < 0.01; and *** < 0.001; N = 204; gender was coded as 0 = female, 1 = male, therefore a positive correlation with gender suggests greater values for males. Instrumental Activities in Daily Living (IADL), Victoria Longitudinal Survey – Activity Lifestyle Questionnaire (VLS-ALQ), Multiple ability self-report questionnaire (MASQ).

4.5.3 Core analysis

A hierarchical linear multiple regression was run on the T1 data to determine the extent to which cognitive variables predict speech difficulty, over and above the covariates. Outliers were visually inspected using boxplots. Significant findings were checked by removing any extreme outliers (values that are more than three times the interquartile range below the first quartile or above the third quartile; Field, 2018).

In model one, age, gender, years of education, general health, hearing, vision, depression, anxiety, stress and independence in daily living significantly accounted for 23.3% of the variance in overall speech difficulty, $F(10, 193) = 5.87$, $p < .001$, with anxiety being the only independent significant predictor ($p < 0.001$). In model two, the addition of activity engagement did not significantly contribute to the proportion of variance explained (23.4%) in overall speech difficulty ($R^2 = 0.23$, R^2 change = .001, $p = .62$; Table 5), although the overall model was still significant, $F(11, 192) = 5.34$, $p < .001$, with anxiety remaining as the only significant predictor ($p < 0.001$). In model three, the addition of cognitive variables significantly contributed to the variance in speech difficulty, over and above the variables entered in models one and two, $F(16, 187) = 7.83$, $p < .001$, $R^2 = .40$, R^2 change = .167, $p < .001$. In this model, language, visual-perceptual ability, verbal memory, visual-spatial memory and attention/concentration (table 5) accounted for an additional 16.7% of the variance. The overall model significantly accounted for 40.1% of the variance in overall speech difficulty, which is a large effect (Cohen, 1988). Two outliers with extreme high values on the anxiety measure were also outliers in the speech execution scale. These two outliers were removed, and the analysis was re-run. However, this did not affect the findings, therefore the outliers were retained.

In the final model, anxiety, language, and attention/concentration were significant independent predictors of speech difficulty (table 5).

Table 5

Standardised and unstandardised coefficients, significance tests and 95% confidence intervals for predictors of overall speech difficulty

Model		Standardised Coefficients	Unstandardised Coefficients				95% confidence intervals for B	
		B	B	*SE*	*t*	*p*	Lower bound	Upper bound
1	Age	0.04	0.01	0.02	0.54	0.59	-0.03	0.05
	Gender	0.03	0.13	0.28	0.47	0.64	-0.42	0.68
	Years of education	-0.02	-0.01	0.04	-0.32	0.75	-0.09	0.06
	General health	-0.06	-0.59	0.72	-0.81	0.41	-2.02	0.83
	Hearing	0.04	0.29	0.51	0.58	0.57	-0.71	1.30
	Vision	0.07	0.94	0.91	1.03	0.30	-0.85	2.73
	Depression	0.02	0.01	0.03	0.26	0.80	-0.05	0.06
	Anxiety	0.40	0.20	0.04	5.32	<0.001	0.13	0.27
	Stress	0.11	0.04	0.03	1.35	0.18	-0.02	0.10
	IADL	0.08	0.49	0.40	1.24	0.22	-0.29	1.27
2	Age	0.04	0.01	0.02	0.57	0.57	-0.03	0.05
	Gender	0.03	0.14	0.28	0.50	0.62	-0.41	0.69
	Years of education	-0.02	-0.01	0.04	-0.25	0.80	-0.09	0.07
	General health	-0.06	-0.64	0.73	-0.87	0.38	-2.08	0.80

	Hearing	0.04	0.30	0.51	0.58	0.56	-0.71	1.31
	Vision	0.07	1.00	0.91	1.05	0.30	-0.84	2.75
	Depression	0.02	0.01	0.03	0.22	0.83	-0.05	0.06
	Anxiety	0.40	0.20	0.04	5.27	<0.001	0.12	0.27
	Stress	0.12	0.04	0.03	1.39	0.17	-0.02	0.10
	IADL	0.09	0.51	0.40	1.29	0.20	-0.27	1.30
	VLS-ALQ	-0.03	-0.003	0.01	-0.49	0.62	-0.02	0.01
3	**Age**	.04	.01	.02	.64	.53	-.02	.05
	Gender	.04	.16	.26	.61	.54	-.35	.67
	Years of education	-.06	-.03	.04	-.92	.36	-.10	.04
	General Health	-.06	-.67	.67	-1.00	.32	-1.10	.65
	Hearing	-.01	-.04	.46	-.09	.93	-.96	.88
	Vision	.06	.85	.84	1.00	.32	-.82	2.51
	Depression	-.06	-.02	.02	-.82	.41	-.07	.03
	Anxiety	.33	.16	.03	4.79	<.001	.10	.23
	Stress	-.01	-.002	.03	-.06	.95	-.06	.05
	IADL	.08	.47	.36	1.31	.19	-.24	1.18
	VLS-ALQ	-.003	.00	.01	-.05	.96	-.01	.01
	Language	.17	.74	.33	2.24	.03	.09	1.39
	Visual-perceptual ability	.03	.10	.32	.30	.76	-.53	.72

Verbal memory	-.03	-.10	.35	-.28	.78	-.79	.60
Visual-spatial memory	.11	.50	.41	1.24	.22	-.30	1.30
Attention/concentration	.27	1.09	.40	2.74	.01	.31	1.87

Note. N = 204 for all variables, dependent variable = speech difficulty

In summary, the findings support our hypothesis that cognitive ability is associated with speech execution in older adults, even after controlling for age, health, demographic and psychological factors. In particular, the significant, independent predictors show that difficulty with attention/concentration and language, and greater anxiety all uniquely predicted individual's perceived speech difficulty.

The following section builds upon the cross-sectional findings by reporting the longitudinal results to determine causal, and potentially bidirectional, relationships between cognition and speech execution in healthy older adults.

4.6 Longitudinal findings

4.6.1 Method

4.6.1.1 Participants

Of the 204 participants who took part at T1, 158 participants provided complete data at T2, meaning 46 participants were lost to attrition. The reasons for attrition were explored using the demographic information collected at T1 (Banack et al., 2019). There were no significant differences between the two groups in terms of age, years of education, general health, hearing and vision (all $p > 0.13$; Table 6). For categorical variables, a chi-square test of association was carried out, showing no association between having complete data (i.e. data at both time points), gender or method of survey completion (i.e. online or via post; all $p > 0.05$). Only three participants expressed ethnicities other than white. Of these three participants, one did not complete timepoint 2.

4.6.1.2 Materials

The materials administered were the same as at T1 (see section 4.3.3 for a description of the measured variables) with the exception of the demographic information as it was not necessary to collect the same data again (e.g. age, gender, SES).

4.6.2 Data analysis

The data from T1 and T2 were analysed using IBM SPSS AMOS version 27.0 (Arbuckle, 2019) to investigate the relationship between the core variables – self-reported cognition and speech execution – over time, using cross-lagged panel models. The data were modelled according to each subscale of the MASQ, and their potential relationships with speech.

Prior to creating any of the cross-lagged panel models, measurement invariance was investigated for each of the core variables (language, visual-perceptual ability, verbal memory, visual-spatial memory, attention/concentration, speech execution). To comprehensively follow up the cross-sectional findings, measurement invariance was also established for the DASS-21 anxiety subscale, which was found to be a significant predictor of speech difficulty in the cross-sectional results. Measurement invariance assesses the psychometric properties of a scale, and their equivalence across repeated administrations, such as over different time points (Putnick & Bornstein, 2016). It is necessary to establish measurement invariance to determine whether any changes observed over time are theoretically

meaningful, and not due to a different structure or interpretation of the items in a scale.

4.6.3 Longitudinal results

4.6.3.1 Measurement invariance

Establishing measurement invariance is a necessary prerequisite to running any type of longitudinal analysis (Kline, 2023) because measuring true change over time requires the psychometric properties of a scale to be consistent across timepoints or groups. In the context of the current research, measurement invariance was carried out to ensure the self-report cognitive and speech execution scales were measuring the same constructs across repeated administrations (Kline, 2023). This was investigated through a series of four measurement steps. Configural invariance (baseline model) is the most lenient step, assessing whether the same items are measuring the same construct over administrations. Building on this, metric invariance (weak model) requires the factor loadings to be equivalent across administrations, and this is done by constraining the factor loadings across time points. Scalar invariance (strong model) builds on metric invariance by requiring that the item intercepts are also constrained over administrations. Finally, residual invariance (strict model) requires equivalence in the residual error terms across administrations (Putnick & Bornstein, 2019). Ideally, a minimum of metric invariance should be established across timepoints. This means that the baseline model must be an acceptable fit to the data and the metric model (where factor loadings are constrained) should not be a significantly worse fit to the data.

To examine model fit using the four stages of configural, metric, scalar and strict invariance we used multiple fit indices (Appendix 3) including Comparative Fit Index (CFI), Root Mean Square Error of Approximation (RMSEA) and Standardised Root Mean Square Residual (SRMR). Change statistics are examined using a cut-off of 0.01 for CFI and 0.015 for RMSEA (Chen, 2007), to ensure model fit did not worsen significantly. The detailed measurement invariance results, including change statistics for core variables, can be found in Appendix 4. The following section briefly summarises these results.

MASQ Language. Measurement invariance was established across the two timepoints for MASQ language subscale. Based on the CFI and RMSEA change values, scalar invariance (the strong model) was accepted and MASQ language was reliably retained for further longitudinal analysis.

MASQ Visual-Perceptual Ability. Measurement invariance was established across the two timepoints for MASQ visual perceptual ability. Overall, the CFI, RMSEA and SRMR values indicated good model fit for the metric model which also held for scalar invariance. Therefore, MASQ visual-perceptual ability was retained for further longitudinal analysis.

MASQ Verbal Memory. Measurement invariance was established for MASQ verbal memory across the two timepoints. The CFI and RMSEA change values show that the scalar model was a significantly worse fit to the data but, importantly, metric invariance was comfortably established for the verbal memory subscale. Therefore, MASQ verbal memory was retained for further longitudinal analysis.

MASQ Visual-Spatial Memory. Measurement invariance was established for MASQ visual-spatial memory across the two timepoints. In this case, the strictest

model (residual invariance) held as there was no significant worsening of model fit as the parameters became more constrained. Visual-spatial memory was therefore retained for further longitudinal investigation.

MASQ Attention/Concentration. Measurement invariance was established for MASQ attention/concentration across the two timepoints. Residual invariance was established as the CFI, RMSEA and SRMR values fell within the acceptable ranges, and the change values showed there was no significant worsening of fit, including for the strictest model. Again, these results provide evidence of measurement invariance and the suitability to include MASQ attention/concentration in further longitudinal analyses.

Speech execution. Measurement invariance was established for the speech execution subscale and scalar invariance was achieved. Therefore, it was acceptable to include the speech execution scale in the longitudinal analysis.

Anxiety. Measurement invariance was established for DASS-21 anxiety. Initially, only the RMSEA and the SRMR values were in the acceptable range for configural invariance, with the CFI values falling beneath the threshold for acceptable model fit. In addition, the change statistics showed that metric invariance could not be established due to worsening model fit. Modification indices (Byrne, 2016) were used to determine which factor loadings were potentially problematic (values greater than 10; Byrne, 2016). A modification index suggested there could be shared unexplained variance between DASS2 ("I was aware of dryness in my mouth") and DASS20 ("I felt scared without any good reason"). A correlated residual (i.e. a double headed arrow) was added to connect these items directly (their

error terms were allowed to correlate), and the metric model improved with change statistics showing no worsening of the metric model.

This improved the model to metric invariance and DASS-21 Anxiety was retained for further exploratory analysis.

In summary, a minimum of metric invariance was established for all core variables. Building upon this, the following section reports the cross-lagged relationships between these core variables, with speech execution as the outcome.

4.6.3.2 Longitudinal associations between cognition and speech

Cross-lagged panel models (CLPM) were used to explore relationships between the cognitive subscales and speech execution at T1 and T2. CLPM are a type of structural equation modelling used to assess reciprocal relationships between variables at multiple timepoints (Selig & Little, 2012). Autoregressive paths tested the stability of each variable from T1 to T2, while cross-lagged paths assessed whether one variable at T1 predicts change in the other variable at T2 (Figure 4).

While CLPM have been criticised for the inability to differentiate within-person processes (e.g. day-to-day state like change) from between-person processes (stable traits), the alternative option to use a random intercepts cross-lagged panel model requires three or more time points (Mackinnon et al., 2022). Therefore, the traditional CLPM was applied here, with limitations acknowledged in the interpretation of the findings.

Before examining the outcome of the models, the model fit was assessed using the same indices used to determine measurement invariance (Appendix 3). Key indicators are the size and significance of the regression paths (Mackinnon et al.,

2022). The model in Figure 4 shows unstandardised regression coefficients (*b*), which will be discussed in the accompanying text in addition to the standardised coefficients (β), which provide information about the strength of associations.

Figure 4:

Cross-lagged panel model examining reciprocal relationships between language and speech execution over two time points
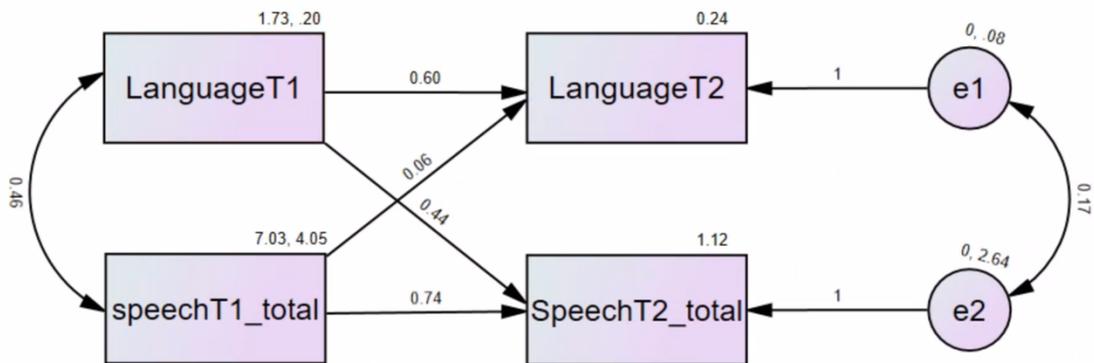
Note. statistics are unstandardised regression coefficients

For the language subscale, the overall model showed perfect model fit (CFI = 1.00, RMSEA = 0.58, SRMR = 0.00). Figure 4 provides an illustration of the language cross-lagged panel model. Speech execution at T1 was significantly associated with language at T2 (β = 0.263, *SE* = .013, *p* < .001), indicating that those who reported greater speech difficulties at T1 tended to report greater language difficulties at T2 (*r* = 0.57, *p* < .001). The unstandardised coefficient shows that a one-unit increase in speech difficulty at T1 predicted an increase of 0.06 in language difficulty.

In contrast, language at T1 did not significantly predict speech at T2 (β = 0.086, p = .196), contrary to our hypothesis that cognition would predict speech. This indicates that, although speech difficulty was associated with subsequent language production, a bidirectional relationship was not observed.

Both autoregressive paths were significant ($p < 0.001$) confirming the earlier test-retest reliability (appendix 4). Follow-up independent samples t-tests also confirmed that there were no significant differences amongst the mean values of the language and speech scales between T1 and T2 (Table 6), indicating that participants reported no significant worsening of language and/or speech abilities over 12 months.

Table 6

Differences in means and standard deviations of core variables at T1 and T2

Variable	Mean (*SD*)		
	T1	T2	*p*
MASQ Language	1.73 (0.44)	1.67 (0.45)	0.08
MASQ Visual-Perceptual Ability	1.70 (0.48)	1.69 (0.45)	0.65
MASQ Verbal Memory	1.97 (0.52)	1.97 (0.53)	0.98
MASQ Visual-Spatial Memory	1.74 (0.44)	1.72 (0.41)	0.27
MASQ Attention/Concentration	1.85 (0.48)	1.81 (0.46)	0.14
Speech	7.03 (2.02)	7.11 (2.29)	0.51

Note. Each MASQ subscale is computed by taking the mean of all items. Higher values represent greater cognitive difficulty. The speech subscale is summed to get the total. Higher values represent greater speech difficulty.

For the visual-perceptual subscale, the overall saturated model showed perfect fit to the data (CFI = 1.00, RMSEA = 0.54, SRMR = 0.00). In this model, visual-perceptual ability at T1 predicted speech execution at T2 (β = 0.13, SE = .070,

$p = .034$) in line with our hypothesis that cognition would predict speech. The unstandardised coefficient showed that a one-unit increase in visual-perceptual difficulty at T1 predicted an increase of 0.62 in speech difficulty.

Again, a bidirectional relationship was not observed as speech execution at T1 did not significantly predict visual perceptual difficulty at T2 ($p = 0.20$). Both autoregressive paths were significant ($p < 0.001$) confirming the earlier test-retest reliability (appendix 4). Follow-up independent samples t-tests also confirmed were no significant differences between visual-perceptual ability at T1 and T2 (Table 6), indicating no worsening of this ability over 12 months.

For the verbal memory subscale, the overall saturated model showed a perfect fit to the data (CFI = 1.00, RMSEA = 0.53, SRMR = 0.00). However, there were no significant cross-lagged correlations (all $p \geq .05$). Both autoregressive paths were significant ($p < 0.001$) confirming the earlier test-retest reliability (appendix 4). Follow-up independent samples t-tests also confirmed that there were also no significant differences in the mean values (table 6). This shows that there was no significant change over time in verbal memory and that verbal memory did not predict speech difficulty, or vice versa.

For the visual-spatial memory subscale, the overall saturated model showed a perfect fit to the data (CFI = 1.00; RMSEA = 0.52, SRMR = 0.00). There were no cross-lagged correlations between visuospatial ability and speech. Both autoregressive paths were significant ($p < 0.001$) confirming the earlier test-retest reliability (appendix 4). Follow-up independent samples t-tests also confirmed no significant differences between the mean values at T1 and T2 (table 6), therefore we

did not observe any change over time within or between visual-spatial memory and speech difficulty.

For the attention/concentration subscale, the overall saturated model showed a perfect fit to the data (CFI = 1.00, RMSEA = 0.58, SRMR = 0.00). Again, there were no cross-lagged correlations between attention/concentration and speech (all ≥ .05). Both autoregressive paths were significant ($p < 0.001$) confirming the earlier test-retest reliability (appendix 4). Follow-up independent samples t-tests also confirmed there were no significant differences between the mean values at T1 and T2 (table 6). Therefore, we did not observe any change over time within or between attention/concentration and speech difficulty.

4.6.3.3. Exploratory analysis

The significant predictors of speech execution at T1 were anxiety, attention/concentration, and language. These relationships were followed up in our longitudinal analysis. Longitudinal bidirectional relationships between language and speech execution, and attention/concentration and speech execution were modelled in the core longitudinal analysis reported above showing just one cross-lagged relationship between speech execution at T1 and language at T2. However, in the cross-sectional analysis (Section 4.5.3), anxiety was the strongest predictor of self-reported speech difficulty. Therefore, an additional cross-lagged panel model was developed to explore longitudinal bidirectional relationships between anxiety and speech execution. The saturated model was a perfect fit to the data (CFI = 1.00, RMSEA = 0.51, SRMR = 0.00). However, there were no significant cross-lagged relationships between anxiety and speech execution (all $p \geq .05$).

Sociodemographic variables that are time-variant were followed up longitudinally to examine potential reciprocal relationships between core variables and covariates. To maintain model parsimony, the MASQ overall mean score was used as a measure of generalised cognition. Longitudinal bidirectional associations were modelled using generalised cognition, activity engagement, independence in daily living and speech execution in one model. The model containing the four variables showed a perfect fit to the data (CFI = 1.00; RMSEA = 0.37, SRMR = 0.00). All autoregressive paths were significant: activity engagement at T1 significantly predicted activity engagement at T2 (β = 0.760, SE = .054, p = .001), indicating that those who reported higher levels of activity engagement at T1 were also those who reported higher levels of activity engagement at T2. However, there was no significant change in activity engagement from T1 based on the mean differences (M = 64.37, SD = 17.37) to T2 (M = 65.34, SD = 17.84, p = .32). Generalised cognition at T1 also predicted generalised cognition at T2 (β = 0.775, SE = .055, p = .001), but there was no significant change in mean scores over time (M_{T1} = 1.81, SD = 0.39; M_{T2} = 1.78, SD = 0.39; p = 0.135). Independence in daily living at T1 was also associated with independence in daily living at T2 (β = 0.620, SE = .097, p = .001). In contrast to the other variables, there was a slight but significant decrease in independence in daily living reported from T1 (M = 7.93, SD = 0.34) to T2 (M = 7.86, SD = 0.52, p = 0.03, d = 0.41). Importantly, there were no cross-lagged unidirectional or bidirectional relationships amongst cognition, activity engagement, independence in daily living and speech execution (all $p \geq$ .05).

In summary, no bidirectional relationships were observed but there were two significant unidirectional relationships between cognition and speech execution.

Speech difficulty at baseline predicted later language difficulty, but language difficulty at baseline did not predict later speech difficulty. Conversely, visual-perceptual ability at baseline predicted later speech difficulty, while the reverse was not found. This pattern supports the hypothesis that visual-perceptual ability, as one aspect of cognition, is linked to perceived speech execution ability. In contrast to the cross-sectional findings, where anxiety was the strongest predictor of speech difficulty, anxiety showed no longitudinal associations with any other variable, demonstrating that the significant longitudinal associations are likely not driven by anxiety or reporting bias. Finally, there was no significant change in perceived cognitive or speech difficulties over the 12-month follow-up.

4.7 Discussion

Previous research has highlighted that both cognitive and speech execution processes show age-related effects (Bilodeau-Mercure & Tremblay, 2016; Harnsberger et al., 2008; Sadagopan & Smith, 2013). Cross-sectional evidence demonstrates that cognitive difficulty is related to motor speech characteristics, such as prevalence of a motor speech disorder (Doneva, 2020) in clinical populations (Cay et al., 2024; Doneva, 2020; Watts, 2001). Control of articulatory features has also been linked to cognitive functioning in typical young adult speakers (Dromey & Bates, 2005; Guo et al., 2017; Liu et al., 2018), suggesting that similar relationships may be observed in typically ageing older adults. While some evidence reports objective relationships between cognition and speech execution (Manderson et al., 2025) the existing data are limited in several ways. These limitations stem from a lack of well-powered studies in the field that are predominantly cross-sectional in

nature, and challenges with specifying the cognitive and motor speech domain under investigation. Furthermore, no prior research has considered self-reported cognition and speech execution, limiting understanding of whether, and how individual's perceptions of these abilities are related. To our knowledge, the present study is the first to investigate potential relationships between self-reported cognitive abilities and speech execution in older age. Moreover, it is the first to investigate longitudinal, bidirectional relationships between cognition and speech execution.

The present aim was to determine the extent to which a range of core cognitive abilities (language, visual-perceptual ability, verbal memory, visual-spatial memory, attention/concentration) predicted speech execution. Additional demographic and health information (e.g., age, gender, general health, vision, hearing, depression, anxiety, and stress) was also collected. Furthermore, independence in daily living and activity engagement were included as covariates. Several key findings emerged from both the cross-sectional and longitudinal datasets.

4.7.1 Cross-sectional findings

Overall, subjective cognition was found to predict speech execution over and above relevant health and demographic variables. That is, people who reported greater cognitive difficulty also reported greater speech difficulty, even when controlling for key demographic, sensory, health and wellbeing, functional, and activity engagement variables. Therefore, the findings show that cognitive abilities, especially attention/concentration and language, are significant, independent predictors of self-reported speech difficulty. This supports our hypothesis, and adds to the body of objective evidence of a relationship between cognition and speech

execution in healthy ageing (Bilodeau-Mercure & Tremblay, 2016; Fournet et al., 2021; Goozée et al., 2005; MacPherson, 2019; Manderson et al., 2025; Tremblay et al., 2018, 2019b). Furthermore, anxiety was the strongest predictor of speech difficulty, indicating a robust association between psychological state and perceived speech ability, which is in line with theories of stuttering (e.g. Smith, 1999). These key findings will be discussed in detail in the following section.

The association between attention/concentration and speech difficulty may suggest that cognitive load influences older adults' ability to produce speech effectively. This interpretation aligns with findings from dual task studies that show articulatory characteristics such as speech rate, syllable rate, duration and articulatory accuracy are adversely affected when individuals engage in cognitively demanding secondary tasks (i.e. doing two things at once; Fournet et al., 2021; Kemper et al., 2009, 2011; Whitfield & Goberman, 2017). The effect appears to be more pronounced when the secondary task is demanding (Bunton & Keintz, 2008; Whitfield et al., 2021) and places a high demand on attentional or executive resources. This relationship is further supported by our recent systematic review (Manderson et al., 2025), in which most of the included literature focused on attention/executive processes and speech execution, typically assessed via correlational designs or experimental dual-task paradigms (e.g. Crutch et al., 2013; Kemper et al., 2009, 2011; Thies et al., 2020; Yu et al., 2019). However, prior research often investigates attention in isolation, limiting the ability to determine its unique contribution to speech execution relative to other cognitive functions. Conversely, the current study provides a more thorough approach by simultaneously examining multiple cognitive domains. The findings suggest that perceived

attention/concentration, a fluid cognitive ability, has a specific and independent relationship with perceived speech difficulty over and above other cognitive abilities including language, visual-perceptual ability, verbal memory, and visual-spatial memory.

The observed relationship between language ability and speech difficulty reinforces the interdependence of these two processes. This is in line with Parrell's (2019) framework (See Section 1.5) in which speech production is described as comprising several interconnected processes including language production, speech motor planning, control, and execution (see also Levelt et al., 1999 & Postma, 2000). Language production difficulties increase in frequency in older age including word-finding difficulties, reduced syntactic complexity and increased off-topic speech (Arbuckle & Gold, 1993; Mortensen, 2006; Kemper et al., 2001a, 2001b). The current research suggests that language difficulties could influence perceived difficulties with aspects of speech execution such as voice, articulation and/or fluency. However, given the cross-sectional and correlational nature of the data and analysis, it is not possible to determine the direction of this relationship. Indeed, it is also possible that speech difficulties might influence perceived language ability and/or other cognitive abilities (see Section 4.6.2 for longitudinal findings). Nonetheless, the results provide support for language being a cognitive ability that is independently associated with speech difficulty. Although these processes are theoretically separable (Parrell et al., 2019; Guenther & Hickok., 2016) future research would benefit from acknowledging their functional overlap by considering both processes, for instance, by controlling for speech execution subsystems in investigations of language production.

Notably, the strongest predictor of speech execution was anxiety, showing that those who self-reported greater levels of anxiety also reported greater speech difficulty. This association is consistent with broader literature in which anxiety, as well as depression and stress, often correlate with self-reported cognition (Spalding et al., 2021, 2025). This raises the possibility of response bias, whereby anxious individuals may be more likely to self-report more speech difficulties. However, given that anxiety, depression and stress were controlled in this study, it remains possible that there are direct relationships between anxiety and speech execution, suggesting that emotions also play a prominent role in how individuals perceive their speech output. It may be useful for SLTs to understand that anxiety is related to perceived speech difficulty, even in typical populations.

The relationship between anxiety and speech has been documented previously, but quite often in the context of public speaking (e.g. McNally et al., 2013; Kwaku Kankam & Boateng, 2017) or in clinical populations, particularly among people who stutter. Smith's (1999) multifactorial model of stuttering explains that speech stability is influenced by cognitive, linguistic, and emotional factors, therefore suggesting a framework in which anxiety can impact speech, even in non-clinical populations. However, research examining this relationship in typical ageing is limited. One experimental study (Baynard-Montague & James, 2023) demonstrated that individuals induced into a stressed mindset produced faster, but more error-prone speech when performing a 'tongue-twister' task, indicating that emotional states can impair fluency. In the current study, anxiety – but not stress – was associated with speech difficulty, supporting the idea that anxiety also uniquely predicts perceived speech difficulty, at least when assessed cross-sectionally. Further

research is therefore required investigating the effects of everyday trait and/or state anxiety on speech production, separate from stress (Grös et al., 2007; Osman et al., 2012). Furthermore, Lo et al. (2018) found that social anxiety moderated the relationship between propensity for self-monitoring and speech impairment. This suggests that those with higher levels of anxiety may experience greater speech difficulties due to being more likely to consciously control and monitor their speech, which disrupts the automaticity of the process (Lo et al., 2020). It is also possible that people with higher anxiety may be more sensitive in noticing subtle vocal changes, such as quivering or pitch instability (Weeks et al., 2012) leading them to self-report greater difficulty with vocal characteristics. The results of our descriptive speech questions support this, as phonation emerged as the main aspect of speech execution being affected. Lortie et al. (2015) found that the relationship between age and self-reported voice difficulty was moderated by depression and anxiety. Therefore, in the current study, anxiety could have influenced perceived speech execution regardless of acoustic factors. Further research is required investigating whether subjective speech difficulty is related to objective speech performance in typical ageing, while controlling for emotional factors (Section 5.0).

In summary, the cross-sectional findings reveal that cognitive ability is associated with speech execution in typical ageing. Furthermore, greater anxiety, attention/concentration and language challenges were each associated with greater speech difficulty. This suggests that individuals' perceptions of their speech are related to cognitive and emotional factors. While language and attention/concentration may influence individuals' speech ability (e.g. fluency, coherence), anxiety may influence individuals' perception of their speech

performance, resulting in greater perceived vocal difficulty. Importantly, the cross-sectional design limits the ability to infer the direction of causality or whether these relationships change over time. This highlights the need for longitudinal research to better understand these associations.

4.7.2 Longitudinal findings

The purpose of the longitudinal analysis was to assess potential enduring bidirectional relationships amongst cognition and speech. As such, data gathered at timepoint one (T1) and timepoint two (T2), 12 months apart, served to address the question of whether cognition may predict speech over time. Based on research reporting a bidirectional relationship between cognition and lifestyle engagement (e.g. Casey et al., 2021; Small et al., 2012), this also enabled us to assess whether baseline levels of cognitive and speech functioning may predict future cognitive and/or speech functioning.

Additionally, it was useful to examine whether any of the core variables showed significant change over time. Other than independence in daily living, which showed a small but significant decrease over the 12 months, none of the core variables showed any reliable change. This could be due to the short time frame between study waves. Twelve months was the longest feasible follow-up duration in the present research. However, it is acknowledged that this is a relatively short time period, compared to other similar longitudinal studies that measured such relationships over a number of years (Armstrong et al., 2019; Brown, 2016; Casey et al., 2021; Henning et al., 2023; Ihle et al., 2021; Small et al., 2012). Despite this, inclusion of the T2 data is a significant strength of this study, as it provided evidence

of good test-retest reliability for all variables, reinforcing the strength of the findings. The longitudinal findings also confirm that older adults experience, or perceive, very little change over the course of one year.

Additionally, several significant relationships emerged from the cross-lagged analyses. Notably, speech execution at T1 significantly predicted language ability at T2, showing that those who reported greater speech difficulty at baseline, also reported greater language difficulty 12 months later. However, the reverse was not found; language at T1 did not predict speech execution at T2. Therefore, the longitudinal association between speech execution and language ability, in this sample, appears to be unidirectional rather than bidirectional. This pattern of findings is contrary to our initial prediction based on psycholinguistic and speech motor control theories that suggest language precedes and drives speech execution. Abstract linguistic messages are formed in the mental system first, before the muscle-movement system is activated and speech is executed as articulation (Levelt et al., 1999; MacKay, 1982; Tourville & Guenther, 2011; Tremblay et al., 2015). However, an alternative model of speech production with reference to self-monitoring (Postma et al., 2015), highlights that there are many feedback loops linking speech and language at all stages of occurrence. Postma (2000) describes 11 feedback loops that occur when speaking with a conversation partner, culminating in 'knowledge of results', in which an individual sees or hears that their message has not been received, prompting detection and correction of speech errors. In older adults who may be experiencing increasing difficulty with speech execution, over time this may result in withdrawal from conversation, leading to declining language faculties. Given that speech functions as the vehicle for expressing spoken language (Borden,

1994; Freed, 2018), decreased speech usage may negatively impact linguistic ability over time. This aligns with the 'use-it-or lose it' hypothesis (Salthouse, 2006), which suggests that disuse of a skill leads to decline of ability. Future research should investigate the extent to which speech usage may influence cognitive factors, including linguistic processing. Furthermore, research may also benefit from investigating relationships between self-reported speech execution and levels of participation, especially in communicative settings (section 6.0). For example, it is possible that social withdrawal could mediate the relationship between self-reported speech execution and language production.

A second relationship emerged between visual-perceptual ability at T1 and speech execution at T2, showing that participants who reported poorer baseline visual-perceptual ability also reported greater speech difficulty at follow-up. Again, the reverse was not found showing that this relationship existed despite controlling for speech difficulty at T1. Visual-perceptual ability is a complex cognitive function requiring sensorimotor integration represented by different neurological pathways (Tsai et al., 2008). Generally, the ventral stream, spreading towards the superior temporal cortex, governs perception, and the dorsal stream, moving from occipital cortex to posterior parietal cortex, governs action (Goodale & Humphrey, 1988; Tsai et al., 2008). The visual perceptual system is therefore primarily concerned with control of goal-directed behaviour (Tsai et al., 2008). Producing speech is one behaviour that belongs to this category (Strijkers et al., 2011) and motor speech production is similarly a sensorimotor process (Tremblay et al., 2019a). From a neurological perspective, ageing is associated with deterioration of white matter tracts in the prefrontal cortex, which explains decreased activity during cognitive

tasks (Nordahl et al., 2006). The prefrontal cortex is also responsible for integration of top-down processes to drive goal-directed behaviour, including across sensory modalities (Knight et al., 1999). Neurological changes in the prefrontal cortex could therefore explain visual-perceptual difficulties and subsequent declines to speech execution, which requires cognitive control (Tremblay et al., 2019b; Tremblay & Deschamps, 2016). Indeed, a meta-analysis revealed that motor speech production consistently recruits the left inferior frontal gyrus (Broca's area), anterior insula, and dorsal anterior cingulate cortex, a network of regions involved in sensorimotor integration and cognitive control (Tourville et al., 2019). Taken together, this aligns with the common cause hypothesis (Baltes & Lindenberger, 1997) suggesting shared neurobiological ageing processes, particularly in the prefrontal cortex, explain age-related declines in distinct domains such as visual-perceptual ability and speech execution.

Contrary to previous research (Armstrong et al., 2019; Borgeest et al., 2020; Small et al., 2012), we did not find any cross-sectional or longitudinal relationships between activity engagement and any of our cognitive measures, nor did activity engagement significantly contribute to the variance explained in speech difficulty. This suggests that overall activity engagement may not be a strong predictor of self-reported cognitive or speech outcomes, at least over a one-year period. The reason for this null finding could be that the 12-month timeframe was too short to capture meaningful changes related to activity levels, especially since age-related decline is typically gradual.

This inconsistency with prior literature could also be due to our subjective measure of cognition, whereas past research has predominantly employed objective

measures (e.g. Casey et al., 2021; Lövdén et al., 2005; Small et al., 2012). Although objective measures are typically more sensitive to variability in performance, they may not sufficiently capture everyday cognitive difficulties experienced by older adults. To our knowledge, no prior similar research has utilised a self-report questionnaire to measure cognition in relation to the VLS-ALQ (Marr et al., 2021).

Finally, most previous research has investigated separate categories of social, intellectual and physical engagement (Casey et al., 2021; Kramer & Erickson, 2007; Phillips, 2017), whereas overall engagement was measured in the current research. Hatt et al. (2021) also found that overall activity engagement did not predict cognitive variables, whereas, when measured separately, cognitive activity predicted verbal cognition, and social activity predicted memory. There is some disagreement in the literature regarding the validity of activity domains and the extent to which they can be separated entirely due to the multidimensionality of activities (Gow et al., 2012; Kramer & Erickson, 2007). Further research over a longer duration is required to investigate whether cognition and speech production may be mediated by activity engagement.

Overall, the findings partially support the common cause hypothesis, which proposes that one common factor accounts for the increasing interdependence between sensory/sensorimotor and cognitive factors in ageing (Baltes & Lindenberger, 1997; Christensen et al., 2001; Li & Lindenberger, 1999; Lindenberger et al., 2000). Walking and grip strength are two sensorimotor abilities that appear to decline conjointly with cognition in ageing (Christensen et al., 2001; Lindenberger et al., 2000). However, speech execution is also a sensorimotor process (Tremblay et al., 2015) that has not been formally considered within the context of the common

cause hypothesis. Cross-sectional associations between attention/concentration and language ability and speech execution suggest overlapping declines across domains, potentially reflecting age-related changes to the functionality of networks in the prefrontal cortex. That anxiety was the strongest predictor likely reflects an independent influence of psychological processes on self-reported speech difficulty, rather than a shared biological mechanism. Conversely, longitudinal relationships between visual-perceptual ability and later speech difficulty, and between speech difficulty and later language ability support the idea of gradual shared decline across cognitive, sensory and motor domains (Baltes & Lindenberger, 1997).

4.7.3 Strengths and Limitations

This study benefitted from implementing a longitudinal follow up. Although it was not feasible to conduct a longitudinal study spanning more than one year in the context of this programme of research, the longitudinal data strengthens the findings, showing that older adults experience very little change over this time frame. Despite the cross-lagged panel models (CLPM) being the most appropriate type of analysis for longitudinal data with two time-points, CLPM are limited by the inability to disentangle within-person variability from between-person stability (Mackinnon et al., 2022). Future research would benefit from inclusion of an additional time-point so that alternative analyses that account for these limitations can be implemented, such as the random-intercepts cross-lagged panel model (RI-CLPM; Mackinnon et al., 2022).

Given the efforts to prioritise accessibility in this study, with the option to complete the survey online or via post, the sample benefitted from containing a

variety of postcodes in the United Kingdom (transformed to IMD rankings) and a wide range of ages (60 – 92). However, the survey was limited by use of self-report measures, of which the speech execution scale, although published, does not appear to be validated or standardised (Hartelius et al., 2008). Additionally, given the small number of items in this scale, it was not possible to disentangle the speech subsystems (e.g. articulation, phonation/respiration), nor was it possible to determine whether responses truly reflected speech ability or whether participants had conflated speech with language difficulties. Development and validation of a more comprehensive scale suitable for use in typical populations is needed, where subscales reflecting speech subsystems can be created. Such a scale would require that items reflecting speech are conceptually distinct from items that represent language, and that the difference between speech and language is emphasised to participants. Self-report data using this scale could then be compared with reference data on voice and speech characteristics (Duchin & Mysak, 1987; Goy et al., 2013) to determine whether older adults' self-perceptions of their speech execution ability (e.g. Whillans & Nazroo, 2014) are aligned with objective speech measures.

The MASQ (Seidenberg et al., 1994) has the benefit of investigating subjective cognition across five cognitive domains, reflecting participants' experiences in everyday life. Subjective reports of cognition are valuable as they have been associated with independence in daily living, social engagement and withdrawal and future dementia diagnosis (Jessen et al., 2020; Liu et al., 2022; Rotenberg et al., 2020). Inclusion of a range of cognitive abilities revealed significant and unique predictors of speech execution, based on responses to several items on a validated scale. However, responses may not be sufficiently accurate, as individuals

can be prone to underestimating or overestimating their own cognitive abilities. Furthermore, it may oversimplify multifaceted domains into a single dimension. For example, the items on the visual-perceptual scale, including assembling flatpack furniture, likely also requires attentional resources. Crucially, it is important that self-assessments are complemented with objective behavioural data to comprehensively understand whether cognition and motor speech abilities are related (See Chapters 5 & 6 for objective, lab-based studies).

Finally, this study was limited by the representativeness of the sample, who were self-selecting and primarily recruited via collaborating partners and word of mouth. In particular, the sample was predominantly white, well-educated and resided in areas of higher socioeconomic status. This could have influenced how individuals interpreted and responded to the items in the scales administered and limited variation in the outcomes.

4.7.4 Future Directions

Future longitudinal research would benefit from including a longer time frame between testing waves, or additional testing waves. Furthermore, it is important to assess whether these results are reflected in objective behavioural data. Given that both methods have their own strengths and limitations (see Section 3.3), approaching a research question using both methods is a reliable approach. To gain a more diverse sample, one avenue may be to include a diversity statement on any advertising materials and participant information sheet, to specifically invite those from a wider range of ethnicities and social backgrounds to participate, or approach specific, diverse groups directly.

4.7.5 Conclusions

To conclude, this study has identified some cross-sectional and longitudinal relationships between cognition and speech execution, therefore supporting our hypothesis. At baseline, self-reported speech difficulty was significantly predicted by anxiety, attention/concentration, and language ability, suggesting that specific cognitive processes, as well as psychological state, independently predict speech difficulty. Unidirectional longitudinal relationships were also observed, potentially revealing some causal connections between cognition and speech execution. However, the direction of these relationships differed by cognitive domain. Speech difficulty at baseline predicted later language difficulty, contrary to our hypothesis that cognitive decline would precede and drive motor speech difficulties. Conversely, and in line with our prediction, visual perceptual ability at baseline predicted later speech difficulty. This could suggest that age-related changes to the prefrontal cortex impede sensorimotor integration, affecting both visual-perceptual ability and subsequently speech execution. Therefore, the findings partially support the common cause hypothesis and show that speech execution is a sensorimotor process that should also be considered in this context. Future objective research is required to assess further whether relationships between fluid and/or crystallised cognitive domains differentially predict the speech subsystems of respiration/phonation and articulation.

4.8 Chapter Summary

This chapter presented the findings from the first study in this programme of research, a longitudinal investigation of relationships between self-reported cognition and speech execution in ageing. The data presented in this chapter were collected via a survey aimed at older adults in the United Kingdom. The same participants were invited to re-take the survey 12 months later. Self-reported anxiety, attention/concentration, and language ability significantly predicted speech difficulty at baseline. Speech execution at baseline predicted language 12 months later, whereas visual-perceptual ability at baseline predicted speech execution 12 months later. However, no longitudinal bidirectional relationships were observed. The subjective nature of this study calls for further assessment of relationships between cognition and motor speech production using objective behavioural data. This has been addressed in the following chapter, the second study in this programme of research.

5. Study 2 – Investigating relationships amongst fluid and crystallised cognition and speech execution subsystems in older adults

5.1 Chapter overview

The previous chapter presented Study 1, a cross-sectional and longitudinal investigation of relationships between subjective cognition and speech execution. The present chapter reports the findings from the second study (Study 2) in this programme of research. Study 2 builds on Study 1 by investigating relationships between cognition and speech execution using objective, behavioural data from a sample of 87 older adults. In this study, a range of cognitive tasks were administered, enabling composite measures to be created based on fluid and crystallised abilities (Horn & Cattell, 1966). In addition, a range of tasks measuring speech execution were administered enabling investigation of the extent to which cognitive domains predict articulation and/or phonation. The findings are discussed with reference to theoretical frameworks including speech motor control theories and the common cause hypothesis, before addressing the limitations of the work and suggested future directions.

5.2 Introduction

5.2.1 Background

There is a growing body of evidence showing that cognition is involved in speech execution (section 1.5). In ageing, gradual cognitive decline may impact on

speech execution subsystems, particularly articulation (Manderson et al., 2025). However, such relationships in typical ageing remain relatively underexplored with existing evidence often limited by poor quality study designs (section 1.6). Study 1 (section 4.0) contributed to this body of work by providing preliminary evidence that there are relationships between certain cognitive domains and speech execution, at least when measured using self-reports. However, subjective measures bring limitations such as potential reporting bias. Study 2 aims to address the limitations of prior published work and to extend the findings of Study 1 by employing objective, behavioural measures of both cognition and speech execution.

5.2.2 Fluid vs crystallised cognition

Ageing across the adult lifespan is associated with gradual changes to 'fluid' cognitive abilities including reasoning, memory, spatial orientation and perceptual speed (Salthouse, 2019) due to structural and functional brain changes (Cabeza et al., 2018; section 1.3.1). Conversely, 'crystallised' cognitive abilities tend to remain stable or even show improvement across the lifespan (Salthouse, 2010; Verhaeghen, 2003; section 1.3.1). These divergent patterns of growth, stability and decline are robust within the literature (Salthouse, 2019; Schaie, 2005; Schaie & Willis, 1993; Singer et al., 2003), demonstrating that fluid and crystallised cognition are separable domains. Inclusion of both fluid and crystallised cognition provides a theory-driven and comprehensive assessment of the potential cognitive predictors of speech execution.

In Study 1, it was not possible to separate self-reported cognitive abilities into fluid and crystallised domains because the Multiple Abilities Self-Report

Questionnaire (MASQ; Seidenberg et al., 1994) is validated for each individual cognitive subscale (language, visual-perceptual ability, verbal memory, visuospatial memory, & attention/concentration). The current study builds on the findings of Study 1 by considering fluid and crystallised cognition separately, based on a range of validated, objective cognitive measures (Section 5.3.3).

5.2.3 Speech execution: the laryngeal and articulatory subsystems

As discussed in Section 1.4.3, models of speech motor control, such as the Direction into Velocities of Articulators (DIVA), simulate the execution of speech motor programmes (i.e. speech execution) and focus on the neural basis of articulation (Guenther & Hickok, 2015; Tourville & Guenther, 2011). The recent laryngeal DIVA model (LaDIVA) of speech motor control (Weerathunge et al., 2022) separates the laryngeal subsystem (i.e. phonation) and articulatory subsystem. Research testing LaDIVA has suggested that the laryngeal and articulatory subsystems rely on partially distinct neural mechanisms (Weerathunge et al., 2022b; section 1.4.3). Therefore, there is a need for these subsystems to be considered separately (Karlsson & Hartelius, 2021), particularly in research that aims to clarify potential underlying mechanisms.

In Study 1, although we observed relationships between cognitive domains and speech execution, it was not possible to create subscales to investigate phonation and articulation separately due to the small number of items ($n = 5$) in the speech execution subscale. Study 2 addresses this limitation by selecting distinct behavioural speech tasks (Section 5.3.3) to assess outcomes associated with the laryngeal and articulatory subsystems independently.

5.2.4 Sensory and physiological decline

Models of motor speech control (Guenther & Hickok, 2015; Tourville & Guenther, 2011; Weerathunge et al., 2022) highlight the central role of sensory functioning to guide feedforward and feedback commands (section 1.4.3). In ageing, these commands may become impaired due to sensory declines (Cruickshanks et al., 1998; Houde & Huff, 2003; Lin, 2012; Tam & Koppel, 2021) resulting in difficulty with articulation and/or phonation. In addition, there are parallel age-related declines in sensory and cognitive domains (section 1.4.2) and the relationship is particularly strong between fluid cognition and sensory functioning (Baltes & Lindenberger, 1997). In contrast, the relationship between crystallised cognition and sensory ability is weaker, possibly due to crystallised cognition being less sensitive to biological ageing (Baltes & Lindenberger, 1997). It is possible that the same common factor underlying age-related declines in cognitive and sensory functioning (section 1.4.2) may also predict speech execution in ageing. Therefore, when examining the relationship between cognition and speech execution in older adults it is important to also consider the extent to which sensory decline contributes to articulatory and phonatory difficulties.

In Study 1, relationships between cognitive domains and speech execution were observed even after controlling for self-reported vision and hearing difficulties. This suggests that, despite the central role of sensory functioning in speech motor control (Guenther & Hickok, 2015; Tourville & Guenther, 2011; Weerathunge et al., 2022), cognitive processes may independently contribute to speech execution in ageing. However, given the limitations of subjective measures (section 3.3.1),

objective measures of sensory functioning are also required to more accurately test speech motor control theories by determining whether cognitive performance predicts speech execution, independently of sensory decline. Study 2 therefore includes objective measures of visual acuity and hearing (section 5.3.3) to control for sensory functioning.

Furthermore, physiological changes to respiratory, laryngeal and oral motor functioning are typically considered to be the primary cause of speech execution changes (section 1.4.4). However, the evidence is more consistent for phonatory difficulties (e.g. breathiness, reduced loudness), which are linked to physiological degeneration in the laryngeal subsystem (Caruso & Mueller, 1997; Rojas et al., 2020; Zraick et al., 2006). The evidence is less consistent for articulatory difficulties (section 1.4.4), which suggests that declines in oral motor functioning, such as tongue strength, plays only a small role in age-related articulatory differences (Goozée et al., 2005; Kuruvilla-Dugdale et al., 2020; Mefferd & Corder, 2014; Neel & Palmer, 2012). Therefore, physiological functioning must also be controlled when assessing relationships between cognition and speech execution.

In Study 1, physiological functioning was measured using self-reports of general health and by excluding participants with diagnosed speech or voice disorders. While this may have reduced some confounding, it did not allow direct assessment of physiological speech functioning, limiting the ability to rule out physiological degeneration as the primary predictor of speech execution in older adults. Study 2 addresses this limitation by applying the same exclusion criteria and additionally including two maximum performance tasks (MPTs) designed to strain the laryngeal and articulatory subsystems (section 3.4.3). These tasks enabled

assessment of the extent to which cognition is differentially associated with articulation compared to phonation, while reducing the confounding influence of linguistic processing.

5.2.5 Varying task complexity

MPTs lack ecological validity and may not accurately reflect speech execution in everyday communication (section 3.4.3). To understand whether cognition predicts speech execution in more naturalistic contexts, it is important to also include ecologically valid speaking tasks. Although MPTs are designed to tax the upper limit of an individual's physiological capacity, they may not be sufficiently cognitively demanding to detect potential relationships between cognition and speech execution. Findings from our systematic review suggest that relationships between cognition and articulation may exist only under more cognitively challenging conditions (Manderson et al., 2025), particularly where attentional or executive 'fluid' cognitive abilities are involved (section 1.6) such as during connected speech (Guenther & Hickock, 2015; Tremblay et al., 2017). However, to our knowledge, no prior research has investigated the relationship between cognition and speech execution across speaking tasks that vary in complexity (Maas, 2017).

Connected speech tasks are more ecologically valid than MPTs as they involve a communicative component engaging a range of cognitive and linguistic processes (section 3.4.4). In Study 1, participants were asked to self-report on their speech execution abilities, meaning it was not possible to test whether cognition predicted speech execution differently across speaking tasks.. Study 2 therefore

addresses this issue by including both MPTs and connected speech tasks. This allows for comparison of such relationships under conditions differing in complexity.

5.2.6 Cognitive screening

The absence of cognitive screening was identified as a key limitation of the published literature in our systematic review (Manderson et al., 2025). It is important to acknowledge that articulatory and phonatory features - such as pause time, speech rate, articulation rate and voice quality - are associated with degree of cognitive impairment in clinical samples (Cay et al., 2024; Martínez-Nicolás et al., 2022; Manderson et al., 2025; Themistocleous et al., 2020). Increasingly, speech analysis is being considered as an alternative, non-invasive method to identify early signs of cognitive impairment (De La Fuente Garcia et al., 2020; Martínez-Nicolás et al., 2021). Given this growing evidence base, it is crucial that research is carried out in healthy ageing to help ensure accurate classification of participants, and to be able to make reliable comparisons between typical and atypical speech patterns. In Study 1, cognitive screening was limited to self-report. In Study 2, eligible participants were required to pass a cognitive screening examination prior to study inclusion (section 5.3.3) addressing key limitations of previous research.

5.2.7 Aims, objectives & research question

Prior research demonstrates that there are significant relationships between cognition and speech execution in older adults when measured objectively (Manderson et al., 2025) and subjectively (Study 1; section 4.0). However, specific associations between cognitive domains (fluid vs crystallised cognition) and speech

execution subsystems (phonation vs articulation) are currently unknown. The present study aimed to investigate these specific relationships using objective, performance-based measures of cognition and speech execution, in a relatively large sample of healthy older adults.

The present research question asked to what extent do fluid and/or crystallised cognitive abilities predict the speech execution subsystems of phonation and/or articulation, over and above demographic factors, sensory functioning, and psychological wellbeing.

5.2.6 Hypotheses

There is emerging evidence of specific relationships between cognition and articulation but not phonation (Manderson et al., 2025). Therefore, our pre-registered hypotheses were (https://osf.io/9f3ax) that one or both cognitive domains (fluid and/or crystallised cognition) would significantly predict articulation but not phonation, when controlling for sociodemographic characteristics (e.g. age, gender, years of education, lifestyle engagement) and sensory functioning (vision and hearing). In addition, it was hypothesised that fluid cognition would explain more of the variance in speech execution than crystallised cognition given that the shared variance between fluid cognition and sensory functioning in older adults is stronger than that of crystallised cognition and sensory functioning (section 5.2.4). Finally, we explored whether potential relationships differed depending on task complexity. Given that MPTs do not contain a communicative component, and evidence suggests that cognitive-articulatory relationships emerge under more complex conditions (section 1.5 & 1.6), we proposed that cognitive-articulatory relationships may

emerge under more complex conditions (i.e. connected speech tasks section 1.5 & 1.6). However, this exploratory prediction was not pre-registered.

5.3 Methods

5.3.1 Design

This study was correlational and cross-sectional. The data obtained in the testing session informed two separate studies, Study 2, reported here, and Study 3 (section 6.0). Study 2 involved testing whether two tested variables (fluid and crystallised cognition) predicted articulatory measures (articulation rate from passage reading and monologue tasks, diadochokinetic 'DDK' rate, DDK coefficient of variation 'CoV') or phonatory measures (F0SD from monologue and sustained vowel tasks, maximum phonation time). A further 10 covariates were included: age, gender, years of education, activity engagement, depression, anxiety, stress, vision, hearing, and self-reported speech difficulty.

5.3.2 Participants

A G*Power calculation for multiple linear regression (fixed model, R^2 increase) indicated that the required sample size to detect a medium effect ($f^2 = 0.15$), with power set at 0.8 and alpha at 0.05, was N = 68. Participants were 89 healthy older adults (female = 57; male = 32; non-binary = 0), aged between 60 and 88 (Table 7). Two participants were excluded from the overall sample due to technical issues during the testing session, leading to complete missing data in one case, and missing data for core variables in the other case. The number of participants included in the analysis was therefore 87.

Prior to study inclusion, all participants carried out and passed a cognitive screening assessment using the Mini-Cog (Borson et al., 2000; section 3.2.3). Participants also completed a health screening questionnaire providing information about any chronic respiratory conditions, medication, and dentition. Sample characteristics are reported in Table 7.

Table 7

Sociodemographic and health characteristics (N = 87)

Variable		Min	Max	Mean (SD)/ Frequency (%)
Age		60	88	71.48 (6.71)
Gender	Female			55 (63.2%)
	Male			32 (36.8%)
	Non-binary			0 (0%)
	Prefer not to say			0 (0%)
Years of education		11	25	16.78 (2.53)
Highest education level	No schooling			0 (0.0%)
	Primary			0 (0.0%)
	Secondary/high school			3 (3.4%)
	Further education/college			20 (23.0%)
	University undergraduate			30 (34.5%)
	University postgraduate			31 (35.6%)
	Doctorate			3 (3.4%)
	Prefer not to say			0 (0.0%)
Ethnicity	White			85 (97.7%)
	Asian/Asian Scottish/Asian British			2 (2.3%)
	Mixed/multiple ethnic groups			0 (0.0%)
	African			0 (0.0%)
	Scottish/Black African			0 (0.0%)
	Caribbean/Black			0 (0.0%)
	Prefer not to say			0 (0.0%)
Employment status	Retired			85 (97.7%)
	Part-time			1 (1.1%)
	Self-employed			1 (1.1%)
	Full-time			0 (0.0%)
	Unemployed			0 (0.0%)
	Homemaker			0 (0.0%)
	Student			0 (0.0%)
	Prefer not to say			0 (0.0%)
Dentition (N = 86)	Uses dentures/plates			16 (18.4%)
	No dentures/plates			70 (80.5%)
Smoking status	Never smoked			48 (55.2%)
	Former smoker, quit < 5 years			2 (2.3%)
	Former smoker, quit > 5 years			35 (39.1%)
	Current smoker			3 (3.4%)
Glasses/contacts	Uses			81 (93.1%)
	Does not use			6 (6.9%)
Hearing aid	Yes			14 (16.1%)
	No			73 (83.9%)
Chronic respiratory disorder	Yes			9 (10.3%)
	No			78 (89.7%)
Chronic heartburn/reflex	Yes			13 (14.9%)
	No			74 (85.1%)
Feel differently today (e.g. common cold)	Yes			7 (8.0)
	No			80 (92.0%)
Speak other languages fluently	Yes			12 (13.8%)
	No			75 (86.2%)
SIMD decile	Most deprived (deciles 1 – 5)			22 (25.3%)
	Least deprived (deciles 6 – 10)			65 (74.7%)
Handedness	Right			81 (93.1%)

	left	5 (5.7%)
	both	1 (1.1%)
Relationship status	Single	11 (12.6%)
	Married/cohabiting	47 (54.0%)
	In a partnership	3 (3.4%)
	Separated/divorced	13 (14.9%)
	Widowed	13 (14.9%)

Note. there was one person with missing data for the dentition variable. Percentages exclude missing data. Postcodes were transformed into socioeconomic status deciles according to the Scottish Index of Multiple Deprivation (SIMD, 2020)

Participants were recruited through older adult participant panels at the University of Strathclyde, via older adult groups/networks across Scotland and through general advertising/word of mouth. Participants met the inclusion criteria by self-reporting good health generally, no diagnosed learning difficulties (e.g. dyslexia), cognitive impairment (e.g. mild cognitive impairment, dementia), neurological disorder that affected functioning (e.g. Parkinson's Disease, stroke, brain injury), speech, language and/or voice disorders (e.g. dysphonia, stutter, dysarthria, aphasia, apraxia of speech) or sensory impairment that could affect performance (e.g. blindness, deafness). Given that data were collected in person, participants received a £10 high street shopping voucher as a thank you for the time taken to travel to the University.

5.3.3 Materials

5.3.3.1 Self-report variables

Three self-report variables were also administered in Study 1 and are described in detail earlier (Section 4.3.3.2). These are: the Depression, Anxiety and Stress Scales (DASS-21; Henry & Crawford, 2005; Lovibond & Lovibond, 1995),

the Victoria Longitudinal Survey – Activity Lifestyle Questionnaire (VLS-ALQ; Marr et al., 2021) and the adapted speech execution subscale from Living with Neurological Difficulties (LwD; Hartelius et al., 2008).

For the DASS-21 and VLS-ALQ, internal reliabilities were similar to that of Study 1. In the current sample, DASS-21 internal reliabilities ranged from moderate for the anxiety subscale ($\alpha = 0.68$), to good for the depression ($\alpha = 0.79$) and stress subscales ($\alpha = 0.81$). Internal reliability for the VLS-ALQ was also acceptable ($\alpha = 0.70$). For speech execution, the Cronbach's alpha was higher in the current sample of older adults ($\alpha = 0.70$) than in Study 1 ($\alpha = 0.59$) suggesting more consistency in responses. This could reflect the controlled testing environment in the current study, contributing to greater focus and attention when answering the questions.

5.3.3.2 Objective sensory and cognitive measures

Nine tasks from the NIH toolbox (https://nihtoolbox.org/) were administered via an iPad air tablet (software version 15.7.9) to measure cognitive and sensory functioning. The tasks were administered according to the NIH toolbox scoring and interpretation guide: (https://www.nihtoolbox.org/app/uploads/2022/05/Toolbox_Scoring_and_Interpretation_Guide_for_iPad_v1.7-5.25.21.pdf).

For all NIH toolbox tasks (except the audition task; see scoring method for Words-in-Noise Test), uncorrected standard scores were used (relative to corrected standard scores), which compares the participant's score to the entire NIH toolbox normative sample (normative $M = 100$, $SD = 15$). This score was selected because it represents a person's overall functioning, regardless of certain demographic

characteristics such as age and gender, which were recorded separately and included in the analyses. The uncorrected standard scores also provided continuous data which is appropriate for regression analysis. This scoring method also enabled us to include participants aged 85 and over because the corrected standard scores can only be computed for up to age 85, despite the tasks being appropriate for ages beyond this (Nolin et al., 2023). In all cases, higher scores indicate better performance.

Visual Acuity Test. Visual acuity was measured using the NIH toolbox Visual Acuity Test. Participants were seated 3 m away from the iPad screen, which was situated at eye level. Participants who usually wore glasses were instructed to wear them. The task involved reading aloud letters that appeared consecutively on the screen, that decreased in size until the smallest optotype was identified. If the participant was unable to identify the first letter, the letter size increased until the participant successfully responded. The task took approximately 3 min to administer.

Words-in-Noise Test. Audition was measured using the NIH toolbox Words-in-Noise test. Participants wore Sennheiser HD201 headphones that met the NIH toolbox specifications (bandwidth/frequency response 21 – 18000 Hz; Sound pressure level – 108 dB). Participants who wore hearing aids were asked to remove them, in case of automatic adjustments to background noise or volume. Participants then repeated aloud single words spoken by a female voice that decreased in volume amid increasing levels of background babble. The test took approximately 6 min to administer, and the researcher scored the participant's responses using the iPad keypad during administration. Accuracy was calculated and a raw score generated for each ear (out of a possible 35) with higher scores indicating better performance. The score for the better (dominant) ear was used in the analysis, in line with the task

technical manual

(https://www.nihtoolbox.org/app/uploads/2022/05/Toolbox_Words_in_Noise_Test_Technical_Manual.pdf).

Fluid and Crystallised Cognitive Composites. The NIH toolbox provides composite scores of fluid and crystallised cognitive abilities using the seven cognitive tasks described below. The fluid composite comprises: Flanker Inhibitory Control and Attention Task; Dimensional Card Sort Test; Picture Sequence Memory Test; List Sorting Working Memory Test; and Pattern Comparison Processing Speed Test. The crystallised composite comprises the Picture Vocabulary Test and the Oral Reading Recognition Test. Composite measures are more reliable than performance on any single task (Amaefule et al., 2021) and ensures measurement of abilities rather than task performance per se.

Flanker Inhibitory Control and Attention Test. Inhibitory control and attention were measured by The NIH toolbox Flanker Inhibitory Control and Attention Test (Flanker). Participants indicated the orientation of the middle arrow in a row of five arrows during congruent and incongruent conditions. In the congruent condition all the arrows faced the same direction (e.g. pointing to the left). In the incongruent condition, the middle arrow faced the opposite direction to the other arrows (e.g. middle arrow faced left while the other 4 arrows faced right). Participants were instructed to always select the button that matched the direction of the middle arrow. Performance on the incongruent trials provided a measure of inhibitory control within the context of selective attention, also a measure of executive function. The distance travelled to touch the iPad was controlled by instructing participants to return their finger to 'home base', a point marked by a

circle situated close to the iPad. This enabled reaction time as well as accuracy to be recorded. The task lasted approximately 3 min and was scored automatically by combining both accuracy and reaction time data.

Dimensional Change Card Sort Task. Cognitive flexibility (e.g. task switching or set shifting) was measured using the Dimensional Change Card Sort (DCCS) task (Figure 5). Participants were shown two images that vary along the dimensions of shape and colour (for example, a white rabbit and brown boat; Figure 5). Participants were then shown a target image and asked to select which of the two images corresponded to the target image on one dimension (e.g. shape). Throughout the task, the dimensions switched so that at times participants were sorting by shape and at other times by colour. Accuracy and reaction time were recorded and combined automatically to produce an overall score. The DCCS task lasted approximately 4 min.

Figure 5

Sample item depicting Dimensional Change Card Sort (DCCS)
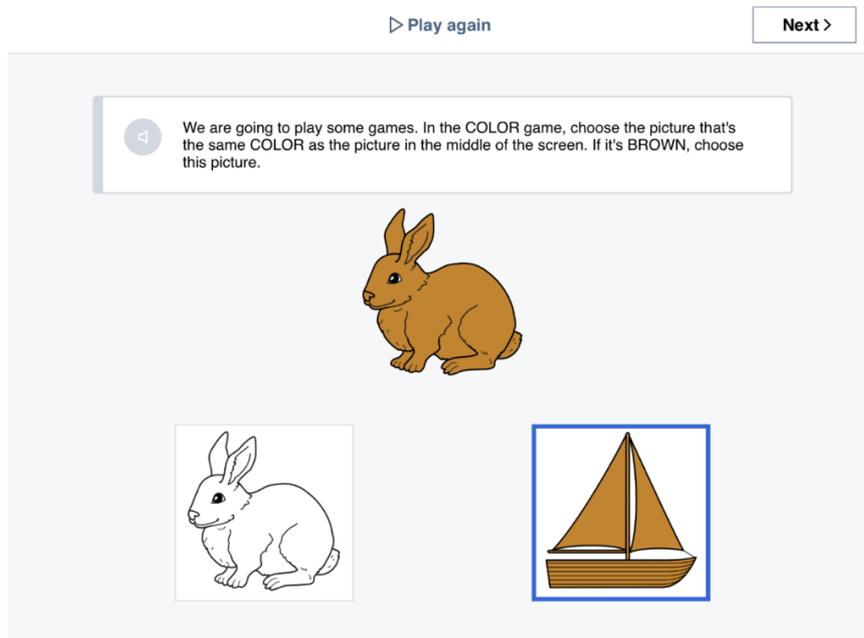
Note. Image reproduced with permission from NIH toolbox

(https://nihtoolbox.org/test/dimensional-change-card-sort-test/).

Picture Sequence Memory Test. Episodic memory was measured using the

Picture Sequence Memory Test (PSMT; Figure 6), which requires encoding, storage,

and effortful recall of new information, in sequential order. Participants were

required to recall a sequence of events (e.g. a camping trip) depicted by images,

which increased in length over two trials. The first sequence of pictures (the learning

trial) contained 15 images that were presented alongside an audio description. The

images were then scrambled before participants attempted to return the images to

their original position. The second sequence of pictures (the scored trial) contained

the same 15 images with 3 additional images included. Participants' scores were

generated automatically based on the second trial, with credit given for adjacent pairs of pictures correctly placed. The test took approximately 7 min to complete.

Figure 6

Sample item depicting the practice trial from the picture sequence memory test

Note. Reproduced with permission from NIH toolbox (https://nihtoolbox.org/test/picture-sequence-memory-test/).
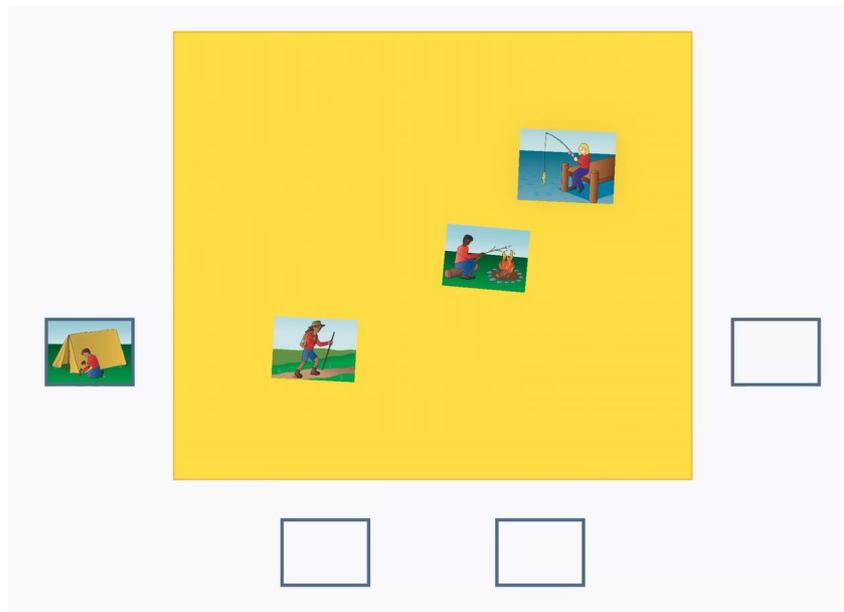
List Sorting Test. Working memory was measured using the List Sorting Working Memory Test ('list sorting') which requires immediate recall and sequencing of visual and auditorily presented items. Participants were first asked to recall items from one category (animals or food) and order them by size (from smallest to largest). For example, elephant, rabbit and sheep (correct recall - rabbit, sheep, elephant). Participants were instructed to pay attention to the size of the objects on the screen when ordering images by size, as the difference in size aligned

with that in the real world. Participants then recalled items in order of size across both categories (food first then animals). For example, orange, dog, corn, turtle (correct recall - orange, corn, turtle, dog). The number of items increased to a maximum of seven. The researcher scored the correct responses, and the task was terminated when, after two attempts, the participant could no longer accurately repeat any more item sequences (i.e. their memory span was at capacity), or if they reached the end of the task. Performance was scored automatically by summing the total number of correct items on both lists. The task took approximately 5 min to complete.

Pattern Comparison Test. Processing speed was measured using the Pattern Comparison Processing Speed Test (Pattern Comparison; Figure 7). Participants were asked to decide as quickly as possible whether two images were the same or different using the touch screen on the iPad to respond. The test took approximately 3 min to administer. Performance was scored automatically by summing the number of items correctly answered within the timeframe of 85 s (out of a possible 130 points).

Figure 7

Sample item depicting pattern comparison test

Note. Reproduced with permission from NIH toolbox

(https://nihtoolbox.org/test/pattern-comparison-processing-speed/).
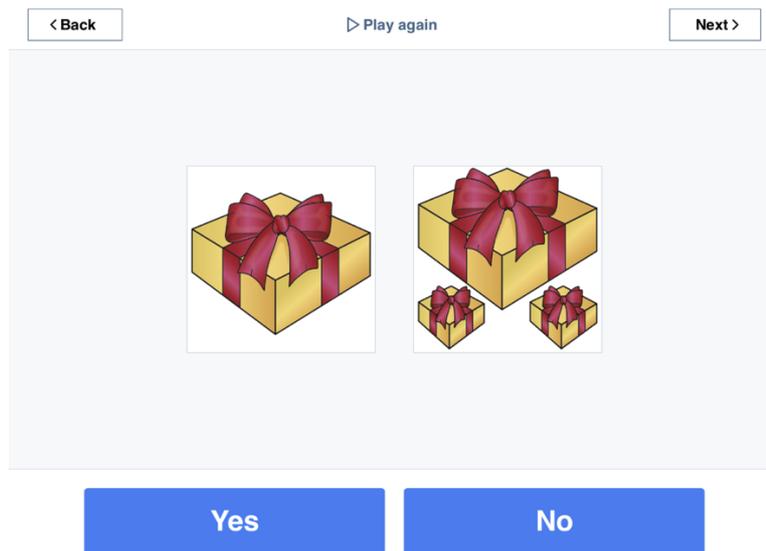
     Picture Vocabulary Test. Receptive vocabulary was assessed using the NIH

toolbox Picture Vocabulary Test (TPVT) which requires the participant to select

which of four pictures best describes the word they hear (e.g. "spoon; Figure 8). The

computer selects the difficulty of the following word based on the response of the

participant on previous items (i.e. it adapts to the participant's ability). Difficulty

increases by words becoming increasingly more abstract (e.g. herd, festive, didactic,

munificence). Scores are automatically generated and converted to a theta score,

which provides an overall measure of the participant's performance. The test takes

approximately 4 min to complete.

Figure 8

Sample item depicting the practice trial on the picture sequence vocabulary test
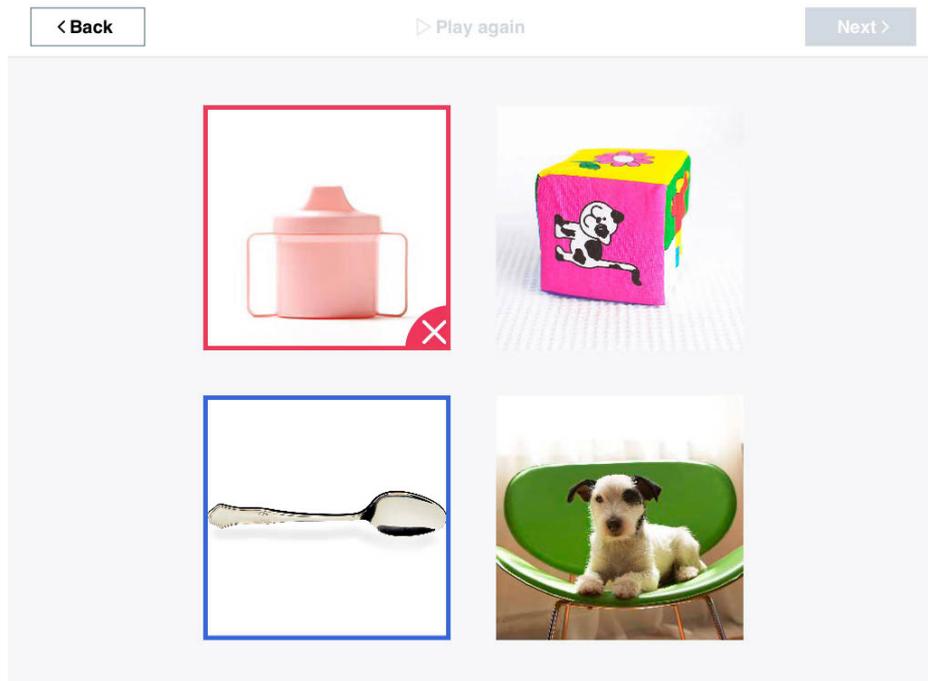
Note. Reproduced with permission by NIH toolbox

(https://nihtoolbox.org/test/picture-vocabulary-test/)

Oral Reading Recognition Test. Reading decoding was measured using the NIH toolbox Oral Reading Recognition Test (ORRT). Participants were asked to read aloud, and pronounce correctly, infrequent or irregularly spelled words (e.g. satiety, forisfamiliate). The researcher, who had previously learned the correct pronunciations, scored the correct responses using the keyboard. Again, a theta score was generated automatically and converted to a normed score. The task took approximately 3 min to complete.

5.3.3.3 Objective speech tasks

To measure speech execution, a suite of tasks comprising two maximum performance tasks (MPTs) and two connected speech tasks was administered (table 8). Guidelines set out by Rusz et al. (2021) were adapted and followed in the administration of the speech tasks (appendix 5). The guidelines provide specific instructions on administration of each of the tasks, including which, and how, tasks should be demonstrated by the researcher, number of repetitions, and common mistakes. The original guidelines were adapted specifically to suit the current study, by excluding versions of the tasks that we did not include (e.g. sustained phonation using the vowel /i/). Audio was recorded through an iPad air tablet (software version 15.7.9) using the application Voice Record Pro7 Full (Danaya Networks Ltd, 2022). Audio was recorded in .wav (PCM) format, with a sampling rate of 44,100, 16 bits, mono. See Table 8 for a description of the acoustic features derived from the speech sample.

Table 8

Speech parameters derived from analysis of speech tasks

Task	Speech parameter	Definition	Calculation
Sustained /a/	Maximum phonation time (MPT)	Assesses breath support for phonation.	Total duration (s) of voiced segment, excluding any audible breathing.
Sustained /a/ task & monologue	Fundamental frequency standard deviation (F0SD)	Fundamental frequency is perceived as pitch. F0SD is based on mean F0 and reflects stability of vocal fold function.	The standard deviation based on the mean F0 of the voiced segment.
DDK	DDK rate	Assesses speed of articulatory movements.	Total number of syllables divided by duration of task.
DDK	DDK rate coefficient of variation (DDK rate COV)	Assesses regularity of articulatory movements.	The standard deviation of syllable repetition length divided by mean syllable repetition length, multiplied by 100.
Passage reading task & monologue task	Articulation rate	Speed of articulation.	Number of syllables divided by total speech duration, excluding pauses > 200 ms

Sustained /a/ Task. For the first maximum performance task, a sound prolongation task, participants were asked to take a deep breath and sustain the vowel /a/ for as long as possible until they ran out of air (Rusz et al., 2021). Participants were asked to complete two trials of the sustained phonation, and the longer one was used in the analysis. Providing two attempts allowed participants to become familiar and comfortable with the task, while also reducing the risk of fatigue or exertion from additional repetitions.

Diadochokinetic (DDK) Task. The second maximum performance task was a (DDK) task. Participants were asked to repeat the syllable string (/pataka/) as quickly and accurately as possible on one breath. Participants completed two trials, and the 'best' trial was used for the analysis. The best trial was selected based on the accuracy of the syllable repetitions (i.e. syllables pronounced correctly and shortly) which is more important than velocity (Rusz et al., 2021) as well as the length of the trial. If the two trials were similar in accuracy the longer one was selected for use in the analysis, as a minimum of 12 repetitions is required (Rusz et al., 2021). The parameters extracted from the DDK task were DDK rate and the coefficient of variation (CoV; see table 8 for definition).

Rainbow Passage. The first connected speech task was a passage reading task. The Rainbow Passage (appendix 6) is a commonly used reading task in English (Rusz et al., 2021), containing most of the phonemes used in English, and has been used previously in research with older adults (e.g. Goy et al., 2013). Participants were asked to read aloud the passage which was printed on A4 paper using 24-point size. Participants did not read through the passage silently before reading it aloud to

reduce the potential influence of reading style or prosody on articulation rate, which may become more pronounced in rehearsed reading. Participants recited the passage only once, to avoid fatigue, particularly given the large battery of tasks. Connected speech obtained from the task was analysed for articulation rate, calculated as syllables per second (table 8).

Monologue Task. Finally, participants were asked to provide a spontaneous monologue about a topic of their choice, for example, a recent or favourite holiday, hometown, or hobbies (Rusz et al., 2021). Participants were asked to speak for 90 s, which was timed by the researcher. The middle 30 s of the connected speech produced was analysed for articulation rate and F0SD (table 8). This approach was chosen to avoid dysfluencies and hesitations commonly present at the beginning and end of speech.

5.3.4 Procedure

Data were collected during one testing session, lasting approximately 1.5 hr, in a quiet room in the University of Strathclyde. Participants attended the lab and, after providing informed consent, completed the cognitive screening task. All participants then went on to complete the paper-based health screening and demographic questionnaires (section 5.3.2). Participants then completed the objective tasks beginning with the two sensory tasks, the Visual Acuity Test followed by the Words-in-Noise Test. Participants then completed the seven cognitive tasks in the following order: Picture Vocabulary Test, Oral Reading Recognition Test, Working Memory List Sorting, Pattern Comparison Test, Picture Sequence Memory

Test, Flanker Inhibitory Control and Attention Test and the Dimensional Card Sort Test. Participants were then offered a 10 min break, after which paper-based versions of the Victoria Lifestyle Survey- Activity Lifestyle Questionnaire (VLS-ALQ; Marr et al., 2021) and the Lubben Social Network Scale (Lubben et al., 2006; described in Section 6.3.3) were administered. Following this, participants completed the speech assessment. First the MPTs (Sustained Vowel Task followed by the DDK Task) were carried out. Then the connected speech tasks (Ranbow Passage followed by the Monologue Task) were completed. Finally, participants completed a further three paper-based self-report questionnaires, including the Communicative Participation Item Bank (CPIB; Baylor et al., 2013; described in Section 6.3.3), the self-reported speech execution scale (Harteluis et al., 2008) and lastly the DASS-21 (Osman et al., 2012).

5.3.5 Data analysis

Speech analysis. For all speaking tasks, the data were analysed using Praat 6.2.23 (Boersma & Weeninck, 2023). For each participant, the recordings from each speaking task were uploaded to Praat. For each recording, a text grid was created so that the speech data could be annotated to extract the following speech parameters: Maximum phonation time and the standard deviation of fundamental frequency were taken from the sustained vowel task; DDK rate, DDK coefficient of variation were calculated from the DDK task; Articulation rate was calculated from the passage reading task; finally, F0SD and articulation rate were calculated from the monologue task. Most annotations were conducted manually. For F0 analyses (see Section 5.5.3

for a definition), a Praat script, developed by Hirst et al. (2011), was used to adjust the measurement settings for F0 in the sustained vowel and monologue tasks to improve pitch tracking. This script was used to automatically adjust the settings for each male and female speaker by changing the default pitch floor and ceiling values to 50 Hz and 700 Hz respectively. Then, based on the first and third quartiles, new values for the pitch floor and ceiling are estimated, with the pitch ceiling set to a higher value to reduce errors with the pitch tracker (Hirst, 2011). In addition, WebMAUS basic (Schiel, 1999) was used to orthographically transcribe the monologue task, before manually segmenting and annotating the syllables and pauses. For details on how each speech task was analysed see Appendix 7.

Ten percent of the audio files from each task were also analysed independently by a second, expert reviewer with 20 years' experience in speech analysis to ensure consistency in the annotation and subsequent analysis. The inter-rater reliability statistics were good and are reported below in the results, Section 5.4.

Statistical Analysis. For the statistical analyses, assumptions of normality, homoscedasticity and collinearity were first checked, and outliers explored (see Results, Section 5.4.2). Descriptive statistics were then calculated, and a correlation matrix was used to examine bivariate relationships amongst core variables (table 10). The core analyses involved a series of hierarchical multiple regressions to assess the extent to which fluid and/or crystallised cognition predicts articulation and/or phonation, over and above demographic, lifestyle and wellbeing factors (Section 5.4.6)

Core Analysis - Primary. The first set of analyses consisted of three regression models to examine potential effects of fluid and/or crystallised cognition

on speech execution using the outcomes from the most ecologically valid tasks: the passage reading task and the monologue task. At step one, age, gender (male/female), years of education, activity engagement, depression, anxiety, stress, and speech difficulty were entered into the model. At step two, visual and auditory ability were entered into the model. At step three, fluid and crystallised cognition were entered into the model. The three primary outcome measures were articulation rate based on the passage reading task, articulation rate based on the monologue task and F0SD taken from the monologue task. The articulation rate measures are reflective of the articulatory subsystem, while F0SD is reflective of the phonatory subsystem.

Core Analysis- Secondary. The second set of analyses consisted of four regression models to examine cognitive predictors of speech execution performance in the more constrained MPTs. The variables were entered into the model in the same way as in the primary analysis. The four secondary outcomes were: DDK rate and DDK coefficient of variation (CoV), both taken from the syllable repetition (DDK) task which reflect the articulatory subsystem, maximum phonation time and F0SD, both taken from the sustained vowel task which reflects the phonatory subsystem.

5.4 Results

5.4.1 Inter-rater reliability

The second, expert rater independently completed the acoustic analysis for all speech tasks on 10% of the speech data files ($n = 9$). *T*-tests were run to examine any significant mean differences in the two raters' results. There were no significant differences between raters for MPT, F0SD, DDK rate, DDK rate CoV, and

articulation rate (Table 9) Therefore, the first rater's data were used in the statistical

analysis.

Table 9:

Mean, standard deviation and p-values for interrater reliability analysis

Task	Measure	Rater 1 Mean (*SD*)	Rater 2 Mean (*SD*)	*p*
Sustained /a/	Maximum phonation time (secs)	16.35 (5.77)	16.36 (5.84)	1.00
	F0 SD prolonged vowel (Hz)	8.16 (9.10)	8.16 (9.12)	1.00
DDK	DDK rate (syll/sec)	6.24 (1.05)	6.23 (0.82)	0.98
	Coefficient of Variation, CoV (%)	28.05 (8.25)	22.69 (2.90)	0.09
Passage	Articulation rate (syll/sec)	4.38 (0.67)	4.44 (0.50)	0.82
Monologue	Articulation rate (syll/sec)	4.14 (0.57)	4.18 (0.46)	0.88
	F0 SD (Hz)	34.27 (25.62)	34.20 (25.70)	1.00

Although there was no significant difference in the raters' CoV values, the

means showed slightly more deviation compared to other variables. This was driven

primarily by a single participant who was subsequently excluded from some analyses

due to poor articulatory performance. Upon review, it was found that one rater had

counted every syllable attempt, including incorrect repetitions, while the other rater

excluded incorrect syllable repetitions.

5.4.2 Missing data

The data met assumptions of normality, collinearity and homoscedasticity of

residuals. Missing data patterns were explored using Little's Missing Completely at

Random (MCAR) test (Little, 1988) on the raw data. The test confirmed that data

were missing completely at random, x^2 (279) = 266.06, p = 0.70. With just eight

values missing from the overall dataset. The missing values were all contained in the

variables that had been measured via self-report (e.g. DASS-21). The researcher was

available for questions at the time of data collection; therefore, the missing data are likely due to participants accidentally skipping an item or preferring not to respond to a particular item. Given the large number of variables, imputation procedures were not performed. Instead, the subscales were scored using the available data (e.g. the mean of available items; Newman, 2014) and included as covariates in the regression.

5.4.3 Correlations

Although the core analyses are the regression models, it was of interest to explore preliminary patterns amongst the bivariate correlations. Table 10 displays bivariate correlations between predictor, control, and outcome variables. Older age was associated with poorer hearing and fluid cognition, but was not associated with crystallised cognition.

Table 10

Correlation matrix of predictor, control, and outcome variables.

	M (SD)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. Age	-	-																	
2. Gender (0 = male, 1 = female)	-	-.04	-																
3. Education years	-	.08	-.09	-															
4. Vision	94.02 (13.84)	-.13	-.04	-.12	-														
5. Hearing	19.15 (5.26)	-.46 **	.28 **	-.13	.11	-													
6. Fluid cognition	92.13 (9.24)	-.48 **	.14	-.07	.15	.21	-												
7. Crystallised cognition	118.23 (5.72)	.14	.08	.19	-.08	-.16	.10	-											
8. Depression	3.84 (4.30)	-.03	-.13	-.03	.10	-.14	.05	.05	-										
9. Anxiety	3.59 (4.19)	.05	-.17	-.01	-.01	-.17	-.04	-.05	.35 **	-									
10. Stress	8.90 (6.55)	.05	-.05	.12	-.11	-.19	-.05	.17	.37 **	.54 **	-								
11. Speech difficulty	8.97 (2.50)	.06	.04	-.20	.05	-.09	-.10	-.03	.21	.34 **	.36 **	-							
12. Activity engagement	71.45 (18.14)	-.19	.01	.01	-.08	-.07	.13	-.01	-.15	-.05	.06	-.11	-						
13. MPT	14.91 (5.70)	.04	-.07	-.04	.03	-.03	-.35**	-.03	-.14	-.03	-.14	-.24 *	-.15	-					
14. F0SD vowel	14.90 (16.24)	.13	.17	-.05	-.08	-.17	-.03	.10	.09	-.10	.04	.12	.02	-.02	-				
15. DDK rate	5.78 (0.78)	-.19	-.09	-.05	-.04	.10	.41**	.24 *	-.11	-.10	.03	.05	.20	-.34 **	-.02	-			
16. DDK CoV	26.25 (6.11)	-.19	.01	-.03	.03	-.03	.02	-.05	.25*	.15	.12	.15	.04	-.08	.28**	-.03	-		
17. AR (passage)	4.52 (0.54)	-.20	-.06	-.30	-.00	.49	.21*	.10	.12	-.04	-.05	.03	-.01	-.23*	.10	.47 **	.08	-	
18. AR (monologue)	4.07 (0.54)	-.03	.11	-.03	-.03	.13	.13	.58	.02	-.13	.11	-.04	.06	-.03	.06	.24 *	-.11	.36 **	-
19. F0SD (monologue)	41.79 (17.94)	.10	.10	.08	.08	.06	.10	.15	-.01	.02	.06	-.06	.001	.02	.29 **	.02	.02	-.19	-.0

* correlation is significant at the .05 level (two-tailed)*,* ** correlation is significant at the .001 level (two-tailed), Maximum Phonation Time (MPT), Fundamental Frequency Standard Deviation (F0SD), DDK coefficient of variation (CoV), Articulation Rate (AR)

There were several significant relationships between cognitive and speech outcomes. Fluid cognition showed small-to-medium correlations with DDK rate and articulation rate from the passage reading task, showing that higher fluid cognitive abilities were related to faster articulation rates. Surprisingly, fluid cognition was negatively associated with maximum phonation time, which is contrary to our prediction that there would be no association between cognition and phonatory characteristics. Furthermore, the negative relationship runs counter to intuitive expectations by indicating that better cognition was related to shorter vowel prolongations. Crystallised cognition showed a small but significant association with faster DDK rates.

In contrast to the Study 1 findings, in which self-reported cognition was associated with self-reported speech difficulty, here fluid and crystallised cognition were not associated with self-reported speech difficulty. However, self-reported speech difficulty showed medium positive associations with self-reported anxiety and stress. For the objective speech parameters, self-reported speech difficulty showed a small but significant association with maximum phonation time, indicating that greater subjective speech difficulty was related to shorter phonation times. This suggests that older adults show a degree of accuracy in self-reporting their phonatory abilities, which supports the findings of Study 1.

Finally, there were significant small-to-medium sized correlations amongst the objective speech outcomes themselves. Counter to intuitive expectations, longer maximum phonation time was associated with slower DDK rate. Since breath support is involved in both tasks, it is possible that those with stronger breath support,

as shown by longer maximum phonation times, favoured accuracy over speed in the DDK task. DDK rate was also positively associated with articulation rate in both the passage reading task and the monologue task, as both measures assess articulatory agility. Fundamental frequency standard deviation (F0SD) from both the sustained vowel task and the monologue task showed small positive correlation, indicating that both tasks capture partially overlapping aspects of phonatory ability. Finally, F0SD from the prolonged vowel task was positively associated with DDK rate CoV, indicating that variability in phonation is related to variability in articulation in a small but significant way.

5.4.4 Primary Analysis

The primary analysis involved investigating outcomes from the connected speech tasks which are considered more ecologically valid. Three hierarchical multiple regression models were run to examine predictors of F0SD (monologue) and articulation rate (passage reading and monologue). In step one of the model, age, gender (0 = male, 1 = female), years of education, activity engagement, depression, anxiety, stress, and speech difficulty were entered. At step two, vision and auditory ability were entered into the model. Finally, at step three, fluid and crystallised cognition were entered into the model. The standardised coefficients, beta weights and 95% confidence intervals are reported in Appendix 8. Analyses were run with and without outliers identified in the core variables.

Articulation Rate from Passage Reading Task. The overall regression model was not significant, $F(12,74) = 0.97$, $p = .49$, nor were there any independent,

significant predictors of articulation rate (all $p > .07$; Appendix 8). For this measure of articulation rate there was one outlier, removal of which did not affect the results.

Articulation Rate from Monologue Task. The overall regression model was not significant, $F(12,74) = 1.05$, $p = .41$, nor were there any independent significant predictors of articulation rate (all $p > .07$; Appendix 8). Removal of four outliers did not affect the results, therefore outliers were retained.

F0SD from Monologue Task. Initially, the overall regression model was not significant, $F(12,74) = .53$, $p = .89$, nor were there any significant independent predictors of F0SD (all $p > .13$; Appendix 8). However, four outliers were identified that showed extreme high values for F0SD. Inspection of these outliers indicated that the pitch tracker in Praat had not accurately predicted pitch for these values. These outliers were removed, and the analysis was re-run in the smaller sample of 83 participants.

Step one of the model was significant, with sociodemographic variables predicting F0SD, $F(8,74) = 3.03$, $p = .005$. Step two of the model, with vision and hearing included, was also significant, $F (10,72) = 2.62$, $p = .009$. However, these sensory variables did not significantly predict any of the variance over and above the step one variables ($p = .37$). Step three of the model, with cognitive variables included, was also significant, $F(12,70) = 2.33$, $p = .01$. However, the cognitive variables did not significantly predict any unique variance. Together, the variables accounted for 29% of the variance in F0SD. In all three models, gender and speech difficulty were significant independent predictors. With all variables entered into the model, gender was positively associated with F0SD ($\beta = .39$, $p < .001$) indicating that being female was associated with higher F0SD (higher variability). In addition,

perceived speech difficulty was negatively associated with F0SD (β = - .29, p = .02), indicating that greater perceived speech difficulty was associated with lower F0SD (lower variability/more stable pitch).

5.4.5 Secondary analysis

DDK Rate. Steps one and two of the model were not significant and there were no significant independent predictors (all p > .07). However, step three of the model was significant, indicating that inclusion of the cognitive variables significantly predicted a proportion of the variance in DDK rate, over and above the other sociodemographic and sensory variables, $F(12,74)$ = 3.07, p = .001. All the variables together accounted for 33% of the variance in DDK rate, a large effect (Cohen, 1988), with fluid and crystallised cognition uniquely predicting 21% of the variance. In terms of individual predictors, gender was negatively associated with DKK rate (β = -0.25, p = .02), indicating faster DDK rates were related to being male. Crystallised cognition was positively associated with DDK rate (β = 0.23, p = .03) indicating that those with better crystallised cognition had faster DDK rates. Fluid cognition was the strongest predictor of DDK rate (β = 0.43, p < .001), indicating that those with better fluid cognition also had faster DDK rates, supporting our hypothesis that fluid cognition would explain a larger proportion of the variance in articulation than crystallised cognition, even when controlling for sensory functioning.

To follow-up this finding, and to check use of the best ear hearing threshold (as recommended by NIH toolbox) did not obscure the potential influence of hearing loss, the analysis was repeated using the worse ear as the hearing variable. All

variables were entered into the analysis in the same way as the original analysis with the only change being the substitution of the participant's worse-performing ear in place of the best ear. The pattern of results did not change, and the third step of the model remained significant, $F(12,74) = 3.21$, $p = .001$ in accounting for a slightly larger proportion of the variance (34%) in DDK rate. In this model, fluid and crystallised cognition still explained 21% of the variance, and the individual predictors of gender ($\beta = -0.26$, $p = 0.01$), crystallised cognition ($\beta = 0.24$, $p = 0.02$) and fluid cognition ($\beta = 0.42$, $p < 0.01$) remained significant.

DDK CoV. The overall model was not statistically significant at any step including step three, $F(12,74) = 1.179$, $p = 0.31$. At step two, age emerged as a significant individual predictor of DDK CoV ($\beta = -0.26$, $p = 0.048$) and it remained significant at step three when all variables were included ($\beta = -0.37$, $p = 0.01$).

Two outliers were identified with unusually high articulatory variability. One participant showed very high irregularity of syllable lengths due to shortening the /ta/ in /pataka/. The other participant's accuracy in repeating /pataka/ was poor, resulting in elevated CoV values. Both cases were excluded due to these measurement difficulties. After removing outliers ($n = 85$) the overall model remained non-significant, $F(12,72) = 0.91$, $p = 0.55$. However, the inclusion of cognitive variables at step three led to a significant increase in explained variance in DDK CoV beyond steps one and two ($p = 0.046$). The cognitive variables uniquely accounted for 8% of the variance in DDK CoV with age ($\beta = - 0.34$, $p = 0.02$) and fluid cognition being independent negative predictors ($\beta = - 0.33$, $p = 0.02$). However, because the overall regression model did not reach statistical significance, these predictor effects should

be interpreted cautiously. It is possible smaller effects could not be reliably detected given the study was powered to detect medium-sized effects.

To explore the possibility of a speed-accuracy trade off, a multiple regression analysis was conducted to examine whether DDK rate predicted articulatory variability (CoV), while controlling for age, gender, years of education, depression, anxiety, stress, activity engagement, fluid cognition and crystallised cognition. The overall model was not significant, $F(11, 73) = 1.03$, $p = 0.43$. This suggests that articulatory speed was not independently associated with articulatory variability and does not support a speed accuracy trade-off in this sample.

Maximum phonation time. Self-reported speech difficulty was a significant independent predictor of maximum phonation time at step one ($\beta = -0.28$, $p = 0.02$) and at step two ($\beta = -0.28$, $p = 0.02$). Despite this, the overall models at steps one and two of the models did not reach significance (all $p > 0.14$).

Step three of the model was significant, indicating that the cognitive variables significantly predicted maximum phonation time over and above the other sociodemographic and sensory variables entered at steps one and two, $F(12,74) = 2.20$, $p = 0.02$. The variables together accounted for 26% of the variance, a large effect (Cohen, 1988) with fluid and crystallised ability uniquely accounting for 12% of the variance. With all variables entered into the model, fluid cognition was the strongest predictor of maximum phonation time ($\beta = -0.42$, $p = 0.001$) followed by speech difficulty ($\beta = -0.33$, $p = 0.006$). This shows that better fluid cognition was associated with shorter phonation times, while conversely greater perceived speech difficulty was related to shorter phonation times. Crystallised cognition did not emerge as a significant independent predictor ($p = 0.56$).

Two outliers at the extreme top end of maximum phonation time were explored. These female participants performed the task very well showing exceptional breath support with maximum phonation times of greater than 30 seconds. With outliers removed, the overall model became non-significant, $F(12,72)$ = 1.70, p = 0.09. However, speech difficulty (β = -0.26, p = 0.04) and fluid cognition (β = -0.31, p = 0.02) remained significant predictors. Although these values are beyond reported values in the literature (Maslan et al., 2011), these cases were retained due to being reflective of the participants' abilities.

F0SD from Sustained Vowel Task. The overall model was not significant, including at step three, F = 12,74) = 0.83, p = 0.62 and there were no significant independent predictors of F0SD. There were five outliers at the extreme top end showing high variability in pitch control. Removal of these outliers did not affect the pattern of results and were therefore retained. As high F0SD reflects poor laryngeal control these values were considered valid reflections of performance rather than measurement error.

In summary, the findings show that cognitive abilities are associated with speech execution in older adults. In particular, fluid and crystallised cognition significantly predicted DDK rate. Fluid cognition was also a significant negative predictor of maximum phonation time and DDK CoV, although the overall model was not significant for DDK CoV. Notably, the speech outcomes from connected speech tasks were largely not predicted by cognitive or sensory variables. However, gender predicted F0SD in the monologue task showing that higher F0SD was associated with being female. Perceived speech difficulty also emerged as a

significant negative predictor of F0SD in connected speech and of maximum

phonation time.

5.5 Discussion

Ageing is characterised by gradual decline across multiple functional domains including fluid cognitive abilities (Madden et al., 1999; Reuter-Lorenz et al., 2000; Salthouse, 2019; Schaie & Willis, 1993), sensory functioning such as vision and hearing (Baltes & Lindenberger, 1997; Curhan et al., 2020; Houde & Huff, 2003; Wayne & Johnsrude, 2015) and sensorimotor integration (Ayers et al., 2014; Christensen et al., 2001; Li et al., 2001). Age-related differences in motor speech, particularly in the subsystems of articulation and phonation (Bilodeau-Mercure & Tremblay, 2016; Karlsson & Hartelius, 2021; Sadagopan & Smith, 2013; Taylor et al., 2020; Tremblay et al., 2017), have also been documented showing slower articulation rates and increased pitch instability in older adults (Karlsson & Hartelius, 2021). Previous research has established a strong association between fluid cognition and both sensory and sensorimotor functioning in ageing (Baltes & Lindenberger, 1997; Li et al., 2001). However, the specific link between cognition and motor speech execution, a sensorimotor process (Bilodeau-Mercure & Tremblay, 2016), has not been as widely investigated (Manderson et al., 2025). The current study aimed to address this by investigating the extent to which fluid and crystallised cognitive abilities relate to motor speech execution in older adults, with particular focus on the subsystems of articulation and phonation.

5.5.1 Observed relationships between cognition and motor speech execution

The results revealed that fluid and crystallised cognition were differentially associated with speech execution in older adults. Fluid cognition was the strongest and most robust predictor of speech execution across the maximum performance

tasks (MPTs), significantly predicting both articulatory (DDK rate) and phonatory (maximum phonation time) measures, though not necessarily in the predicted directions. Crystallised cognition was also associated with articulation (DDK rate) but was less strong of a predictor than fluid cognition. This set of findings supports our hypothesis that fluid cognition would explain a larger proportion of the variance in speech execution than crystallised cognition. Importantly, these relationships were observed even after controlling for sensory functioning, suggesting that associations between cognition and speech execution are not driven solely by age-related sensory decline to hearing and/or vision.

However, the relationships observed across the MPTs did not transfer to connected speech tasks. The speech outcomes of articulation rate from the passage reading and monologue tasks and F0SD from the monologue task were largely not predicted by cognitive, sensory or sociodemographic variables, except for gender and perceived speech difficulty which predicted F0SD in the monologue task. Therefore, our exploratory prediction that such relationships would be detected in connected speech was not supported. Perceived speech difficulty was also associated with maximum phonation time from the sustained vowel task, reinforcing suggestions from Study 1 (Section 4.5.2) that subjective measures align more with phonatory performance. The following sections discuss these findings in the context of prior literature and in relation to theories of speech motor control and cognitive ageing.

5.5.2 Fluid and crystallised cognition differentially predict articulation and phonation

The findings reveal that cognitive functioning, particularly fluid cognition, plays a significant and independent role in articulatory functioning in older adults. The observed relationship between fluid cognition and DDK rate shows that older adults with superior fluid abilities had faster articulation rates. Dual-task studies have shown that increasing cognitive load by introducing a concurrent secondary task negatively impacts articulation in young and older adults, especially when the secondary task taps into fluid cognition (i.e. memory or attention; Dromey & Benson, 2003; Dromey & Shim, 2008; Fournet et al., 2021; Whitfield et al., 2021; Whitfield & Goberman, 2017). The current findings add to this literature by demonstrating that individual differences in fluid cognition predict articulation, even in the absence of a secondary task. Furthermore, while DDK performance has previously been a physiological measure of articulatory timing and control (Kent et al., 1987), the present findings demonstrate that cognition is involved in articulatory speed in the absence of linguistic processing.

In addition, the findings may indicate that better fluid cognition is linked to more stable articulatory movements as shown by the relationship between fluid cognition and DDK CoV. This aligns with prior research finding that articulatory timing and coordination are cognitively demanding (e.g. Fournet, 2021; MacPherson, 2019). However, even though fluid cognition was an independent predictor, the overall DDK CoV model was non-significant, and this finding is therefore interpreted cautiously. To determine whether fluid cognition predicts both articulatory timing and coordination, replication is required in studies with larger samples that are powered to detect smaller effects.

Crystallised cognition was also a significant predictor of DDK rate but not DDK CoV. Therefore, older adults with superior crystallised ability produced faster, but not more variable, repetitions of the syllable string *pataka*. However, the exploratory analysis did not show a negative relationship between DDK rate and DDK CoV. Therefore, there was no evidence of a speed-accuracy trade-off in this sample. This suggests that older adults with higher crystallised ability produced faster syllable repetition rates without compromising articulatory stability. It is important to highlight that the crystallised composite contained two measures: vocabulary and word decoding. The word decoding task measures the accuracy of pronouncing low frequency words with irregular spelling, also an estimate of general intelligence (Gershon et al., 2013, 2014). DDK performance relies on a similar process whereby unfamiliar phonemes are decoded and articulated, resulting in those with higher crystallised abilities producing faster DDK rates. It may also be the case that these individuals understood the task more quickly, given crystallised cognition is an estimate of general intelligence. Levelt et al. (1999) predicts that frequently articulated syllables are stored as motor representations and are available for rapid retrieval, facilitating faster repetition rates. Although pa, ta and ka are not necessarily amongst the most frequently used syllables in English (Pasaribu et al., 2024), 'p' and 't' are amongst the earliest sounds a child acquires and therefore have strongly embedded articulatory representations (Dodd et al., 2003). Therefore, it is likely that DDK rate relies on the ability quickly to map speech sounds on to articulation, a crystallised skill.

Fluid cognition was also associated with maximum phonation time, suggesting the involvement of cognition in phonation, which is contrary to our

hypothesis that cognition is involved specifically in articulation. However, the association between fluid cognition and maximum phonation time showed a negative relationship, indicating that older adults with better fluid cognition produced shorter vowel prolongations, contrary to the expectation that better cognition would predict better speech outcomes (i.e. longer phonation times). This finding could reflect how participants interpreted the task or the strategies they implemented to complete it. Prior dual-task research has shown that older adults prioritise task demands by allocating more attentional resources to one task, depending on perceived importance. For example, Li et al. (2001) found that when performing a walking and memory task, older adults prioritised walking by slowing down and using a handrail over memory performance, which declined under dual-task conditions. Together with the current findings, this suggests that older adults prioritise physiological stability over task performance. Therefore, in the current study, even though participants were asked to sustain the vowel /a/ for as long and as constantly as possible, older adults with higher fluid cognition may have ended the task before reaching their physiological limit as a compensatory strategy to avoid discomfort. This could reasonably be assessed in future research by examining participants' subjective task appraisals, strategies implemented, or maximal effort (Maslan et al., 2011). Importantly, this evidence suggests that maximum performance tasks such as prolonged vowels are not purely physiological, but contain a cognitive component, as there may be indirect influences from task interpretation, even when standardised instructions are provided.

Given that there were no other relationships between cognition and phonation, our prediction that cognition – especially fluid abilities – primarily

predicts articulation relative to phonation is partially supported. This hypothesis aligns with models of speech motor control (Guenther & Hickok, 2015; Tourville & Guenther, 2011; Weerathunge et al., 2022), particularly the Laryngeal DIVA model (LaDIVA; Weerathunge et al., 2022a), which distinguishes between the articulatory and laryngeal subsystems (Weerathunge et al., 2022b). The current research supports the suggestion that the two subsystems may rely on distinct neural mechanisms. Building on the findings of our systematic review that identified executive attentional abilities as most strongly linked to articulation, the current findings demonstrate that executive functioning as well as other fluid processes (i.e. cognitive flexibility, working memory, attentional control and inhibition, processing speed, episodic memory) contribute to articulation in typically ageing older adults.

5.5.3 Relationships in connected speech

Two covariates emerged as significant predictors of phonation, with gender and perceived speech difficulty significantly predicting F0SD in the monologue task. Being female was associated with higher F0SD while greater perceived speech difficulty was associated with lower F0SD. This is consistent with previous literature, including a meta-analysis (Rojas et al., 2020), demonstrating that older females exhibit higher F0SD values than older males. Together, these results may suggest that F0SD in connected speech was capturing variation in intonation, with females and those reporting fewer speech difficulties showing greater intonational variability. However, this may also be an artefact of measuring F0 variability in Hertz (Hz), a linear scale. Since pitch perception is logarithmic, pitch variations result in larger absolute Hz differences for speakers with higher mean F0, such as females.

Analytically, this can result in female pitch appearing more variable than male. Further research is required to understand if gender and self-reported speech difficulty are associated with greater pitch variability, by measuring F0SD in semitones.

Unlike in the maximum performance tasks (MPTs), we did not observe any relationships between cognition and articulation or phonation in the connected speech tasks. Specifically, neither fluid nor crystallised cognition predicted articulation rate across passage reading and monologue tasks, nor was F0SD from the monologue task predicted by the cognitive variables. This was unexpected given some previous experimental research using connected speech tasks has found that articulation (e.g. articulation rate, lip aperture variability) is negatively impacted under cognitively demanding conditions (Fournet et al., 2021; MacPherson, 2019; Walsh & Smith, 2013), particularly when attentional or executive 'fluid' abilities are involved (Manderson et al., 2025). In the current study, the connected speech tasks were selected to reflect more cognitively challenging conditions because they contain a communicative component (section 3.4.4). However, it is likely that such relationships were not strong enough to be detected in correlational research. Indeed, this null finding is consistent with some prior cross-sectional research reporting no significant relationships between cognition and articulation rate or phonatory measures when using connected speech tasks such as sentence or passage reading (e.g. Abur et al., 2021; de Looze et al., 2018; Lowit et al., 2016; Thies et al., 2020; Whitfield et al., 2019). Conversely, significant relationships have been reported between cognition and speech rate (syllables per second including pauses) during connected speech (Kemper et al., 2003, 2005, 2009, 2011, Yu et al., 2014). This is

likely because speech rate includes pauses and may therefore reflect linguistic processing as well as motor speech planning. Taken together, this suggests that cognitive abilities are involved in articulation when measured using MPTs, but this relationship is too weak to be detected in connected speech tasks. The age-related slowing of articulation rate in connected speech (Duchin & Mysak, 1987; Jacewicz et al., 2009) may therefore be due to linguistic planning or speech motor planning/programming difficulties. It is also possible that speech measures taken during a single testing session provide only a snapshot in time and may not reflect everyday speech. Test conditions, participant fatigue or atypical performance could have influenced the motor speech outcomes. Further research involving more complex speaking tasks, such as conversational speech, is required to determine the extent of the cognitive-articulatory relationship in naturalistic settings.

5.5.4 Linking Study 1 and Study 2

In study 1, we identified cross-sectional and longitudinal relationships between self-reported cognitive abilities and speech execution. Additional descriptive data suggested that older adults' perceptions of their speech execution was based on phonation (volume of their voice) rather than articulation, as participants reported very little difficulty with articulation. In Study 2, we separated the subsystems of articulation and phonation to assess whether objective measures of cognition predicted either or both. We found that fluid and crystallised cognition predicts articulation but not necessarily phonation, which is also in line with our systematic review (Manderson et al., 2025). The dissociation between Study 1 and Study 2 highlights that different relationships emerge through objective evaluation versus

subjective, self-report measures. Study 1 revealed that perceived difficulties in several cognitive domains (e.g attention/concentration, language and visual-perceptual ability) relate to perceptions of speech difficulties in general. Study 2 provided more direct evidence of specific links between fluid and crystallised cognition and articulatory timing, even after controlling for sensory functioning, suggesting that cognitive decline independently affects articulation, but not phonation. This could suggest that, in ageing, cognitive resources become less available for monitoring somatosensory feedback during articulation. The fact that there was no transfer to connected speech explains why older adults did not self-report articulatory difficulties in Study 1.

5.5.5 Strengths and limitations

Relative to previous research that has focused on assessing cognition using a single task (Fournet et al., 2021; MacPherson, 2019; Wisler et al., 2020), the current research benefitted from administration of a battery of seven standardised cognitive tasks computed into composite measures of fluid and crystallised cognition. Furthermore, by controlling for sensory and sociodemographic variables, this study reliably investigated specific relationships between cognition and speech execution in typically ageing older adults. This study also benefitted from disentangling the speech subsystems of articulation and phonation (Karlsson & Hartelius, 2021; Weerathunge et al., 2022), enabling precise examination of how cognition relates to distinct speech execution subprocesses. Furthermore, inclusion of multiple speaking tasks such as maximum performance tasks and connected speech, enabled us to assess whether relationships are task dependent or transfer to naturalistic speech.

However, several limitations should be noted. Firstly, participants were primarily recruited through older adult participant panels, or through classes run at the University. Therefore, the sample was predominantly well-educated and motivated to maintain an active and independent lifestyle. This bias may limit the generalisability of the findings to more diverse populations of older adults, particularly those with lower educational attainment, limited access to resources and poorer health. Furthermore, the work was focused within healthy older adults only, with the absence of a comparison group limiting the ability to determine how these relationships might change across the lifespan. Nevertheless, the aim was to investigate individual differences within older adults and age was included as a covariate in all analyses.

5.5.6 Future Directions

Future research would benefit from conducting a similar study in young and middle-aged adults to determine the trajectory of cognitive and/or speech changes across the lifespan. Future experimental research is needed to determine causal relationships between fluid cognition and articulation. For example, assessing whether DDK performance deteriorates under dual-task conditions with varying cognitive load (e.g. a task measuring executive functioning versus a task measuring processing speed) would clarify the causal role of executive functioning in articulation. In addition, eliciting conversational speech using dyads or in a group setting would allow greater investigation of real-world communications.

In addition, while it might not be feasible for individuals with cognitive impairment to complete the full battery of tasks used in the current study, having identified

specific relationships between cognition and speech execution, future research in clinical populations could follow an adapted protocol, focusing on targeted measures. This would contribute towards understanding how speech is differentially affected by healthy and pathological cognitive ageing and may help to support methods for early detection of cognitive impairment.

5.5.7 Conclusion

To conclude, this study extends upon previous lab-based research by addressing methodological limitations due to confounding in the speech tasks, small sample sizes and poor measurement techniques. In addition, this study extends the findings of Study 1 in which perceived cognitive difficulty was associated with perceived speech difficulty. In the current study, the objective findings revealed a specific pattern, in that cognition was associated with articulation, but not phonation. Cognitive abilities were associated with articulation when measured using maximum performance tasks. Specifically, both crystallised and fluid abilities were associated with articulatory timing, measured using DDK rate. This suggests that older adults with better fluid abilities benefit from more flexible moment-to-moment functioning, which results in better articulatory control, whilst better crystallised cognition allows speech sounds to be quickly recognised and articulated. Importantly, these relationships were task specific, emerging only in the DDK task that imposed maximal demands on articulatory speed and control. Accordingly, the relationship between fluid/crystallised cognition and articulation did not transfer to connected speech tasks. Connected speech tasks more closely mirror naturalistic speech which involves greater flexibility and the opportunity to employ compensatory strategies

that could mask articulatory inefficiencies. This may explain why, in Study 1, older adults did not self-report difficulties with articulation, as although articulatory challenges may be present, they are likely too subtle to be detected in everyday speech and instead can be identified only under maximum performance conditions. These findings provide novel insights into the cognitive mechanisms underlying speech execution in ageing and highlight DDK performance as a potentially useful indicator of cognitive ability.

5.6 Chapter summary

This chapter presented findings from the second study in this programme of research, a cross-sectional objective investigation of relationships amongst fluid and crystallised cognition and the speech subsystems of respiration/phonation and articulation. In line with our hypothesis, there were significant relationships between fluid and crystallised cognition and speech execution subprocesses (articulation, phonation) when measured using maximum performance tasks. Notably, there were no significant relationships between cognition and speech execution in connected speech. Despite this, everyday communication goes through age-related changes and even subtle cognitive-speech difficulties may impact older adults' social and communicative participation. The next chapter describes the third and final study in this programme of research, which extends the findings of Study 2.

6. Study 3 – Investigating the roles of fluid cognition, crystallised cognition, and articulation in older adults' social participation

6.1 Chapter overview

The previous chapter presented the second study in this programme of research (Study 2). The current chapter presents Study 3, the third and final study. The data were collected during the same participant testing session as Study 2. However, they were analysed differently to assess a distinct research question. Specifically, Study 3 aimed to address the extent to which fluid and crystallised cognition and speech execution (articulation rate from monologue) predicted social participation. This chapter begins by introducing the background literature and theory related to the multifaceted outcome of social participation. This is followed by the methods section in which the self-report measures specific to this study are described. The results section describes the analysis and results of a series of hierarchical regression models, followed by a discussion of the findings including limitations and future directions.

6.2 Introduction

6.2.1 Background

As well as being associated with reduced risk of dementia (Fratiglioni et al., 2004, 2020) social participation contributes to improved mental wellbeing (Tomaz et al., 2021; section 2.4), reduces depressive symptoms (Liu et al., 2024) and enhances

quality of life (Levasseur et al., 2008). Despite these positive associations, most socialisation research is correlational. Intervention studies using social engagement techniques to improve health outcomes are sparse or contain mixed evidence (Ibrahim et al., 2021). Therefore, it remains unclear whether increasing social participation directly enhances cognitive functioning. That being said, increasing social contact is one of the 14 key modifiable lifestyle factors identified that could half dementia prevalence along with other preventative factors (Livingston, 2023; Livingston et al., 2024). A key action point in the Lancet Commission for Dementia Prevention (Livingston et al., 2024) is to prioritise creating age-friendly community environments to reduce social isolation and facilitate participation. However, given that social participation relies on communication (Meeker et al., 2021), age-related changes in cognitive and speech abilities may limit the willingness, desire or confidence to engage socially. While research has reported health-related barriers, such as cognitive and speech impairments (Townsend et al., 2021), very little research has considered whether typical age-related difficulties in cognition and speech execution predict social participation in older adults.

Studies 1 and 2 in this programme of research identified key relationships between cognitive abilities and speech execution in older adults. Study 1 identified cross-sectional and longitudinal self-reported relationships between specific cognitive domains (attention/concentration, language and visual-perceptual ability) and speech execution, suggesting a shared underlying mechanism, such as neural degeneration, may contribute to both processes. Study 2 found mixed results showing specific objective relationships between cognition (fluid and crystallised abilities) and articulation during a diadochokinetic (DDK) task, but not during connected

speech. Building on these findings, Study 3 aims to determine whether objective measures of cognition and speech execution are associated with social participation in older adults. In doing so, this study contains three tested predictors: fluid cognition, crystallised cognition and articulation rate.

6.2.2 Cognitive predictors of social participation

As discussed in Section 2.4, social participation is a key indicator of successful ageing (Douglas et al., 2017). Not only does it enhance mental wellbeing (Tomaz et al., 2021) and reduce the risk of cognitive impairment (Fratiglioni et al., 2004, 2020; Livingston et al., 2024), but also predicts cognitive levels and rate of cognitive decline in healthy ageing (Reuter-Lorenz & Park, 2024). This suggests that limited or reduced social participation has the potential to accelerate age-related cognitive decline. Therefore, it is important to consider whether cognitive functioning itself is a predictor of social participation in ageing.

The Scaffolding Theory of Aging and Cognition (STAC-R; Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Park, 2014, 2024) proposes that engaging with enriching lifestyle activities, including social participation, facilitates compensatory scaffolding (i.e. recruiting alternative or additional brain areas) which can ameliorate the negative effects of age-related cognitive decline (section 2.4). Importantly, the most recent update to STAC-R (Reuter-Lorenz & Park, 2024) highlights that the relationship between life course experience and cognitive level is bidirectional. Specifically, while experiences across the lifespan can influence cognitive levels and rate of cognitive change, it is also true that variation in cognitive ability may influence the extent of engagement in lifestyle activities, including social

participation. Therefore, STAC-R provides the theoretical framework for investigating the reverse relationship, that is, whether cognitive functioning may also predict social participation.

Although evidence in support of STAC-R is generally unidirectional (section 2.3.3), showing that a range of lifestyle activities are longitudinally associated with reduced risk of cognitive decline (e.g. Fratiglioni et al., 2020), some longitudinal research has considered whether such relationships may be bidirectional (section 2.3.4). However, there is no clear consensus on whether cognition predicts social participation. This may be due to inconsistency in longitudinal timeframes. For example, timeframes have ranged from two to twelve years (Lövdén et al., 2005; Small et al., 2012). In addition, studies differ in how they measure cognition, relying on performance on a single cognitive task or several cognitive tasks. For example, one study measured perceptual speed while another measured verbal speed, episodic memory and semantic memory (Lövdén et al., 2005; Small et al., 2012). This makes it challenging to compare data across studies. Last, studies have tended to vary in how they measure social participation, using social network size or frequency of social activity engagement (Casey et al., 2021; Lövdén et al., 2005; Small et al., 2012). These limited, mixed findings highlight that there is still a gap in understanding whether cognitive functioning predicts later involvement in social participation. Furthermore, it is even less clear whether such relationships exist in this direction at a single point in time as limited studies have considered this from a cross-sectional perspective. Given the time and resources involved in longitudinal research, coupled with limitations such as high attrition rates and practice effects (section 3.2.2), cross-sectional research is valuable in providing a direct assessment

of associations, potentially revealing some specific relationships on which future longitudinal research can be built. This study therefore directly addresses this need in the literature by investigating whether cognition predicts social participation in older adults (section 6.3). To address the limitation of previous work focusing on performance on individual cognitive tasks, Study 3 builds on Study 2 by including composite scores of fluid and crystallised cognitive abilities as the first two theoretical predictors of social participation.

6.2.3 Articulation rate as a potential predictor of social participation

In the cognitive ageing literature, social participation has been described and measured in diverse ways (section 2.4). However, there is little direct acknowledgement that communication lies at the heart of social participation (Meeker et al., 2021). As well as gradual age-related cognitive decline, older adults experience age-related changes to speech execution (section 1.4.4), which may impact their ability to engage in social participation. This connection has been addressed more widely in speech science, where communication is recognised as a prerequisite to participation in society (Yorkston & Baylor, 2010). While speech and communication difficulties are significant predictors of participation in people with speech, language, voice and/or hearing problems (Jin et al., 2021; McAuliffe et al., 2017; ter Wal et al., 2023), the research is limited in typical ageing. There is some evidence that broader communication difficulties, for example, self-reports of difficulty using the telephone (Palmer et al., 2016) can lead to a reduction in social networks and activities in typical ageing (Cruice et al., 2005; Meeker et al., 2021; Palmer et al., 2016, 2019; Verdonck-de Leeuw & Mahieu, 2004). However, despite consistent evidence of age-related differences in speech execution (section 1.4.4),

very little is known about whether objective acoustic measures of speech execution relate to social participation. This study directly addresses this by investigating the extent to which speech execution predicts social participation in healthy older adults.

In Study 2, it was hypothesised that cognition would predict articulation and not phonation. Relationships between cognitive abilities and articulation emerged during a diadochokinetic (DDK) task, but not in connected speech tasks. However, there was one unexpected relationship between cognition and phonation showing that better fluid cognition was related to shorter maximum phonation times. The counter intuitive direction of this relationship suggests that this was due to task interpretation rather than a direct relationship between cognition and phonation. Therefore, the hypothesis was partially supported. Returning to the common cause hypothesis (Baltes & Lindenberger, 1997; section 1.3.2) decline in shared underlying neural resources may be the reason for parallel declines across cognitive and articulatory processes (section 1.3.2). Given the relationships amongst fluid and crystallised cognitive abilities and articulation observed in Study 2, it is theoretically justifiable to include articulation as well as cognition as predictors in Study 3. Furthermore, the age-related slowing of articulation rate is commonly reported in the literature (Bilodeau-Mercure & Tremblay, 2016; Duchin & Mysak, 1987; Goozée et al., 2005; MacPherson, 2019, Sadagopan & Smith, 2013). Therefore, it is important to consider whether this has any association with real world outcomes, potentially acting as a barrier to engaging socially. Although articulation rate was not related to cognition in Study 2, it remains an ecologically valid, and potentially independent, predictor of social participation. In the present study, articulation rate from older adults' spontaneous monologues is therefore included as the third theoretical predictor.

6.2.4 Social participation as a multidimensional construct

As mentioned above in Section 6.2.3, there is inconsistency in how the construct social participation has been conceptualised and operationalised in previous research (section 2.5), with one notable limitation being little recognition that it contains a communicative component. To address this issue, and to highlight the multidimensionality of individuals' social lives, three outcome measures are included in Study 3 to reflect overall social participation. These are activity engagement, social network size and communicative participation. The justification for including these measures can be found in Section 2.5.

In Studies 1 and 2, activity engagement was included as a covariate but was not found to predict speech execution in either study. Neither did it show any bivariate correlations with cognitive domains. However, activity engagement is retained in Study 3 as an outcome due to its theoretical relevance (Reuter-Lorenz & Park, 2009; 2024). Returning to the Scaffolding Theory of Ageing and Cognition – Reversed (STAC – R; Reuter-Lorenz & Park, 2024) the relationship between enriching lifestyle experiences and cognitive level is bidirectional. As such, Study 3 aims to assess the reverse: whether cognitive and articulatory ability predict frequency of activity engagement. Furthermore, by including all three outcome measures, this study aims to examine the extent to which cognition and articulation are uniquely associated with social participation variables. This provides a more nuanced investigation of whether activity engagement, social network size and/or communicative participation are related or separable dimensions of social participation.

6.2.5 Aims, objectives and research questions

The current research aims to investigate whether objective measures of cognition and articulation predict older adults' social participation. Using the data collected in the same testing session as in Study 2, this study was designed to address the extent to which fluid cognition, crystallised cognition and/or articulation rate predict: 1) frequency of activity engagement; 2) social network size; and 3) communicative participation.

Our pre-registered hypothesis (https://osf.io/cew63) was that, over and above sensory functioning and other covariates including age, gender, education, and wellbeing, objective measures of cognition and/or articulation would predict one or more social participation outcomes (i.e. activity engagement, social network size and communicative participation).

6.3 Methods

6.3.1 Participants

The present study comprised the same 87 participants as reported in Study 2 (section 5.3.2). A G*Power calculation for multiple linear regression (fixed model, R^2 increase) was carried out to determine the sample size required for a total of 12 predictor variables with three tested variables (crystallised cognition, fluid cognition and articulation rate). The required sample size to detect a medium effect ($f^2 = 0.15$) with power set at 0.80 and $\alpha = 0.05$ was N = 78. Therefore, this study was sufficiently powered.

6.3.2 Design

The study design was cross-sectional and correlational. The data reported here were collected in the same testing session as Study 2. The methods used to obtain the cognitive and acoustic speech data, as well as sociodemographic covariates were presented in Chapter 5 (Section 5.3.3). Two additional self-report scales were administered in the same testing session to inform this study specifically (social network size and communicative participation). These are therefore described in the following section.

6.3.3 Materials

Participants completed the screening, self-report, cognitive and speech tasks that were described in Study 2 (Section 5.3.3.2). The following self-report questionnaires were also administered to further measure social participation.

Social Network Size. Social network size was measured using the Lubben Social Network Scale (LSNS-6; Lubben et al., 2006) which assesses social integration. The six item scale has been validated cross-culturally (Chang et al., 2018; Kuru Alici & Kalanlar, 2021; Myagmarjav et al., 2019) and in community dwelling older adults (Lubben et al., 2006). Three items are used to evaluate kinship (family) and non-kinship (friendship) ties (e.g. "How many relatives/friends do you see or hear from at least once a month?"). Internal reliability has been assessed for both kinship and non-kinship subscales. Across three countries, coefficient values ranged from $\alpha = 0.84$ to 0.89 for kinship ties and $\alpha = 0.80$ to 0.82 for non-kinship. In the current sample of older adults, internal reliability was acceptable to good ($\alpha = 0.83$ kinship ties; $\alpha = 0.76$ non-kinship; $\alpha = 0.78$ the whole scale). Scores were summed to give an overall score out of a possible 30 (Lubben et al., 2006).

Communicative Participation. Communicative participation was measured using an adapted version of the communicative participation item bank – short form (CPIB; Baylor et al., 2013). The CPIB measures the ability to take part in everyday communicative activities such as talking with familiar people or talking with strangers. The CPIB has been validated in clinical samples and further developed to be applicable to a wide range of speech and/or health conditions (Baylor et al., 2009, 2013). Reliability and validity have not yet been established in typically ageing older adults. Therefore, the current study provides an opportunity to assess the potential to develop the CPIB for use in typically ageing populations. Internal reliability in the current sample was good ($\alpha = 0.86$). Prior to study inclusion, the CPIB (Baylor et al., 2013) was adapted to be appropriate for use in healthy older adults. Details about how the scale was adapted can be found in Section 3.5. Briefly, clinical terminology ("your condition") in each of the items was removed and replaced with "your age" (e.g. "does your age affect talking with people you know"). The items were also reverse scored, resulting in higher scores representing greater difficulty with participation in line with our self-report measures of cognition (section 3.3.1) and speech execution (section 3.4.1) in which higher scores reflect greater difficulty.

6.3.4 Procedure

The procedure was the same as is reported in Study 2 (section 5.3.4). The social participation scales were administered in the second part of the session, after an optional 10 min break. Participants completed the Lubben Social Network Scale (LSNS; Lubben et al., 2006) shortly after the break. The Communicative Participation Item Bank (CPIB; Baylor et al., 2013) was administered towards the end of the testing session, after the speech assessment had taken place.

6.3.5 Data analysis

The speech analysis for the articulation rate measure is described in Chapter 5

, Section 5.4.1. Similarly, assumptions of normality, homoscedasticity and

collinearity were checked using simple slopes, scatterplots, variance inflation factors

(VIF) and a correlation matrix (Tabachnick, 2014). Outliers were also explored,

descriptive statistics were calculated, and a correlation matrix was used to investigate

bivariate correlations between core variables (section 6.4). Correlation effect sizes (*r)*

are reported for bivariate associations based on Cohen's (1988) guidance (small =

0.10, medium = 0.30, large = 0.50).

Three regression models were constructed to examine the extent to which

crystallised cognition, fluid cognition and articulation rate predicted social

participation, over and above the other health and sociodemographic variables. The

first model investigated activity engagement, the second model investigated social

network size and the third model investigated communicative participation.

6.4 Results

For all three dependent variables, normality was assessed using simple

slopes, homoscedasticity was assessed using scatterplots and collinearity was

checked using collinearity diagnostics and a correlation matrix (Table 11). None of

these assumptions were violated. Outliers were retained at this stage and will be

discussed in more detail for each individual analysis.

6.4.1 Correlations

Table 11 displays bivariate correlations between core variables assessed in this study (Section 5.4.4 contains the full correlation matrix). The table also includes the speech parameters included as outcomes in Study 2, namely, F0SD from vowel and monologue tasks, DDK rate, DDK Coefficient of Variation (CoV) and articulation rate from vowel prolongations. Although these articulatory and phonatory variables are not central to the current analyses, they were included in the correlation matrix for potential exploratory purposes.

Table 11:

Correlations amongst demographic, sensory, cognitive, speech and social participation variables

	M (*SD*)	Activity engagement	Social network size	Communicative participation
Age	71.48 (6.71)	-0.19	0.04	0.12
Gender	55 f/ 32 m	0.01	0.11	-0.07
Education years	16.78 (2.53)	0.01	-0.07	-0.06
Vision	94.02 (13.84)	0.44	-0.03	-0.01
Hearing	19.15 (5.26)	-0.07	0.01	-0.03
Fluid Cognition	92.13 (9.24)	0.13	**0.23***	-0.16
Crystallised cognition	118.23 (5.72)	-0.01	0.14	0.04
Depression	3.84 (4.30)	-0.15	-0.02	0.20
Anxiety	3.59 (4.19)	-0.05	0.01	0.20
Stress	8.90 (6.55)	0.07	0.01	0.17
Speech difficulty	8.97 (2.50)	-0.11	-0.01	**0.46****
Maximum phonation time	14.91 (5.70)	-0.15	0.02	0.07
F0SD vowel	14.90 (16.24)	0.02	0.20	0.04
DDK rate	5.78 (0.78)	0.20	0.08	-0.10
DDK CoV	26.25 (6.11)	-0.04	0.08	0.05
Articulation rate (passage)	4.52 (0.54)	-0.01	0.02	-0.05
Articulation rate (monologue)	4.07 (0.54)	0.06	0.14	0.04
F0SD monologue	41.79 (17.95)	0.001	**0.29****	-0.09
Activity engagement	71.45 (18.14)	1.00	0.12	-0.15

Social network size	18.68 (4.48)	0.12	1.00	-0.15
Communicative participation	3.00 (3.61)	-0.15	-0.15	1.00

Note: *$p < 0.05$, **$p < 0.01$; gender was coded as 1 = male, 2 = female, higher scores are associated with being female. Participants' better performing ear was used to measure hearing. The CPIB was reverse scored so that higher scores reflect greater difficulty with communicative participation.

There was a small but significant positive relationship between fluid cognition and social network size, indicating that those with better fluid skills tended to have larger social networks. Similarly, F0SD from the monologue task showed a small-to-medium positive association with social network size, showing that greater pitch variation was related to larger networks. Speech difficulty was moderately correlated with communicative participation, indicating that those who self-reported greater difficulty with speech execution subsystems (i.e. phonation/articulation) also tended to have difficulty with communicative participation. There were no significant correlations between activity engagement, social network size and communicative participation, indicating that these three constructs are theoretically distinct.

6.4.2 Core analyses

For each analysis a hierarchical multiple linear regression was conducted with the outcomes of activity engagement, social network size and communicative participation. For each analysis, at step one, age, gender, years of education, vision, hearing, depression, anxiety, stress, and speech difficulty were entered. At step two,

fluid cognition and crystallised cognition, and articulation rate from the monologue task, were entered into the model.

Tables 12 - 14 contain the standardised coefficients (β), unstandardised coefficients, significance tests, and 95% confidence intervals for covariates and predictor variables for step one and step two of the models. Effect sizes for individual predictors are based on standardised regression coefficients (β) following Cohen's (1988) guidance (small = 0.10, medium = 0.30, large = 0.50). Importantly, power analyses (section 6.3.1) were conducted based on the expected change in R^2 associated with the three theoretical predictors (articulation rate, fluid cognition, crystallised cognition). The inclusion of additional covariates was primarily to control for potentially confounding factors and improve accuracy in the unique predictive value of the primary variables. Given that the study was not powered to detect statistically significant effects in the covariates, any observed effects between covariates and the outcome are interpreted cautiously. Outliers were visually inspected using boxplots and significant findings were checked by removing any extreme outliers (values that are more than three times the interquartile range below the first quartile or above the third quartile; Field, 2017). Any impact of removing the outliers on the findings is highlighted below.

Activity Engagement. At step one, age was a significant negative predictor of activity engagement (β = - 0.30, $p = 0.02$), indicating that older age was associated with less activity engagement. However, the overall model was not significant at step one, $F(9, 77) = 1.34$, $p = 0.23$. At step two, the model was also not significant, $F(12, 74) = 1.01$, $p = 0.45$. There were no outliers for the activity engagement variable, or for fluid and crystallised cognition. There was one outlier for the articulation rate

variable. Removal of this outlier did not affect the findings, which remained non-significant, $F(12, 73) = 1.02$, $p = 0.44$. Therefore, the outlier was retained.

Table 12

Standardised and unstandardised coefficients, 95% confidence intervals and significance tests for predictors of activity engagement

Model 1	Standardised Coefficients	Unstandardized Coefficients				95% confidence intervals for B	
		B	*SE*	*t*	*p*	Lower bound	Upper bound
Age	-0.30	-0.81	0.33	-2.48	**0.02**	-1.46	-0.16
Gender	0.03	1.14	4.24	0.27	0.79	-7.31	9.59
Years of education	-0.06	-0.39	0.80	-0.49	0.63	-1.99	1.2
Vision	-0.06	-0.08	0.14	-0.52	0.60	-0.36	0.21
Hearing	-0.23	-0.79	0.44	-1.78	0.08	-1.66	0.09
Depression	-0.21	-0.90	0.50	-1.80	0.08	-1.90	0.10
Anxiety	-0.05	-0.94	0.57	-0.34	0.74	-1.33	0.94
Stress	0.19	0.51	0.38	1.35	0.18	-0.24	1.27
Speech difficulty	-0.13	-0.92	0.87	-1.06	0.29	-2.66	0.81
Model 2							
Age	-0.27	- 0.72	0.38	- 1.92	0.60	-1.47	0.03
Gender	0.02	0.91	4.40	0.21	0.84	-7.85	9.67
Years of education	-0.05	- 0.32	0.83	- 0.39	0.70	-1.97	1.33
Vision ability	-0.06	- 0.08	0.15	- 0.52	0.61	-0.38	0.22
Hearing ability	-0.23	- 0.80	0.46	- 1.76	0.08	-1.71	0.11
Depression	-0.22	- 0.91	0.51	- 1.78	0.08	-1.93	0.11
Anxiety	-0.05	- 0.20	0.60	- 0.34	0.74	-1.40	0.99
Stress	0.09	0.52	0.40	1.29	0.20	- 0.28	1.32
Speech difficulty	-0.12	- 0.87	0.89	- 0.98	0.33	-2.65	0.91
Fluid cognition	0.06	0.12	0.26	0.49	0.63	- 0.39	0.64
Crystallised cognition	-0.04	- 0.13	0.37	- 0.36	0.72	- 0.87	0.61
Articulation rate	0.03	0.95	3.93	0.24	0.81	- 6.88	8.78

Note. N = 87

Social Network Size. For social network size, the overall model was not significant at step one, $F(9, 77) = 0.40$, $p = 0.93$. At step two, fluid cognition was a significant independent predictor of social network size ($\beta = 0.27$, $p = 0.047$), however the overall model was not significant, $F(12, 74) = 0.89$, $p = 0.56$. One outlier was identified as having a very small social network containing just six individuals relative to the sample mean ($M = 18.68$). When this outlier was removed, the overall model was still non-significant, $F(12, 73) = 0.88$, $p = 0.57$ and fluid cognition became non-significant ($\beta = 0.22$, $p = 0.09$) in predicting social network size. The outlier was removed as it was clearly skewing the data, making the observed relationship between fluid cognition and social network size not a true reflection of the sample.

Table 13

Standardised and unstandardised coefficients, 95% confidence intervals and significance tests for predictors of social network size

Model 1	Standardised Coefficients	Unstandardized Coefficients				95% confidence intervals for B	
		B	**SE**	**t**	**p**	**Lower bound**	**Upper bound**
Age	0.08	0.05	0.08	0.60	0.55	-0.12	0.21
Gender	0.06	0.57	1.06	0.54	0.59	-1.54	2.67
Years of education	-0.13	-0.23	0.20	-1.14	0.26	-0.62	0.17
Vision	0.02	0.01	0.04	0.14	0.89	-0.67	0.08
Hearing	-0.00	-0.00	0.11	-0.02	0.98	-0.23	0.21
Depression	-0.06	-0.07	0.13	-0.59	0.56	-0.32	0.18
Anxiety	0.04	0.04	0.14	0.27	0.79	-0.24	0.32
Stress	0.22	0.15	0.10	1.54	0.13	-0.45	0.35
Speech difficulty	-0.18	-0.31	0.22	-1.46	0.15	-0.74	0.12
Model 2							
Age	0.18	0.11	0.09	0.87	0.39	-0.10	0.26
Gender	0.03	0.22	1.06	0.10	0.92	-1.95	2.16
Years of education	-0.12	-0.20	0.20	-1.13	0.26	-0.60	0.17
Vision ability	0.02	0.01	0.04	0.24	0.81	-0.06	0.08
Hearing ability	-0.00	-0.00	0.11	-0.33	0.74	-0.25	0.18
Depression	-0.09	-0.09	0.12	-0.73	0.47	-0.33	0.15
Anxiety	0.07	0.07	0.14	0.45	0.66	-0.22	0.34
Stress	0.18	0.12	0.10	1.04	0.30	-0.10	0.30
Speech difficulty	-0.15	-0.30	0.21	-1.07	0.29	-0.64	0.19
Fluid cognition	0.22	0.10	0.06	1.38	0.17	-0.04	0.21
Crystallised cognition	0.02	0.02	0.09	0.00	1.00	-0.18	0.18
Articulation rate	0.13	1.00	0.95	1.31	0.19	-0.63	3.06

Note: N = 86

Communicative Participation. The variables at step one significantly predicted 26% of the variance in communicative participation, $F(9, 77) = 2.95$, $p = 0.01$. Step two of the model was also significant, $F(12, 74) = 2.36$, $p = 0.02$, accounting for 27% of the variance, which is a large effect in multiple regression (Cohen, 1988). However, the tested predictor variables did not explain any of the variance over and above the variables entered at step one (R^2 change $= 0.02$, $p = 0.68$). Self-reported speech difficulty was a significant predictor of communicative participation at step one ($\beta = 0.47$, $p < 0.001$) and remained significant at step two ($\beta = 0.46$, $p < 0.001$). While the study was not powered to detect effects in covariates (section 6.4.2) this pattern suggests that participant's subjective experiences of their speech difficulty are associated with communicative participation. There were three outliers showing relatively high scores in communicative participation, suggesting these participants had difficulty with communicating in a range of contexts. In contrast to the social network size outlier, removal of these outliers did not affect the overall findings, nor did they disproportionately skew the data. Therefore, they were retained in the final model reported in Table 14.

Table 14

Standardised and unstandardised coefficients, 95% confidence intervals and significance tests for predictors of communicative participation

Model 1	Standardised Coefficients	Unstandardized Coefficients				95% confidence intervals for B	
		B	*SE*	*t*	*p*	Lower bound	Upper bound
Age	0.15	0.08	0.06	1.31	0.19	-0.04	0.20
Gender	-0.10	-0.75	0.78	-0.96	0.34	-2.31	0.81
Years of education	0.03	0.05	0.15	0.33	0.74	-0.25	0.34
Vision	-0.04	-0.01	0.03	-0.42	0.68	-0.06	0.04
Hearing	0.13	0.09	0.08	1.06	0.30	-0.08	0.25
Depression	0.13	0.11	0.09	1.19	0.24	-0.07	0.30
Anxiety	0.01	0.01	0.12	0.12	0.91	-0.20	0.22
Stress	-0.05	-0.03	0.07	-0.42	0.68	-0.17	0.11
Speech difficulty	0.47	0.67	0.16	4.19	**< 0.001**	0.35	1.00
Model 2							
Age	0.09	0.05	0.07	0.67	0.50	- 0.09	0.18
Gender	-0.10	- 0.72	0.81	- 0.90	0.37	-2.33	0.89
Years of education	0.03	0.04	0.15	0.24	0.81	- 0.27	0.34
Vision ability	-0.02	- 0.01	0.03	- 0.18	0.86	- 0.06	0.50
Hearing ability	0.12	0.08	0.08	0.95	0.34	- 0.09	0.25
Depression	0.13	0.11	0.09	1.16	0.25	- 0.08	0.30
Anxiety	0.05	0.04	0.11	0.39	0.70	- 0.18	0.26
Stress	-0.09	- 0.05	0.07	- 0.69	0.49	- 0.20	0.10
Speech difficulty	0.46	0.67	0.16	4.08	**< 0.001**	0.34	0.99
Fluid cognition	-0.11	- 0.04	0.05	- 0.91	0.36	- 0.14	0.05
Crystallised cognition	0.08	0.05	0.07	0.73	0.47	- 0.09	0.19
Articulation rate	0.08	0.55	0.72	0.76	0.45	- 0.89	1.98

Note. N = 87

6.4.3 Exploratory analysis

A significant bivariate correlation between F0SD from the monologue and social network size emerged (Table 11). To explore this correlation, an additional model was examined, with F0SD included as a predictor. In the final model, age, gender, years of education, vision, hearing, depression, anxiety, stress and speech difficulty were entered at step one. At step two, fluid cognition, crystallised cognition, articulation rate (monologue) and F0SD (monologue) were entered (Table 6.3). The model at step one was not significant, $F(9, 76) = 0.59$, $p = 0.80$. In addition, the model at step two was not significant, $F(13, 72) = 1.25$, $p = 0.27$. Although F0SD showed a significant association with social network size ($p = 0.03$), this was not interpreted further due to the overall model's non-significance.

To further explore the non-significant activity engagement model, individual subscales of the VLS-ALQ (Marr et al., 2021) were created to examine potential correlations with the theoretical predictor variables. The VLS-ALQ subscales were devised according to the six factor structure reported in Marr et al., in which the 22 items loaded onto one of the following factors: manual (e.g. "repair a mechanical device"), intellectual (e.g. "engage in creative writing"), games (e.g. "play board games"), religious (e.g. "engage in prayer, meditation or philosophical contemplation"), exercise (e.g. "do weight lifting or strength training") and social ("visit friends, relatives or neighbours"). A correlation matrix including fluid cognition, crystallised cognition, articulation rate and the six activity subscales was constructed. The only significant correlations were between the VLS-ALQ exercise subscale and fluid cognition, ($r = 0.28$, $p = 0.01$) VLS-ALQ manual ($r = 0.24$, $p =$

0.03) and VLS-ALQ intellectual ($r = 0.22$, $p = 0.045$; all other $p < 0.09$). Another regression model was therefore carried out with the exercise subscale as the outcome. The overall model was not significant, $F(13,73) = 1.67$, $p = 0.09$.

6.4.4 Summary of results

Across three hierarchical regression models, few variables significantly predicted variance in the outcomes of activity engagement, social network size and communicative participation. For activity engagement, age was a significant predictor at step one, with a small to medium effect size, but this association disappeared at step two when the cognitive variables and articulation rate were entered. Further analyses of activity subscales revealed a bivariate association between fluid cognition and exercise frequency, although the follow-up regression model was non-significant. Given that the study was powered to detect medium effects, it is possible that smaller effects were not detected.

Social network size was also not consistently predicted by fluid and/or crystallised cognition or articulation. The exploratory analyses identified a significant association between F0SD (monologue) and social network size, although the overall model remained non-significant.

For communicative participation, the variables together accounted for a significant proportion of the variance in communicative participation, showing a large effect. None of the tested predictors (fluid cognition, crystallised cognition, articulation rate) explained a significant proportion of variance beyond the covariates. Perceived speech difficulty, a covariate, emerged as a significant

independent predictor with a large effect size. However, since the study was not powered to detect effects in covariates, this is interpreted cautiously.

6.5 Discussion

Social participation plays a crucial role in maintaining brain health and mental wellbeing in ageing (Casey et al., 2021; Fratiglioni et al., 2004; Lövdén et al., 2005; Oh et al., 2021; Sepúlveda-Loyola et al., 2020; Tomaz et al., 2021; section 2.2.1). Importantly, social isolation in older age has been identified as a modifiable risk factor for dementia (Livingston, 2024; Sommerlad et al., 2023). Therefore, unrecognised barriers to social participation may reduce the protective health benefits. Evidence suggests that cognitive and speech impairments are amongst the most common health-related barriers to social participation in ageing (Townsend et al., 2021), yet limited cross-sectional research has examined cognitive predictors of social participation in healthy older adults (section 6.2.2). Furthermore, research investigating motor speech abilities as predictors of social participation has focused only on clinical groups, leaving a gap in addressing the extent to which cognition and speech execution predict social participation in healthy ageing. Study 1 identified cross-sectional and longitudinal relationships between self-reported cognition and speech execution, while Study 2 identified specific relationships between fluid/crystallised cognition and articulation. The present study builds upon these findings by investigating the extent to which fluid cognition, crystallised cognition and articulation rate predict social participation in healthy older adults.

Social participation is a multifaceted construct (Fuller-Iglesias & Rajbhandari, 2016) and was used here as an umbrella term. Three everyday outcomes of activity engagement, social network size and communicative participation were

included as measures of social participation. Contrary to our hypotheses, none of the tested predictors (fluid cognition, crystallised cognition and articulation rate) significantly predicted any of the three outcomes of social participation. The following sections discuss the findings in context of each outcome.

6.5.1 Activity Engagement

The findings show that activity engagement was not significantly predicted by fluid cognition, crystallised cognition, or articulation rate. This was the case for overall activity engagement and for the six subdomains of manual, intellectual, games, social, religious and physical activities (Marr et al., 2021). These null findings may be explained by several factors.

First, the present study was cross-sectional, in contrast to much of the existing literature, which has examined social participation and cognitive decline longitudinally over periods ranging from two to twelve years (e.g. Casey et al., 2021; Lövdén et al., 2005; Small et al., 2012). However, even the longitudinal evidence remains inconclusive, with mixed findings due to varying study designs (section 6.2.2). In contrast, cross-sectional designs offer an understanding of relationships at a single point in time. The null findings may suggest that current cognitive and articulatory performance do not predict current activity engagement, at least in this sample.

Second, overall activity engagement was measured in contrast to previous studies in which multiple subdomains of activity engagement have been created. In this study, we administered a shortened (22-item) version of the Victoria Lifestyle Survey-Activity Lifestyle Questionnaire (VLS-ALQ; Marr et al. (2021). Previous

studies have used longer or differently structured versions of the VLS-ALQ (Hultsch et al., 1993; Jopp & Hertzog, 2010). For example, Hultsch et al. (1993) utilised a 70-item version of the scale that grouped activities into six domains, finding that higher levels of social activity were associated with better cognitive functioning. Jopp and Hertzogg (2010) validated an 11-factor structure, finding that fluid cognitive abilities were significantly correlated with 10 of the 11 activity subdomains, whereas crystallised cognition was associated with 5 out of the 11 subdomains. Similarly, Small et al. (2012) grouped items into three subdomains - social, intellectual, and physical activity - finding that cognitive measures were longitudinally associated with social activity. However, Gow et al. (2012) have highlighted the difficulty in categorising activities into distinct domains, instead recommending a general measure of overall engagement. The findings therefore suggest that current levels of fluid and crystallised cognition as well as articulatory ability are not associated with activity engagement in general.

However, this null finding is interpreted cautiously. Although previous studies have used the same measurement timeframe ("over the past two years") and have reported significant associations with cognition (e.g. Hultsch et al., 1992; Jopp & Hertzog, 2010), the current study may have been limited in detecting similar relationships due to the shortened questionnaire and cross-sectional design. Future research may consider assessing activity engagement using alternative methods, for example, using mobile phones to collect activity data (e.g. ecological momentary assessment; Shiffman et a., 2008), or diary methods which may provide a more objective understanding of activity engagement (e.g. Lane et al., 2014). In addition,

recall may be more reliable when asked with reference to a more recent time frame, for example, over the past week or month (Holman et al., 2021).

6.5.2 Social Network Size

The second outcome of social participation examined was social network size. Contrary to our hypothesis, the results revealed no significant associations between cognitive or articulatory predictors and social network size. In terms of cognition, this contrasts with previous literature in which there are associations between cognition and social network size. For example, Casey et al. (2021) found that, in a sample of older adults, language ability predicted number of social contacts longitudinally, while social contacts predicted later executive functioning. However, no such relationship was observed in the current cross-sectional data, again pointing to the suggestion that current levels of cognition do not appear to be associated with current social network sizes.

In terms of articulation, no previous literature has explored potential articulatory predictors of social network size in healthy older adults. Palmer et al. (2016, 2019) previously reported that poorer self-reported communication effectiveness was associated with both smaller social networks and less frequent social activity, in older adults with and without a communication disorder. The current findings contribute to this literature by focusing on a population of older adults without communication impairments and by using objective articulatory measures, rather than relying on self-reported communication effectiveness. The current findings suggest that slowing of articulation rate does not influence older adults' social network size. However, it is possible that phonatory characteristics may

influence social network sizes as there was a bivariate correlation between F0SD values and social network size. Future research may consider examining whether phonation predicts social network size in older age.

It appears that neither cognition nor articulation predict social network size in this sample of older adults, however, this observation cannot be readily generalised to the older adult population. Also using the Lubben Social Network Scale (LSNS), Röhr et al. (2020) classified the participants into either socially isolated or socially integrated using a cut-off score of 12 (Lubben et al., 2006). Socially isolated older adults had lower global cognitive scores, greater mobility and vision difficulties, higher depressive symptoms, and were more likely to be older and living alone. In the current research, just six participants had scores of less than 12 on the LSNS, therefore suggesting that most participants fell within the socially integrated category. This may indicate that associations between cognition and social network size are more likely to emerge in socially isolated populations. Röhr et al. (2020) recruited participants through general practitioners (GPs), possibly capturing a more diverse and vulnerable group. In contrast, the current research recruited participants primarily through university participant panels, collaborating partners, and lifelong learning classes, suggesting that this sample is relatively well connected. Overall, this result is encouraging in suggesting that, in a generally well-connected older adult population, age-related changes to cognition do not appear to influence social network size. Further research in more diverse samples could benefit from collaboration with health partners, for example, local charity organisations focused on working with those who are less well connected, or the UK National Health Service.

While Socioemotional Selectivity Theory (Carstensen et al., 1999) proposes that older adults reduce their social networks to prioritise emotionally meaningful relationships, reports from the World Health Organisation (2021) highlight concerns about loneliness and social isolation in ageing. The current research suggests that, in relatively high-functioning older adults, any changes that occur in cognition or speech execution are relatively subtle and unlikely to act as barriers to social network size. Further research involving a wider range of participants is needed, however, to explore effects across different populations directly.

6.5.3 Communicative Participation

The third and final outcome of social participation investigated was communicative participation. Again, fluid cognition, crystallised cognition and articulation did not predict communicative participation.

Very little research has investigated predictors of communicative participation in healthy ageing (Meeker et al., 2021). However, clinical studies suggest that objectively measured speech in patients with speech impairments are not the strongest predictors of real-world participatory outcomes (Donovan et al., 2008; Dykstra et al., 2015; Page & Yorkston, 2022). Instead, perceptual ratings – how individuals sound to others - of speech are more closely linked to communicative participation than lab-based measures such as articulatory precision (McAuliffe et al., 2017). This shows that subtle speech changes or difficulties may not be relevant for functional communication. In the present study, articulation rate did not predict communicative participation, suggesting that any age-related changes to articulation,

if present, may not be strong enough to disrupt participation in communicative contexts.

Although not a primary focus of the study, self-reported speech ability emerged as a significant covariate predicting communicative participation. This may suggest that older adults' perceptions of their speech predict their level of communicative participation. This is in line with clinical research in which perceived severity of speech impairment has been found to be a predictor of communicative participation, when objective measures are not (McAuliffe et al., 2017). In the current study, subjective speech difficulty was a covariate but was the only variable to significantly predict communicative participation, whereas the theoretical predictors of cognition and articulation rate did not. This aligns with the findings of Study 1 and Study 2, where subjective speech difficulty was most strongly associated with voice and phonatory features, rather than articulation. However, more research is needed to confirm these findings using studies that are appropriately powered to detect effects in self-reported speech difficulties, using validated measures of self-reported speech execution, a limitation acknowledged in Section 4.6.3.

Measuring communicative participation in typically ageing populations is a relatively new area of research. Instruments such as the Communicative Participation Item Bank (CPIB; Baylor et al., 2013) and the Communicative Effectiveness Survey (Ball et al., 2004) were developed and validated in clinical populations (Eadie et al., 2006). As a result, studies involving healthy older adults have relied on indirect or proxy measures of communicative participation. For example, Meeker et al. (2021) analysed older adults' social networks to gain a measure of number of 'communication partners' including lifelong friends and strangers. They found that

scores on the Mini Mental State Examination (MMSE; Folstein et al., 1975) predicted number of communication partners. Although social networks highlight the extent to which an individual is connected to others (Meeker et al., 2021), this measure does not necessarily capture the extent to which they are communicating within such networks. Furthermore, the MMSE is a dementia screening tool, which does not sensitively measure cognitive performance in healthy older adults but, rather, the presence or absence of cognitive impairment. The present study therefore improves on prior research by selecting appropriate measures to capture variation in cognitive performance in healthy older adults.

In addition, Palmer et al. (2016) found that greater communicative difficulty was associated with a reduction in key aspects of social relationships in community-dwelling older adults, such as number of friends, engagement in social activities, and perceived social belonging. Communicative difficulty was assessed using a composite of three items; one self-report item on telephone use, and two experimenter-rated items evaluating participant's hearing and comprehension. These approaches highlight an emerging interest in measuring communicative participation in healthy ageing. However, there is a clear gap in the literature for tools that are developed for and validated within typically ageing older adults. The present study contributes to this literature by successfully applying the CPIB in a healthy ageing sample.

Inclusion of the CPIB also acknowledges that social participation contains a communicative component. This study included three separate outcome measures, which capture different aspects of social participation. The correlational results confirm, for the first time, that the included measures of social participation (social

network size, communicative participation, and activity engagement) are not theoretically related, as there were no significant correlations between the measures. This provides support for treating them as measures of distinct functions and skills, rather than overlapping constructs.

6.5.4 Theoretical implications

The findings of this study provide a comprehensive understanding of social participation in healthy ageing by considering its multidimensional nature. Given there were no significant associations between the predictors and three outcomes of activity engagement, social network size and communicative participation, this suggests that older adults' fluid/crystallised cognition and articulation rate may not be linked with reduced social involvement, at least when measured cross-sectionally. This contrasts with existing literature on social participation in ageing that has implemented longitudinal designs (Casey et al., 2021; Fratiglioni et al., 2004, 2020; Small et al., 2012). In addition, The Scaffolding Theory of Ageing and Cognition (STAC-R; Reuter-Lorenz & Park, 2014, 2014) shows that social participation contributes to cognitive reserve over time, while declining cognition may also lead to disengagement. The absence of such relationships at a single time point suggests that cognition and articulation may not be primary drivers of reduced social participation and increased social isolation (WHO, 2021) in ageing. Therefore, the findings partially align with Socioemotional Selectivity Theory (Carstensen et al., 1999), which predicts that older adults prioritise emotionally meaningful relationships resulting in smaller social networks by strategic choice. Our findings demonstrate that, in a relatively well-connected and high-functioning population, cognitive and

articulatory abilities do not significantly predict social participation. Therefore, age-related declines in cognition and speech execution may not act as barriers to social participation in healthy ageing. On the other hand, the association between subjective speech difficulty and communicative participation suggests that older adults' perceptual experience of their speech is associated with everyday communication, regardless of objective abilities. Although this model was successful in predicting 27% of the variance, a large effect in multiple regression (Cohen, 1988), the remaining variance is unexplained. It would be beneficial for future research to consider other individual difference variables such as personality as previous research has demonstrated that extraversion is associated with social participation in older adults (Lai & Qin, 2023)

6.5.5 Strengths and limitations

This study improved on methodological limitations of previous research (e.g. Fournet et al., 2021; MacPherson, 2019; Wisler et al., 2020) by administering a standardised battery of cognitive tasks. The NIH toolbox allows composite measures of fluid and crystallised cognition to be collected, providing a metric of an individual's general ability, rather than basing analyses on individual task performance (Amaefule et al., 2021). In addition, inclusion of both subjective and objective measures of speech performance enabled examination of how perceptions of speech ability and articulatory performance may be differentially associated with social participation. Finally, several outcome measures were included to capture the multifaceted nature of social participation, which involves frequency of activity

engagement, social networks and communication (Douglas et al., 2017; Page & Yorkston, 2022).

However, several limitations must be acknowledged. This study suggests that, within healthy older adults, cognition and articulation may not affect social participation. However, this explanation may be limited to high functioning older adults, as the sample were primarily recruited from University participant panels, many of whom are actively involved in research. In the absence of an appropriate standardised measure, an additional limitation was the use of adapted scales to measure both self-reported speech difficulty and communicative participation. Nevertheless, this research has highlighted some novel preliminary findings and addressed important gaps in the literature, especially around validation of communication scales in healthy older adult populations. Finally, although the analysis was powered to only detect medium effects in the predictor variables (fluid cognition, crystallised cognition, articulation rate), subjective speech difficulty - a covariate – emerged as a significant predictor. This finding should therefore be replicated in future research powered to detect effects for all independent variables.

6.5.6 Future directions

This study suggested that older adults' subjective experience of their speech functioning may predict social participation, especially in communicative contexts. This raises the possibility that subjective cognition may also predict social participation. Therefore, it would be beneficial in future research to assess whether subjective cognition, for example using the Multiple Ability Self-Report

Questionnaire (MASQ; Seidenberg et al., 1994), relates to social participation outcomes.

Furthermore, work is needed to better understand activity engagement in the context of adult ageing. Despite widespread use of the VLS-ALQ (Hultsch et al., 1993; Marr et al., 2021; Jopp & Hertzog, 2010) there is currently no consensus on administration of the scale, with some researchers focusing on individual subdomains (e.g. social, intellectual, physical) and some using the overall construct (Gow et al., 2012). To eliminate the possibility of response bias (Lane et al., 2014), future research may benefit from introducing complementary approaches using shorter time frames, using activity diaries or measuring engagement over the past week or month (Holman et al., 2021), as well as longer term assessments. This would lessen reliance on recall and enable comparisons of short-term and long-term activity patterns of engagement. Furthermore, it would be prudent to include personality traits (Lai & Qin, 2023), as potential predictors of social participation.

Although an ongoing challenge in the ageing field (Banack et al., 2019), researchers should continue attempts to gain more diverse samples. The response to our call for research participations via University networks and the Scottish Older People's Assembly (SOPA) was overwhelmingly positive, showing that older adults were highly interested in this topic. However, future research should embed specific processes into recruitment strategies to ensure feasibility to go beyond the high functioning population. One method of doing so may be to seek collaborations with partners for whom health is the focus. In the United Kingdom, for example, collaborating with the National Health Service or health-based charities may be the

best avenues towards reaching those who fall into the 'healthy' category, but vary on other sociodemographic indicators such as education and socioeconomic status.

6.5.7 Conclusion

Research shows that social participation is positively related to maintaining brain health and emotional well-being in older age and is a protective factor for reducing the risk of dementia. However, older age is also associated with smaller social network sizes, and increased prevalence of social isolation and loneliness. This study therefore aimed to identify health-related predictors of social participation. Building on the findings of Study 2, in which specific relationships between cognitive functioning (fluid and crystallised cognition) and articulation were identified, this study investigated the extent to which cognitive domains and articulation rate predicted older adults' social participation across a range of related, but distinct, social variables. We did not find any relationships between the core theoretical predictors and outcomes of social participation (frequency of activity engagement, social network size, communicative participation). Conversely, self-reported speech difficulty, a covariate, significantly predicted communicative participation. Overall, these results suggest that cognitive and articulatory abilities are, at least, not moderately related to social participation in healthy older adults. Further research with larger samples is required to investigate whether older adults' subjective experience of their cognition and/or speech abilities is more important to social participation than objective measures.

6.6 Chapter Summary

This chapter presented Study 3, the final study in this programme of research. This study drew upon the same data collected and described in Study 2 (Chapter 5), in which a relationship between fluid cognition, crystallised cognition and articulation was observed. Study 3 aimed to investigate whether cognition and articulation predicted social participation, measured by three separate constructs (activity engagement, social network size, communicative participation). Contrary to our hypotheses, we generally did not find that objective measures of cognition (fluid and crystallised cognition) and measures of speech (articulation rate) predicted activity engagement, social network size or communicative participation.

The following chapter (Chapter 7) is the final chapter in this thesis. It presents a general discussion of the findings reported across all studies with reference to core theories, and implications of the research.

7. General Discussion

7.1 Chapter overview

The final chapter of this thesis forms the general discussion of the findings from the three data chapters. The chapter begins with an overview of the studies and research questions. Then, the findings from each data chapter are synthesised, highlighting key patterns of results. Notable findings are integrated within key literature, followed by discussion in the context of relevant theories. The practical implications of the research are then discussed, followed by the key limitations and suggested directions for future research. Finally, several recommendations for research and practice are made.

7.2 Summary of research

The overall aim of this programme of research was to further understand the relationship between cognitive functioning and motor speech execution in older adults, and to explore whether these relationships predict everyday social participation, given its beneficial effects on older adults' brain health (Bourassa et al., 2017; Douglas et al., 2017; Lövdén et al., 2005). This was investigated across three separate studies that addressed key methodological limitations identified in our systematic review (Manderson et al., 2025). A combination of cross-sectional and longitudinal designs was used, along with subjective and objective measurements, and required sample sizes were obtained based on power calculations.

This work extended previous research investigating interactions between cognition and motor speech production in older adults, which have predominantly been experimental (Bailey & Dromey, 2015; Fournet et al., 2021; Kemper et al., 2009, 2011; MacPherson, 2019; Thies et al., 2020), and often examining whether increasing cognitive load negatively interferes with motor speech outcomes. While experimental paradigms have been valuable in isolating specific effects in controlled conditions, such as the effect of concurrent task completion (e.g. talking while walking) on articulation rate (Kemper et al., 2003, 2005), they are limited in assessing the interplay of several cognitive abilities (e.g. Bailey & Dromey, 2015; MacPherson, 2019). The correlational designs utilised in the current work enabled exploration of associations amongst variables, with inclusion of relevant covariates such as demographic, health and wellbeing, and environmental characteristics.

Three research questions were developed and investigated in turn in each of the three studies presented in this thesis. Study 1 investigated whether self-reported cognitive abilities were associated with self-reported speech execution difficulties in older adults, and whether these relationships were bidirectional. Using a longitudinal survey design, with data collected 12 months apart, the study also found that subjective language and attention/concentration difficulty predicted speech difficulty at baseline, over and above sensory and sociodemographic factors. No longitudinal bidirectional relationships were observed, however, visual-perceptual difficulty at baseline predicted future speech difficulty, and speech difficulty at baseline predicted future language difficulty.

Study 2 investigated the extent to which objective measures of cognition predicted objective measures of speech execution. Building on Study 1, Study 2

included a range of cognitive tasks, combined to create composite measures of fluid and crystallised cognition, and a range of speech tasks, designed to measure the speech subsystems of articulation and phonation across maximum performance tasks (MPTs) and connected speech. It was found that fluid and crystallised cognition predicted articulation in the diadochokinetic task (DDK), measuring articulatory speed/agility, but not in the connected speech tasks. Furthermore, subjective speech difficulty was negatively associated with maximum phonation time, a measure of breath support for phonation.

Study 3 investigated whether objective measures of fluid/crystallised cognition and articulation predicted social participation, measured by frequency of activity engagement, social network size and communicative participation. None of the objective measures served as unique predictors of any social participation outcomes. However, participants' self-reported speech difficulties were significantly associated with less communicative participation.

7.3 The relationship between cognition and speech execution in older adults

This programme of research provides evidence that, broadly speaking, cognitive functioning is associated with speech execution in older adults. This supports our initial hypothesis and extends the findings of our systematic review (Manderson et al., 2025) by demonstrating that relationships exist when studies are sufficiently powered and methodologically robust (see Chapter 3). This addresses key limitations of previous studies in this area that contained small sample sizes relative to the type of analysis selected, lack of cognitive screening, and limited inclusion of potentially confounding covariates (e.g. Bunton & Keintz, 2008;

Kemper et al., 2009, 2011; Morris, 1987; Whitfield et al., 2019; Whitfield &

Goberman, 2017).

The findings demonstrate that the association between cognitive functioning

and speech execution is multifaceted, and specific relationships emerge depending

on: the method of measurement (subjective vs objective); the domain of cognition

assessed (e.g. fluid vs crystallised); the aspect of speech execution examined (e.g.

articulation vs phonation); and the speaking task context (e.g. maximum performance

tasks vs connected speech). Therefore, this programme of research provides a novel

view on how cognitive domains relate to aspects of speech execution in older adults,

by examining relationships using comprehensive methods. The following sections

discuss each of these aspects in turn.

7.3.1 Subjective vs objective measurement

In both subjective and objective assessments, cognition was associated with

speech execution, even after controlling for vision and hearing. This demonstrates

that cognition is independently and meaningfully associated with speech execution in

general, regardless of sensory functioning. Previous research has highlighted the

importance of auditory feedback in speech motor control (Guo et al., 2017; Liu et al.,

2018; Stathopoulos et al., 2014; Yates, 1963), suggesting that age-related hearing

difficulties may affect the monitoring of pitch and loudness (Lane et al., 1997),

resulting in vocal difficulty. Furthermore, there are strong associations between age-

related declines to cognitive functioning and sensory functioning, particularly to

vision and hearing (Baltes & Lindenberger, 1997; Dawes et al., 2015), making it

difficult to disentangle the unique contribution of cognition and sensory functioning

in speech execution. The findings suggest that cognitive functioning contributes to speech execution independently of sensory decline. Importantly, this association was found across both subjective and objective measures, highlighting its reliability in both measurement approaches.

However, there were key differences in the overall findings depending on whether relationships were assessed subjectively or objectively. A notable result that distinguishes the subjective and objective findings is that, as well as subjective cognitive abilities, anxiety predicted subjective speech difficulty but not speech execution in objective measurements. Indeed, anxiety was the strongest predictor of speech execution in Study 1, suggesting that emotional factors strongly influence how individuals perceive their speaking ability, with more anxious individuals reporting greater speech difficulty. While emotional factors such as anxiety have been linked to speech stability in people who stutter (e.g. Smith, 1999), research exploring the influence of anxiety in typical speech is limited to public speaking contexts (e.g. McNally et al., 2013; Kwaku Kankam & Boateng, 2017). The current findings suggest that, in typical populations, levels of anxiety are closely associated with individual differences in perceptions of speech execution ability, but not with motor speech performance. This is further supported by anxiety levels being slightly higher in Study 2 ($M = 3.59$, $SD = 4.19$) than in Study 1 ($M = 3.17$, $SD = 3.84$), showing that the significant relationship in Study 1 cannot be attributed to a more anxious group in general. Furthermore, there was a significant bivariate correlation between anxiety and self-reported speech execution in Study 2, showing that this relationship was present across both samples.

The distinction between the subjective and objective findings is also demonstrated in Study 3, in which predictors of social participation were examined. Subjective speech difficulty was associated with lower levels of communicative participation. Conversely, articulation rate was not associated with any social participation outcomes, despite articulation rate being measured from an ecologically valid monologue task – the most similar to naturalistic speech of all the included speaking tasks. This suggests that older adults' subjective experience of their speech ability may be more important in predicting real-world outcomes than objective measures of ability. However, this interpretation is speculative, as Study 3 was not powered to detect effects of the covariates. Further research is needed using validated, subjective measures in a larger sample to further assess this association. One possibility is that individuals who perceive greater speech difficulty may withdraw from communicative contexts, regardless of their actual performance. This mirrors clinical research findings in which patients' perceptions of their speech impairment relates to their levels of communicative participation, as opposed to objective measures of their speech, such as speech intensity or intelligibility (Borrie et al., 2022; Donovan et al., 2008; Dykstra et al., 2015; McAuliffe et al., 2017). The current research suggests therefore that older adult's perceptions of their abilities are more accurate in predicting social participation than ability level itself. This may reflect internal processes such as loss of confidence or indeed estimation of the effort involved in social involvement that cannot be obtained from lab-based testing.

7.3.2 Cognitive domain

Different patterns of relationships also emerged depending on the domain of cognition assessed, and whether the relationship was assessed cross-sectionally or longitudinally. Out of five subjective cognitive domains, difficulty with language, attention/concentration and visual-perceptual ability were associated with increased perceived speech difficulty. Spalding et al. (2021), also using the Multiple Abilities Self Report Questionnaire (MASQ; Seidenberg et al., 1994), found that increasing cognitive anxiety was associated with difficulties with language and attention in older adults. Our cross-sectional findings add to this literature by showing that language and attentional abilities independently predict speech difficulty, even when anxiety is controlled. Our longitudinal findings also extend previous literature utilising the MASQ (Nicholls et al., 2021; Spalding et al., 2021) by showing that the relationship between cognitive difficulty and speech difficulty differs over time, highlighting that both types of analyses are beneficial in capturing such complex interactions.

Similarly, in Study 2, relationships between cognition and speech execution performance differed by domain. Poorer cognitive performance in both fluid and crystallised domains predicted slower articulatory speed. However, poorer fluid cognition also predicted reduced articulatory coordination, and longer maximum phonation times. This is in line with theory and empirical evidence (Salthouse, 2010, 2019; Schaie, 2005; Schaie & Willis, 1993; Singer et al., 2003; Verhaeghen, 2003), demonstrating that fluid and crystallised cognitive abilities are separable in older age. In the present programme of research, it was predicted that fluid cognition would explain a larger proportion of the variance in speech execution than crystallised cognition. This hypothesis was based on previous reports of strong links between

fluid cognition and sensorimotor functioning in ageing (Christensen et al., 2001; Lindenberger et al., 2000; Baltes & Lindenberger, 1997), and weaker links between crystallised cognition and sensory ability (Baltes & Lindenberger, 1997). This hypothesis was supported, as fluid cognition was a stronger predictor of articulatory speed than crystallised cognition, while also predicting articulatory coordination and maximum phonation time, showing that there are direct links with articulation, and indirect links with phonation via task performance. Crystallised cognition, on the other hand, only articulatory speed.

7.3.3 Aspect of speech examined

It was predicted that cognition would be associated with articulation but not phonation in older adults, based on generally agreed assumptions that phonatory difficulties in older age are due to muscular degeneration, stiffness and muscle atrophy (Meyerson et al., 1976; Rojas et al., 2020; Zraick et al., 2006). In Study 1, we were unable to disentangle the speech subsystems assessed in the self-reported speech execution scale. However, descriptive data from the individual items in the scale, and from additional speech questions, revealed that older adults self-reported more difficulty with phonation rather than articulation. This suggests that the relationship between cognition and speech difficulty in Study 1 was specifically targeting phonation. This provided a more nuanced perspective than what was anticipated, by suggesting that, when measured via self-report, perceived cognitive difficulties are associated with phonatory, but not articulatory, difficulties. This suggests that articulatory changes may be too subtle to be detected in everyday speech, and that older adults themselves are possibly unaware of articulatory changes.

Conversely, the objective data revealed a different pattern. In line with our hypothesis that cognition would predict articulation but not phonation, better cognitive ability predicted faster articulation and this was in the expected direction. Contrary to our hypothesis, there was also a relationship between cognition and phonation, but this relationship was in the opposite direction: it was found that better fluid cognition predicted shorter maximum phonation times, suggesting that this negative relationship is indirect and may be caused by uncontrolled confounding such as differing task interpretations. The divergent findings of similar relationships measured via self-report versus objectively demonstrate that self-reports of speech do not necessarily correlate with objective measures assessed in lab-based settings, which is also true of subjective and objective cognition (e.g. Cacciamani et al., 2021; Fastame et al., 2022; Johnco et al., 2014. Nevertheless, both are important because self-reports are associated with experiences of everyday functioning (e.g. Baylor et al., 2009; Liu et al., 2022), while objective measures contribute to understanding mechanisms of change, as well as advancing theories of speech motor control (Gunther & Hickok, 2015; Tourville & Guenther, 2011). The Laryngeal Diva Model of Speech Motor Control (LaDIVA: Weerathunge et al., 2022) suggests distinct neural mechanisms are responsible for the subsystems of articulation and phonation. This programme of research is the first to explore cognitive predictors of speech execution while isolating specific subprocesses. The results provide preliminary evidence that cognition may be directly related to articulation, but not phonation. Importantly, this is only true when using objective lab-based measurements.

7.3.4 Speech task (MPTs vs connected speech)

Finally, the findings from Study 2 revealed that, while poorer fluid and crystallised cognitive abilities predicted articulation during a constrained diadochokinetic (DDK) task, a similar relationship was not observed in connected speech tasks. This is in line with previous research that also found no relationship between cognitive abilities and articulation rate in naturalistic speech (de Looze et al., 2018; Lowit et al., 2016; Thies et al., 2020; Whitfield et al., 2019). Age-related slowing of articulation rate is commonly reported in the literature (Bilodeau-Mercure & Tremblay, 2016; Duchin & Mysak, 1987; Goozée et al., 2005; Mefferd & Corder, 2014), and some studies have attempted to understand the underlying mechanism (e.g. Mefferd & Corder, 2014; Neel & Palmer, 2012). For instance, Goozée et al. (2005) reported that older adults typically employ a speed accuracy trade-off to compensate for diminishing tongue strength, introducing a possible role for cognition. Our findings did not support a speed accuracy trade-off in the current sample, as there was no relationship between DDK rate and DDK Coefficient of Variation (CoV) in Study 2. Despite this, a relationship between cognition and articulation was observed, suggesting that cognition is directly involved in articulation, even when a speed-accuracy trade-off can be ruled out.

The findings also suggest that age-related declines to fluid and crystallised cognition may not be driving the age-related slowing of articulation rate in connected speech observed in the literature (e.g. Duchin & Mysak, 1987), at least when measured using the cognitive tasks included in this programme of research. The composite measures of fluid and crystallised cognition were grounded in theory (Salthouse, 2010, 2019; Schaie, 2005; Schaie & Willis, 1993; Singer et al., 2003; Verhaeghen, 2003), with the additional benefit of reducing measurement variance

(Amaefule et al., 2021) due to measuring general ability rather than performance on a single task. However, composites may be limited in revealing domain-specific processes relevant for naturalistic speech. For example, although our cystallised composite contained vocabulary and word decoding tasks, these may not capture age-related slowing in other domains that could be important for articulation rate in connected speech, such as lingustic planning and/or motor speech planning or programming. Furthermore, aspects of fluid cognition, such as the central executive component of working memory (Baddeley, 2017), may be specifically related to articulation, whereas other aspects of fluid cognition, such as episodic memory, may not show the same relationship. Therefore, some domain specific relationships may have be masked.

Furthermore, inclusion of maximum performance tasks such as DDK which minimises lingustic processing demands enabled the direct measurement of cognition and articulation, without the confounding influence of lingustic processing. The presence of a relationship in this condition, but not in connected speech, suggests that linguistic processing may indeed be a key predictor of articulation rate during connected speech (Mortensen et al., 2006). Spontaenous speech draws on a broader range of cognitive and linguistic factors (Angelopoulou et al., 2024), that were not necessarily captured in the cognitive tasks. To assess this potential relationship correlationally, additional cognitive tasks such as verbal fluency may be required. Verbal fluency tasks capture both lexical retrieval and executive control (Whiteside et al., 2016) and may provide a more sensitive measure of the cognitive abilities underlying articulation rate in spontaneous speech.

The findings discussed thus far demonstrate that, generally, our prediction that cognition would predict speech execution in older adults is supported. However, this programme of research has revealed that this depends on measurement type, domains of cognition and speech execution, and the context of measurement.

An additional aim of this research was to explore the extent to which cognitive abilities and speech execution predicted real-world outcomes of social participation. Several key patterns emerged in relation to this aim and these are discussed in the following section.

7.4 Key Patterns

7.4.1 Self-perceptions of speech difficulty predict real-world outcomes

Contrary to our prediction that fluid and/or crystallised cognition or articulation would predict at least one aspect of social participation, no such relationships were observed (Section 6.5). However, inclusion of additional covariates across all three studies enabled a broader assessment of the outcomes, revealing one consistent predictor, which was self-reported speech difficulty.

One issue is understanding what the self-reported speech difficulty questionnaire was targeting as it contained items relating to phonation, articulation and intelligibility, but did not allow for differentiation between speech subsystems. However, our additional descriptive data provided preliminary evidence that participants primarily reported difficulties with phonation, particularly regarding challenges with vocal loudness, rather than other aspects of speech execution. Although prior literature shows objective evidence of age-related changes to

phonation and articulation (Section 1.6) our findings suggest that phonatory changes are more salient to older adults themselves.

This is further supported by significant correlations between self-reported speech difficulty and objective phonatory measures (shorter maximum phonation times and lower pitch variability in monologue), but not with any articulatory outcomes. This suggests that perceptions of speech difficulty in older age reflect changes to phonation rather than articulatory ability. Moreover, the relationship between subjective speech and objective phonatory measures suggests that older adults are relatively accurate in self-reporting phonatory challenges. The significance of studying self-reported speech execution is highlighted by showing that it may predict the real-world outcome of communicative participation, which may be more vulnerable to the effects of ageing than other participatory outcomes such as social network size and frequency of activity engagement.

Overall, these findings suggest that perceived age-related changes in phonation, as opposed to articulation, may predict communicative participation. This suggests that future research should incorporate communication, especially self-perceived vocal and speech difficulties, when examining predictors of social participation or social isolation/withdrawal.

7.4.2 Predictive validity of lab-based cognitive and speech assessments

Conversely, objective measures of fluid/crystallised cognition and articulation did not predict any social participation outcomes. The divergence between subjective and objective measurements may reflect limitations in the ecological validity of lab-based cognitive and speech assessments in predicting social participation. Although

ecological validity was considered in our study design by including connected speech tasks as well as maximum performance tasks, articulation rate from the monologue task, the most ecologically valid speaking task, still did not predict social participation.

One possible interpretation is that older adults' perceived speech abilities may be more influential on their social behaviour than objective measures which lack salience in everyday communication. If so, older adults may be withdrawing from communicative situations unnecessarily, based on perceptions of their speech ability, rather than actual declines in speech. This has important implications for clinical assessment of speech, in suggesting that subjective accounts remain a valuable tool to better understand the impact of perceived speech ability on everyday communicative activities. This raises the possibility that psychological factors may be indirectly influencing social participation. Social anxiety has been closely linked with speech and communication skills in young adults, with research showing that greater social anxiety is associated with poorer self-reported communication skills, and an increased propensity for self-monitoring which disrupts speech fluency (Lo et al., 2018; Üstündağ et al., 2025). Although the current research was not designed to assess such psychological mediators, these findings suggest that self-reported speech difficulty may be associated with communicative participation via individual differences in anxiety or even personality dimensions. Targeting anxiety may be a reasonable approach for improving communicative participation.

While subjective cognition was included in Study 1, it was not included in Study 2 or 3, in order to reduce the risk of participant fatigue. This limited the opportunity to compare subjective and objective predictors of speech execution and

social participation. Future research could incorporate subjective cognition into assessments of social participation to examine whether it similarly predicts communicative participation, and/or social network size.

One final reason for finding no relationship between cognition, articulation and social participation may be due the characteristics of the sample, who had relatively high levels of functioning and engagement, potentially limiting the ability to detect associations. As mentioned in Section 6.5.6, efforts to recruit diverse samples should ideally be embedded into the research design. For example, collaborating with health-based charities or NHS organisations has been shown to increase participation from underrepresented groups (e.g. Barts Health NHS Trust, 2023).

7.4.3 Activity engagement unrelated to cognition or speech execution

Across all three studies, frequency of activity engagement was included either as a covariate (Studies 1 and 2) or as an outcome (Study 3), to account for or assess individual differences in lifestyle participation. Previous empirical evidence (Bielak & Gow, 2023; Borgeest et al., 2020; Henning et al., 2023; Jopp & Hertzog, 2010) and theory (STAC-R; Reuter-Lorenz & Park, 2014, 2024) consistently reports a relationship between lifestyle engagement and cognition. Engaged older adults are more likely to perform better on cognitive tests, with fewer symptoms of age-related cognitive decline and a decreased risk of developing dementia (Fratiglioni et al., 2020; Hassing, 2020; Kelly et al., 2017; Yates et al., 2016). However, we did not observe such a relationship between activity engagement and cognition.

The possibility of reverse causality has also been considered in the literature, in which withdrawing from activity engagement may be a consequence of declining cognition (Bielak & Gow, 2023). Still, we did not find that cognition predicted activity engagement in this sample. Furthermore, although aspects of communication have been associated with some leisure activities (Bransby et al., 2022; Cruice et al., 2005; Nagayoshi et al., 2017) we also did not observe any relationships between speech execution and activity engagement.

Several factors may explain these findings. First, it is possible that the activity engagement measure was not sensitive enough to detect variation in relation to cognition, speech execution or other sociodemographic factors (discussed in detail in Section 6.5.1). It should also be noted that, while cross-sectional relationships have been observed (e.g. Cruice et al., 2005; Nagayoshi et al., 2017), much of the literature is longitudinal in nature. While Study 1 included a 12-month follow-up, the overall design of this programme of research was largely cross-sectional, in contrast to the longitudinal studies that have reported significant relationships. It is possible that we could not capture the cognitive and communicative benefits of lifestyle engagement over a short timeframe. Finally, our measure of activity engagement was global in nature, whereas the cognitive measures focused on specific domains. A prior meta-analysis showed that different relationships emerge depending on how cognition and lifestyle engagement are measured, with one of the strongest associations being between global cognition and lifestyle engagement (Kelly et al., 2017). This suggests that the specificity of constructs (e.g. global vs domain-specific) must be carefully considered relative to study aims and research questions.

7.4 Theoretical implications

7.4.1 Common Cause Hypothesis

The common cause hypothesis (Baltes & Lindenberger, 1994) proposes that age-related declines across sensory/sensorimotor, cognitive and motor domains are driven by shared neural degeneration (Section 1.4.2). Several findings from this programme of research support the common cause framework. First, there were cross-sectional and longitudinal relationships between perceived cognitive abilities and speech difficulty in Study 1. Notably, the longitudinal relationship between visual-perceptual difficulty and speech difficulty may reflect declines to similar brain regions. Both visual-perceptual ability and speech execution are goal-directed behaviours that require sensorimotor integration (Strijkers et al., 2011; Tsai et al., 2008). The prefrontal cortex, which is responsible for integration of top-down processes (i.e. goal-directed behaviour), including across sensory modalities (Knight et al., 1999), may therefore be the underlying common cause responsible for difficulties with cognition and speech execution. Subjective reports may act as early indicators of subtle changes, even before objective declines can be observed (Fastame et al., 2022; Jessen et al., 2020; Spalding et al., 2025).

Second, the objective findings of Study 2 demonstrate that individual differences in cognitive ability – particularly fluid cognition – were associated with articulation during a 'maximum performance' DDK task. Extending the preliminary evidence of Manderson et al. (2025), this suggests that fluid cognition may support the monitoring and regulation of somatosensory feedback during articulation. This is consistent with the common cause hypothesis, because fluid cognition and articulation rely on overlapping brain areas. These include the posterior cingulate

cortex (PCC; Tremblay et al., 2017; Tremblay & Deschamps, 2016), which is an area associated with cognitive control. Therefore, age-related degeneration in common brain regions may be responsible for functional declines to both fluid cognition and articulation. Interestingly, our systematic review suggested that connected speech may be particularly vulnerable to age-related decline in fluid cognition. This interpretation was based on evidence that increasing cognitive complexity negatively impacts articulatory performance (Manderson et al., 2025) and suggestions that longer utterances require additional brain areas in the left prefrontal cortex (PFC; Guenther & Hickock, 2015). However, our objective findings contradict this interpretation, as no relationships were observed during connected speech. One possible explanation is that the connected speaking tasks used in the current research were not sufficiently cognitively demanding. Reading aloud and producing an uninterrupted monologue lack competing demands such as turn-taking, topic shifts, working memory, and attention, which tend to be involved in everyday conversational speech (Dodge et al., 2015). The use of conversational speech has been helpful in distinguishing healthy older adults from those with mild cognitive impairment (MCI) via proportion of words spoken (Dodge et al., 2015), and in examining differences in the conversational experience of adults with and without hearing impairment (Nicoras et al., 2023, 2025). However, very little research has been conducted investigating the relationship between cognition and articulation rate in the context of conversational speech. Addressing this gap could further contribute to identifying relatively inexpensive, non-invasive behavioural markers of early cognitive decline in conversational speech.

7.4.2 Compensation theories

Beyond the shared neural decline proposed by the common cause hypothesis, compensation theories can be used to explain why some older adults are able to maintain articulatory performance despite age-related cognitive decline. At the behavioural level, Selection, Optimisation and Compensation (SOC) theory (Baltes et al., 1999) suggests that individuals employ strategies to promote resilience and maintenance of behaviours in the face of cognitive decline by focusing on a particular task, enhancing 'good' abilities and compensating with alternative strategies. SOC theory has been used to explain a wide variety of continuing abilities and functions in older age, including musical ability (Baltes et al., 1999) and walking (Li et al, 2001; Lindenberger et al., 2000). Evidence shows that the highest convergence between all three strategies is in middle age with poorer performance across the three elements in older age (Freund & Baltes, 2002). This suggests individual differences in cognitive abilities influence the extent to which older adults can implement SOC. However, SOC theory has not been applied in the context of motor speech performance. In the current research, individuals with greater fluid cognition may have been more effective at allocating cognitive resources to monitor somatosensory feedback, optimising articulatory speed and coordination.

At the neural level, theories such as HAROLD (Hemispheric Asymmetry Reduction in Older Adults, Cabeza, 2002) and CRUNCH (Compensation-Related Utilization of Neural Circuits Hypothesis; Reuter-Lorenz & Cappell, 2008) propose that older adults recruit additional or alternative brain regions to maintain task performance under increased cognitive demand. These compensatory mechanisms may be more available to older adults with greater cognitive reserve (Stern, 2002),

with the accumulation of neural resources (Cabeza, 2002; Cabeza et al., 2018) allowing them to maintain articulatory performance. Although DDK is typically considered a physiological task because it minimises the cognitive load imposed by linguistic processes (Karlsson & Hartelius, 2021), it requires motor coordination, sequencing and somatosensory feedback monitoring to alternate between syllables. Indeed, executive control has been found to be associated with alternating (*pataka)* DDK performance in young adults (Janse et al., 2023; Shen & Janse, 2020). Together with our findings, this suggests that cognition contributes to articulation even in tasks with low linguistic complexity, and that older adults with greater cognitive reserve (Stern, 2002, 2003; Stern et al., 2019) may recruit additional brain areas to support articulatory performance.

7.4.3 Scaffolding Theory of Ageing and Cognition-Revised (STAC-R)

Cognitive reserve can be accumulated across the lifespan through modifiable lifestyle factors (Legdeur et al., 2018; Peeters et al., 2020), attenuating the effects of age-related cognitive decline (Stern, 2002). The Scaffolding Theory of Ageing and Cognition - Revised (STAC-R; Reuter-Lorenz & Park, 2014, 2024) is a testable model including lifestyle factors, such as engagement and social participation, as predictors of cognitive ability and change. STAC – R builds upon the common cause hypothesis and compensation theories by proposing that the ageing brain utilises alternative neural pathways as 'scaffolding' to compensate for structural and functional decline. STAC-R also proposes that the relationship between lifestyle and cognition is bidirectional. Accordingly, we investigated the less commonly researched direction: the extent to which cognition and/or speech execution predict

social participation (encompassing activity engagement, social network size and communicative participation). No significant relationships emerged between our objective cognitive and speech data and subjective measures of participation in our cross-sectional analysis (discussed above in Section 7.4.3 and in Section 6.5). Nevertheless, STAC-R remains a prominent theory in this work as it can potentially explain the null findings through the characteristics of the sample. Across all studies, the older adults in this research were socially connected, highly educated and in relatively good physical and cognitive health. It is therefore possible that this sample had high levels of cognitive reserve. From the perspective of STAC-R, participants may have already accumulated compensatory scaffolds across the lifespan, allowing their cognitive and motor speech abilities to remain relatively preserved. Therefore, the benefits associated with lifestyle engagement may have already been accounted for in the characteristics of the sample. A longitudinal follow-up would be beneficial to clarify whether the null findings represent an absence of association or reflect the influence of a well-connected sample with good cognitive reserve. Monitoring changes in cognition, speech execution and social participation over several years would provide a more robust test of the bidirectional relationships proposed by STAC-R than is possible with a cross-sectional design. Nevertheless, this research has highlighted a promising avenue for future longitudinal research.

7.4.4 Theories of speech production

Theories of speech motor control such as The Direction into Velocities of Articulators (DIVA) model (Guenther & Hickok, 2015; Tourville & Guenther, 2011) highlight the crucial role of sensory processing in the feedforward and feedback

commands required to execute and articulate speech. The Laryngeal Directions into Velocities of Articulators (LaDIVA; Weerathunge, et al., 2022a) is an extension of DIVA that acknowledges the presence of the laryngeal as well as the articulatory subsystem, suggesting that the two systems may rely on partially distinct neural mechanisms (Weerathunge, et al., 2022b). The current findings confirm these models in several ways.

First, the current research addresses the limitations of previous models. The development of speech motor control models was based on typical young adult speakers and has since been applied only to apraxia of speech (Miller & Guenther, 2021). Furthermore, speech production models tend to focus narrowly on cognition, primarily recognising the role of linguistic input and phonological planning (e.g. Levelt et al., 1999; Postma, 2000), with less attention given to other cognitive functions such as attention, working memory or executive control. The current research applies theories of speech motor control to a typically ageing population, showing that articulation is variable in older adults. Moreover, our findings demonstrate that cognitive abilities, beyond that of linguistic or phonological input, potentially contribute to speech motor control, particularly in tasks that require precise monitoring of auditory and somatosensory feedback such as DDK. Therefore, speech motor control models should acknowledge the involvement of cognition more broadly, which would enable them to be applied more readily to ageing populations.

Second, our findings show that sensory decline does not explain all speech changes in ageing. Speech motor control relies on the integration of sensory feedback, particularly via auditory and somatosensory input (Guenther & Hickok, 2015). Vision has also been proposed to be involved in mirroring a conversation

partner's lip and jaw movements to prime the motor system for speech production (Jarick & Jones, 2009). Older adults commonly experience sensory decline to vision and hearing (Amieva et al., 2015; Cruickshanks et al., 1998; Houde & Huff, 2003). Previous work in the ageing of speech production has suggested that age-related declines in peripheral sensory abilities contribute to speech and voice changes in older age (Caruso & Mueller, 1997; Schultz et al., 2023; Yorkston et al., 2011). As such, it was considered important to measure and control for sensory functioning in our analyses. Notably, relationships between cognition and speech execution were observed even after controlling for age and sensory functioning, suggesting that the association was not driven solely by general sensory declines. Returning to the common cause framework, this raises the possibility that cognitive resources may become important in older age to compensate for sensory degradation. This is also consistent with compensatory models such as SOC theory (Baltes & Lindenberger, 1994) and STAC-R (Reuter-Lorenz & Park, 2014, 2024) which propose that older adults with higher levels of cognitive reserve are better able to allocate cognitive resources to maintain performance. However, despite the importance of somatosensory feedback in articulation, this sensory ability was not measured in the current programme of research. Prior experimental research has examined the effect of disrupting somatosensory feedback on articulation, for example, by using a balloon protrusion in the mouth of speakers (Golfinopoulos et al. 2011). This demonstrates the practical difficulty in measuring such a construct. However, future correlational research may consider incorporating validated measures of somatosensory ability into their design. For example, the NIH toolbox offers a somatosensation assessment including measures of kinesthesia, tactile discrimination

and self-reported pain (Dunn et al., 2013). Further work may be required to determine whether these somatosensory measures accurately reflect somatosensory abilities involved in speech. This understanding may offer support to the interpretation that fluid cognition is involved in monitoring somatosensory feedback for articulation (Manderson et al., 2025) and that older adults with greater cognitive reserve may be better able to allocate cognitive resources to this process.

Finally, the current research confirms that the laryngeal and articulatory subsystems are separable in older adults (Weerathunge et al., 2022a, b). While articulatory performance was related to fluid and crystallised cognition, phonation was not. This shows that, despite ageing being associated with changes to both articulation and phonation, cognition is more strongly linked with articulation, possibly reflecting the ability to draw upon cognitive resources to monitor articulatory speed and coordination. This may become increasingly important in older age due to reduced support from sensory and physiological processes (Goozée et al., 2005).

The dissociation between articulation and phonation is further emphasised by the finding that perceived speech difficulty was predictive of communicative participation, whereas objective measures of articulation did not predict any participatory outcomes. The subjective speech difficulty measure largely reflected phonatory challenges including vocal loudness. These perceived voice difficulties may be more salient to a speaker than subtle articulatory challenges. This suggests that subjective voice difficulties may affect communicative confidence, in turn leading to reduced participation. This extends prior evidence showing that perceptions of speech impairment in clinical samples are more predictive of

communicative participation than objective measures of speech (McAuliffe et al., 2017). In older adults, perceptions of phonatory ability may therefore act as a barrier to continued engagement in social and communicative contexts.

7.5 Practical implications

According to the World Health Organisation (WHO, 2021), an important outcome of ageing research is to delay or prevent cognitive decline as well as enhance independence and wellbeing in later life. Prior research has already identified protective lifestyle factors, such as social participation, as being beneficial for brain health and reducing the risk of dementia (Bourassa et al., 2017; Fratiglioni et al., 2020; Holt-Lunstad et al., 2015; Kelly et al., 2017; Livingston et al., 2023; Lövdén et al., 2005; Sepúlveda-Loyola et al., 2020). Therefore, understanding predictors of social participation in older age is a key factor in helping to tackle age-related cognitive decline.

However, communicative participation (Baylor et al., 2013) is often overlooked in research investigating social participation. This thesis highlights that communicative participation may be particularly vulnerable in healthy ageing. As well as age-related changes to cognitive and speech execution abilities, hearing-loss is highly prevalent in older age and may further affect engagement in social settings. Hearing impairment has been linked to both communicative difficulties in everyday settings (Holman et al., 2021; Palmer et al., 2016, 2019) and increased dementia risk (Thomson et al., 2017; Wayne & Johnsrude, 2015). The common cause hypothesis links hearing to fluid cognition in healthy ageing, by proposing there are shared mechanisms underlying both cognitive and sensory declines (Baltes & Lindenberger,

1997). Furthermore, hearing loss is reported as one of the key factors as to why older adults often struggle to communicate, especially in groups (Holman et al., 2021). Although not a core variable in this thesis, hearing loss likely represents an additional factor that contributes to the vulnerability of communicative participation. This knowledge may be helpful for those organising events aimed at older adults, as it emphasises the importance of creating supportive social environments that facilitate communication. For example, small group activities held in a quiet, acoustically friendly community setting may encourage participation from those who feel their speech or cognition is limited. Inclusive spaces may help to foster sustained engagement, ultimately contributing to improved wellbeing and cognitive functioning of all older adults.

The World Health Organisation (2022) also introduced the concept of functional ability, which encompasses intrinsic capacity and the environment to capture the multidimensional nature of healthy ageing. This programme of research was successful in applying the functional ability framework to its design. Intrinsic capacity was assessed through older adults' cognitive and motor speech abilities, functional ability was assessed through the extent of participation in lifestyle activities, and the environment was assessed by controlling for key variables that contribute to successful ageing such as education (Bickel & Kurz, 2009; Li et al., 2023), lifestyle engagement (Hertzog et al., 2008) and independence in daily living (Kim & Yoon, 2022).

Furthermore, this programme of research assessed functional ability from varying perspectives by measuring both subjective and objective cognition and speech execution. This resulted in subjective measures emerging as valuable

indicators of change and real-world outcomes. A recent UK survey of the communication needs of older adults living in care homes revealed that many residents purposefully isolate themselves socially due to perceived communication difficulties (Davis et al., 2024). The current research confirms that subjective tools remain highly valuable in clinical contexts (Guntupalli et al., 2006) in predicting participation. In addition, acoustic analysis of speech is emerging as a promising, non-invasive avenue for detecting cognitive impairment (Martínez-Nicolás et al., 2021). The current findings suggest that self-reported speech difficulties may also be an early indicator of cognitive change in non-clinical samples.

The objective findings complemented the subjective results by providing a clear picture of older adults' intrinsic abilities. The relationship between fluid cognition and articulation has important implications for Speech and Language Therapists (SLTs). While articulatory changes may not require direct intervention in residential settings where care is focused on more severe communication and swallowing disorders (Davis et al., 2024), SLTs should be aware that cognition supports speech execution as well as language processing. This should be incorporated into SLT training programmes as this knowledge may support early identification and prevention of cognitive and/or communicative impairment.

In healthy older adults, maintaining good verbal communication skills through frequent social participation may be an additional preventative strategy that, along with other modifiable lifestyle factors (Livingston et al., 2023; Livingston, 2024), could reduce the likelihood of cognitive decline and maintain motor speech skills.

Furthermore, self-perceptions of speech may have severe implications for older adults' communicative participation, regardless of objective speech ability. Raising awareness of these issues may help improve confidence levels or challenge negative self-perceptions around speech. Overall, incorporating both subjective and objective assessments in clinical practice and research is essential in building a comprehensive understanding of how cognition and speech execution affect older adults' lives and their overall functional ability.

7.6 Strengths and limitations

Before outlining future directions and practical recommendations, it is important to acknowledge the strengths and limitations of this research. A notable strength was that, across all three studies, subjective speech difficulty emerged as a significant predictor, indicating it as a reliable measure. However, the subjective speech execution scale used contained some limitations. Although it was adapted from a previously published scale measuring communication (Hartelius et al., 2008), it had not been formally validated as a separate speech execution subscale. In the current sample, internal reliability was moderate to weak in Study 1, but improved to a good level in Studies 2 and 3, where the scale was administered in-person, suggesting possible effects of administration mode. The limitations of this scale were addressed as much as possible, by including additional theoretically-informed questions designed to supplement the original five-item scale.

Since this research was interdisciplinary and focused on the multidimensional nature of healthy ageing, the integration of several core theories was needed to guide

study development and to select measurement variables. From an ethical perspective, it was essential to balance the depth of the investigation with feasibility to minimise participant fatigue, which could have compromised data quality, particularly in the objective testing session. As a result, certain measures were omitted which might have otherwise enriched the findings. For example, somatosensory functioning was not assessed, despite it being potentially relevant in clarifying the causal influence of cognition on articulation. Instead, vision and hearing were prioritised as control variables due to their established links with cognitive and motor speech control in ageing (Baltes & Lindenberger, 1997; Parrell & Houde, 2019). In addition, it is possible that the motor speech measures were not truly representative of participants' speech as the measures were taken on a single occasion. It would have been informative to include the Multiple Abilities Self Report Questionnaire (MASQ; Seidenberg et al., 1994) in Studies 2 and 3 as well as Study 1, in order to explore whether subjective cognition was associated with social participation similarly to subjective speech execution. However, this was not feasible due to the overall length of the testing session. In future, questionnaires could be completed outside of the testing session to reduce the risk of fatigue.

Finally, across all studies the participant samples were limited in diversity, containing primarily White, well-educated participants from the least deprived socio-economic backgrounds. This reflects approximately 96% of research in the behavioural sciences that has recruited samples from WEIRD (Western, Educated, Industrialised, Rich and Democratic) societies (Gutchess & Cho, 2024). Cultural differences in how individual's view the world has been shown to lead to differences in cognitive processes, in particular how memories are encoded (Gutchess & Cho,

2024). Importantly, the findings of the present research may not only be less applicable to older adults from more diverse backgrounds but also may have limited cross-cultural generalisability.

7.7 Future Directions

This research has demonstrated that subjective reports of speech execution are valid predictors of real-world communicative outcomes. However, there remains a gap in the availability of validated self-report tools designed for use in in older adult populations who do not have a diagnosed speech or communication disorder (Eadie et al., 2006). Development of such a questionnaire is a key priority for future research. The 15 supplementary questions introduced in Study 1 (appendix 2) showed good internal reliability and potential for the development of subscales targeting different speech subsystems. With further psychometric evaluation across diverse samples, this could serve as a promising avenue for self-report measures tailored to typically ageing populations.

This thesis has also highlighted that communicative participation may be particularly vulnerable in ageing, emphasising the importance of considering communication as a key component of social participation. Future research exploring social withdrawal or isolation in later life should integrate the communicative aspect of social participation into their study designs to capture a more comprehensive picture of social participation.

Additionally, carrying out similar research in young and/or middle-aged adults would help to clarify whether the relationship between cognition and speech execution changes across the adult lifespan. This would enable testing of the

hypothesis that the link between fluid cognition and articulation strengthens with age, as older adults may increasingly rely on compensatory neural mechanisms to scaffold declines in physiological and sensory processes.

7.8 Recommendations for research and practice

Based on the evidence acquired from this programme of research, several recommendations can be made:

1. This research identified a gap in available measurement tools for speech execution and communicative participation in non-clinical samples (e.g. Baylor et al., 2013; Donovan et al., 2008; Eadie et al., 2006). Therefore, there is a need for standardised and validated self-report scales appropriate for assessing speech execution and communicative participation in healthy older adults.

2. This research identified different relationships between cognition and speech execution depending on whether such relationships were assessed via subjective or objective methods. From a clinical perspective, subjective and objective perspectives of cognition and speech production should be incorporated into assessments, to gain an accurate understanding of the functional ability of older adults. This may also contribute to developing non-invasive, behavioural markers to identify early signs of cognitive impairment.

3. This research also identified objective relationships between fluid and crystallised cognition and articulatory performance. This should be included in SLT degree/training courses in modules focused on ageing highlighting that age-related differences in speech execution are not just physiological

(e.g. Zraick et al., 2006; Meyerson, 1972) but have subtle connections with cognition.

4. This research identified that activity engagement, social network size and communicative participation are distinct constructs. Future research should acknowledge that social participation contains a communicative component which may be particularly vulnerable in healthy ageing due to age-related cognitive and motor speech decline (e.g. Rojas et al., 2020; Salthouse, 2019; Tremblay et al., 2017).

5. In this research, connected speech was measured using a passage reading and monologue task, however, older adults may find conversational communication particularly difficult (Hadley et al., 2021). Future research should therefore consider potential relationships between cognition and articulation using dyads or group conversational speech.

6. This interdisciplinary research was grounded in theory and evidence from both cognitive and speech sciences. Given the complexity in selecting appropriate tools to measure cognition and speech execution, an interdisciplinary approach is recommended for future research to ensure designs and measurement tools are methodologically robust.

7.9 Conclusions

In conclusion, this thesis extends the findings of our systematic review by providing methodologically robust empirical evidence of a relationship between cognition and speech execution in healthy ageing. Notably, our findings reveal that this relationship is not simply uniform, but complex and multifaceted. It was demonstrated that different relationships emerge when assessed via self-report

relative to objective measurements. Subjective relationships between cognitive domains and speech execution, especially phonation, may act as early indicators of change, even in the absence of objective cognitive and/or speech impairments. Objective relationships were observed between cognition, especially fluid cognition, and articulation, although this relationship was too subtle to be detected in naturalistic speech. This shows that self-perceptions of cognitive and speech abilities do not necessarily reflect lab-based performance. Objective measures of cognition and articulation also did not predict wider social participation, but subjective speech difficulty was associated with more limited communicative participation. This suggests that perceptions of speech ability, rather than objective performance, may be more strongly associated with real-world outcomes. However, further validation of the self-reported speech and communicative scales is required. Overall, this thesis provides a more nuanced perspective than previously published literature, demonstrating that an interdisciplinary approach and integration of multiple theoretical frameworks is required to fully interpret the findings.

7.10 Chapter Summary

This final chapter of this thesis presents a general discussion of the findings from the programme of research. The findings from the three data chapters were synthesised with key patterns and contradictions highlighted. The findings were then discussed in detail in the context of the core theories underpinning the work, from both the speech and cognition literatures The practical implications of the work were then discussed, followed by the limitations and future directions. The chapter ends by making recommendations for research and professional practice.

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Appendices

Appendix 1:

Adapted speech execution questionnaire (Hartelius et al., 2008)

The following questions ask about your speech production. Speech involves how you say words and sounds. Producing understandable speech depends on how well you move your lips, jaw and tongue. Speech also involves voice quality. For example, your voice can be soft, quiet, loud, smooth, or harsh.

I run out of air when I speak:

Never	Seldom	Sometimes	Frequently	Always

I sound hoarse:

Never	Seldom	Sometimes	Frequently	Always

My speech is slow:

Never	Seldom	Sometimes	Frequently	Always

My speech is slurred:

Never	Seldom	Sometimes	Frequently	Always

I need to repeat what I've said because people don't understand me:

Never	Seldom	Sometimes	Frequently	Always

Appendix 2:

Communicative Participation Questionnaire adapted from Baylor et al. (2013)

<u>Communicative Participation</u>
The following questions describe a variety of situations in which you might need to speak to others. For each question, please mark the extent that your age negatively affects your participation in that situation. Think about an AVERAGE day for your speech – not your best or worst days.

	Not at all	A little	Quite a bit	Very much
Does your age affect talking with people you know?				
Does your age affect communicating when you need to say something quickly				
Does your age affect talking with people you do not know				
Does your age affect communicating when you are out in your community (e.g. errands; appointments)				
Does your age affect asking questions in a conversation?				
Does your age affect communicating in a small group of people?				
Does your age affect having a long conversation with someone you know about a book, movie, show or sports event?				
Does your age affect giving someone detailed information?				
Does your age affect getting your turn in a fast moving conversation?				
Does your age affect trying to persuade a friend or family member to see a different point of view?				

Appendix 3:

Means and standard deviations of the descriptive speech items

Subsystem	Item	N	Mean (SD)
Respiration	1. I struggle to say more than a few words in one breath.	203	1.19 (0.48)
	2. I feel myself rushing my speech towards the ends of sentences.	204	1.32 (0.60)
	3. I feel my speech sounds breathy	204	1.28 (0.61)
	4. It takes a great deal of effort to speak	204	1.12 (0.37)
	5. I pause during or between utterances	204	1.56 (0.71)
Phonation	6. My voice is loud	204	2.39 (1.02)
	7. My voice is quiet	202	2.42 (1.03)
	8. My voice feels unstable	204	1.26 (0.56)
	9. I feel my voice sounds strained	202	1.36 (0.63)
	10. I feel my voice is high pitched	201	1.52 (0.82)
	11. I feel my voice is low-pitched	202	1.91 (1.15)
	12. I feel my voice sounds nasal	202	1.29 (0.62)
Articulation	13. I find myself mumbling	202	1.49 (0.67)
	14. My friends and family find it difficult to understand me	204	1.38 (0.59)
	15. Unfamiliar people find it difficult to understand me	203	1.45 (0.61)

Note: Each item was scored on a 5 point Likert scale (1 = never, 2 = seldom, 3 = sometimes, 4 = frequently, 5 = always).

Appendix 4:

Core parameters for assessing model fit and their cut-off values

Measure	Description	Notes	Good fit if:
Chi Square (X^2)	Assesses overall model fit relative to a perfectly fitting model.	A smaller X^2 value is better. Sensitive to small sample sizes and small deviations from 'perfect' fit.	$p > .05$
Comparative Fit Index (CFI)	Incremental fit index. Compares target model to independent, sample size and model size-adjusted, null model.	Not sensitive to sample size, but sensitive to model complexity.	1 = perfect fit $\geq .0.95$ = excellent fit ≥ 90 = acceptable fit
Root Mean Square Error of Approximation (RSMEA)	Absolute fit index. Accounting for sample size, assesses amount of error in comparison to a perfect fit.	Sensitive to small sample sizes. Smaller values are better.	> 0.10 = unacceptable $0.06 – 0.08$ = acceptable fit ≤ 0.05 = excellent fit
(Standardised) Root Mean Square Residual (SRMR)	Badness-of-fit index based on residuals.	Higher values indicate worse fit.	< 0.08 = acceptable

Note. Definitions taken from Kline (2023), pp 156 – 181, and Putnick and Bornstein

Appendix 5:

Detailed measurement invariance results

Model fit is be examined using CFI (0.01) and RSMEA (.015; Chen, 2007). CFI values approaching 1 show good model fit, whereas RMSEA values approaching 0.05 show good model fit.

MASQ: language T1, T2 (N = 158)

model	CFI	CFI difference (cut off = -.01)	RMSEA	RMSEA difference (cut-off = .015)
Configural	.930		.062	
Metric	.936	.006	.057	-.05
Scalar	.937	.001	.057	.00
Residual	.921	-.016	.063	.06
Notes	All CFI values show acceptable model fit.	There was an improvement of model fit from configural to metric and from metric to scalar. The strictest model (residual) was a significantly worse fit than scalar. Scalar (strong invariance) accepted.	All RMSEA values show acceptable model fit.	Although the change statistic from configural to metric is larger than the cut-off of 0.15, the model fits better as it becomes more constrained. The scalar model did not show worsening of fit, but the residual model model was significantly worse than scalar. Scalar (strong invariance) accepted.

MASQ: visual perceptual ability T1, T2 (N = 158)

model	CFI	CFI difference (cut off = -.01)	RMSEA	RMSEA difference (cut-off = .015)
Configural	.940		.068	
Metric	.942	..002	.063	.005
Scalar	.948	-.006	.057	.006
residual	.781	.167	.111	-.054
Notes	Configural – scalar acceptable fit.	No worsening of fit from configural to metric (slight improvement), or from metric to scalar (again improvement).	Configural, metric and scalar RMSEA shows acceptable fit.	No worsening of model fit and improvement from configural to metric and metric to scalar. Significant worsening of fit from the residual

		Scalar model accepted		model. Scalar model accepted.

MASQ: verbal memory T1, T2 (N = 158)

model	CFI	CFI difference (cut off = -.01)	RMSEA	RMSEA difference (cut-off = .015)
Configural	.990		.944	
Metric	.907	.083	.014	.93
Scalar	.910	- .003	.030	- 0.016
Residual	.905	.005	.029	.001
Notes	All CFI values fall within acceptable range.	Significant worsening of model fit from configural to metric. Slight improvement from metric to scalar and residual.	Metric, scalar and residual values are excellent.	There was a large improvement in model fit from configural to metric invariance. However, the scalar model was a significantly worse fit than the metric model. The residual model did not fit significantly worse than the scalar model.

MASQ: visuospatial memory T1, T2 (N = 158)

model	CFI	CFI difference (cut off = -.01)	RMSEA	RMSEA difference (cut-off = .015)
Configural	.921		.059	
Metric	.915	..006	.058	-.001
Scalar	.915	.000	.056	-.002
Residual	.883	.032	.064	.008
Notes	Metric, scalar and residual values show good model fit	No significant worsening of model fit from configural to metric, or metric to scalar. Worse fit from scalar to residual. Scalar invariance accepted.	Values fall within the acceptable range	No significant worsening of model fit from configural to metric, from metric to scalar to from scalar to residual. Strictest model accepted.

MASQ: attention/concentration T1, T2 (N = 158)

model	CFI	CFI difference (cut off = -.01)	RMSEA	RMSEA difference (cut-off = .015)
Configural	.931		.081	
Metric	.932	.001	.078	.003

Scalar	.936	.005	.074	.004
Residual	.924	-.006	.076	-.002
Notes	All CFI values show good model fit	No significant worsening of model fit. Improvement from configural to metric and from metric to scalar. Residual model accepted.	All values fall within the acceptable range	The RMSEA for the configural model was slightly above the accepted threshold (0.001). However, given the CFI values were also good, the baseline model is accepted. There is no significant worsening of model fit from configural to metric, metric to scalar or scalar to residual. Residual model accepted.

Speech execution T1, T2 (N = 158)

model	CFI	CFI difference (cut off = -.01)	RMSEA	RMSEA difference (cut-off = .015)
Configural	.926		.086	
Metric	.925	.001	.081	.005
Scalar	.912	.013	.083	-.002
Residual	.251	.661	.227	-.144
Notes	Configural, metric and scalar models show acceptable fit	No significant worsening of fit from configural to metric invariance. No significant worsening of fit from metric to scalar. Residual model significantly worse fit to the data. Scalar invariance accepted.	Configural, metric and scalar models show acceptable fit.	Small improvement of model fit from configural to metric. No worsening from metric to scalar. Significant worsening from scalar to residual. Scalar invariance accepted.

Anxiety T1, T2 (N = 158)

model	CFI	CFI difference (cut off = -.01)	RMSEA	RMSEA difference (cut-off = .015)
Configural	.891		.076	
Metric	.869	.022	.080	-.04

| Scalar	.891	-.022	.073	.024
Residual	.885	-.006	.074	-.001
Notes	All CFI values below acceptable cut-off	The CFI change values showed worsening model fit	All RMSEA values show acceptable model fit	RMSEA change values indicate worsening of model fit from configural to metric invariance
Modification index for metric invariance: correlated residual between DASS2 and DASS20	.90	.009 – no significant worsening of model from configural to metric. Metric invariance accepted	.071	.005 – no significant worsening from configural to metric. Metric invariance accepted

MASQ Language

Figure 4a shows a graphical depiction of the language measurement invariance model. Following Kline's (2023) guidance on reporting model fit evaluations, the configural model initially failed the exact-fit chi-square test ($X^2 = 152.57$, $df = 95$, $p < .001$). However, alternative fit indices showed good model fit (CFI = 0.93, RSMEA = 0.06, 90% CI = 0.04 – 0.08, SRMR = 0.761). The metric model was then run, with factor loadings constrained across administrations. The metric model was not a significantly worse fit to the data than the configural model in terms of the chi-square test ($X^2 = 2.17$, $df = 7$, $p = .95$). CFI (0.01) and RSMEA (-0.05) change values showed improvement in the metric model. The scalar model was then run with item intercepts constrained across administrations. The scalar model was not a significantly worse fit to the data than the metric model ($X^2 = 1.12$, $df = 7$, $p = .99$, CFI = 0.001, RMSEA = 0.00). Finally, the residual model was run with residual error terms constrained across administrations. The residual model was not a significantly worse fit than the scalar model ($X^2 = 15.26$, $df = 8$, $p = .05$, CFI = - 0.02), indicating that the strictest model did not differ significantly from the baseline model. However, t~T~he RMSEA from scalar to residual was 0.06, which shows worsening of model fit. Therefore, measurement invariance can be accepted at the scalar level (Appendix 4.8~7~).

The language subscale at time one and time two showed acceptable internal reliability (time one α = 0.76, time two α = 0.77; Tavakol & Dennick, 2011), and test-retest reliability using the mean score ($r = 0.73$, $p < .001$, two-tailed). The factor loadings can be found in Appendix 4.10~8~. The latent variables, language at time one and language at time two, were significant predictors of the manifest variables (p's $< .001$). Overall, the language model showed acceptable measurement invariance across the two timepoints.

Appendix figure 1

Structural equation model showing measurement invariance for MASQ language subscale at T1 and T2
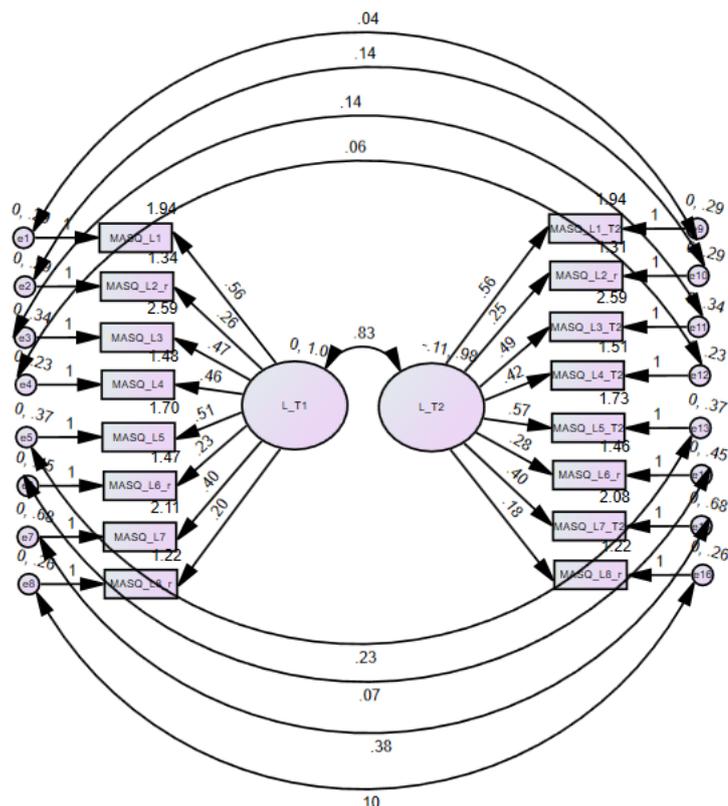
Note: statistics are unstandardised regression coefficients

MASQ Visual perceptual ability

The configural model for the latent variable visual perceptual ability at time one and time two failed the exact fit Chi-square test ($X^2 = 80.70$, $df = 47$, $p = .002$). However, the CFI and RMSEA showed good model fit (CFI = 0.94, RMSEA = 0.07, 90% CI = 0.04 – 0.09). The SRMR also showed good model fit (SRMR = 0.07). The metric model did not differ significantly from the configural model, and even showed a slight improvement of model fit based on the CFI and RMSEA change values (Appendix 7) showed significant worsening of model fit (CFI = 0.07; RMSEA = -0.03). The scalar model also showed an improvement of model fit. However, the residual model showed a significant worsening of fit. Therefore, for the visual perceptual subscale, scalar invariance was established.

Internal reliability for the visual perceptual subscale at time one was α = 0.68 and at time two was α = 0.67. Test-retest reliability based on the mean scores at time one and time two showed a significant correlation ($r = 0.76$, $p < .001$, two-tailed). The factor loadings can be found in Appendix 8. The latent variable, visual perceptual ability at time one and time two significantly predicted the manifest variables (p's < .001).

MASQ Verbal memory

The configural model for the latent variable verbal memory ability at time one and time two passed the exact fit Chi-square test ($X^2 = 104.37$, $df = 95$, $p = 0.24$). The CFI and RSMEA also showed excellent model fit (CFI = 0.99, RSMEA = 0.03, 90% CI = 0.00 – 0.05). The SRMR also showed good model fit (SRMR = 0 .04). The metric, scalar and strict models showed significantly worse model fit than the configural model based on the chi-square test ($ps < .001$). However, the RMSEA change values show a large improvement of fit (0.93) from configural to metric invariance. Although the CFI change value shows a significant worsening of model fit from configural to metric invariance (CFI = 0.08), the CFI values for all models and the RMSEA values for metric, scalar and residual models fall within the acceptable ranges (see Table 6 & Appendix 7). Therefore, metric invariance is established.

Internal reliability for the verbal memory subscale at time one was α = 0.837 and at time two was α = 0.829. Test-retest reliability based on the mean scores at time one and time two showed a significant correlation ($r = 0.70$, $p < .001$, two-tailed). The factor loadings can be found in Appendix 8. The latent variable, verbal memory at time one and time two significantly predicted the manifest variables (p's < .001).

MASQ Visuospatial memory

The configural model for the latent variable verbal memory ability at time one and time two failed the exact fit Chi-square test ($X^2 = 146.17$, $df = 95$, $p < .001$). However, the CFI and RSMEA showed good model fit (CFI = 0.92, RMSEA = 0.59, 90% CI = 0.04 – 0.08). The SRMR also showed good model fit (SRMR = 0.07). BASED on the CFI and RMSEA change values, the metric model was not a significantly worse fit than the configural. The scalar model was also not a significantly worse fit than the metric model, nor was the residual model a significantly worse fit than the scalar model. Therefore, for the visuospatial memory subscale we can accept the strictest (residual) model.

Internal reliability for the visuospatial memory subscale at time one was α = 0.746 and at time two was α = 0.731. Test-retest reliability based on the mean scores at time one and time two showed a significant correlation ($r = 0.67$, $p < .001$, two-tailed). The factor loadings can be found in Appendix 8. The latent variable, verbal memory at time one and time two significantly predicted the manifest variables (p's < .001).

MASQ Attention/concentration

The configural model for the latent variable attention/concentration at time one and time two failed the exact fit Chi-square test ($X^2 = 153.61$, $df = 95$, $p < .001$). However, the CFI and RSMEA showed good model fit (CFI = 0.92, RSMEA = 0.06, 90% CI = .04 – .08). The SRMR also showed good model fit (SRMR = .07). The metric, scalar and strict models did not significantly worsen based on the CFI (0.01)

and RMSEA (0.015) change values. Therefore, for the attention/concentration subscale, we can accept strict (residual) invariance.

Internal reliability for the attention/concentration subscale at time one was α = 0.760 and at time two was α = 0.758. Test-retest reliability based on the mean scores at time one and time two showed a significant correlation ($r = 0.75$, $p < .001$, two-tailed).

Speech execution

The configural model for the latent variable speech execution at time one and time two failed the exact fit Chi-square test ($X^2 = 62.50$, $df = 29$, $p < .001$). However, the CFI showed an excellent model fit (CFI = 0.93) and the RMSEA was borderline but acceptable (RSMEA = 0.09). In addition, the SRMR also showed good model fit (SRMR = 0.06). The metric, scalar and strict models were a significantly worse fit to the data according to chi-square (ps < .001). However, according to CFI and RMSEA change values, the metric (CFI = 0.001, RMSEA = 0.005) and scalar models were not a significantly worse fit to the data (CFI = 0.01, RMSEA = - 0.002). The residual model did however significantly worsen (CFI = 0.25, RMSEA = - 0.14). Therefore, for the speech subscale scalar invariance was achieved. Internal reliability for the speech execution subscale at time one was α = 0.628 and at time two was α = 0.704. Although, these values are borderline for internal reliability, this may be due to there being only five items in the scale. Test-retest reliability based on the mean scores at time one and time two showed a significant correlation ($r = 0.70$, $p < .001$, two-tailed).

Anxiety

The configural model for the latent variable anxiety at time one and time two failed the exact fit Chi-square test ($X^2 = 131.44$, $df = 69$, $p < .001$). The CFI value also did not meet the threshold for acceptable model fit (CFI = 0.89). However, the RMSEA value was acceptable for configural invariance (0.076), as was the SRMR (.073). The CFI and RMSEA change values showed that the metric model was a significantly worse fit to the data than the configural model, suggesting difficulty in establishing measurement invariance. A modification index suggested there could be shared unexplained variance between DASS2 ("I was aware of dryness in my mouth") and DASS20 ("I felt scared without any good reason"). A correlated residual was added to connect these items directly, and the metric model improved (CFI = 0.90, RMSEA = .071) with change statistics showing no worsening of the metric model.

Internal reliability for the anxiety subscale at time one was α = 0.628 and at time two was α = 0.704. Test-retest reliability based on the mean scores at time one and time two showed a significant correlation ($r = 0.70$, $p < .001$, two-tailed). Due to this modification, and the CFI change value being (.009) being just below the acceptable threshold of .01, scalar invariance was not explored and metric invariance was accepted.

Appendix 6:

Motor Speech disorders examination test (Rusz et al, 2021)

General instruction for examiner:
- For recording choose a quiet room. Avoid lecture halls or other large rooms where there is the risk of echo or rooms with a large amount of medical devices.
- Try to reduce the level of draught as much as possible. Close windows and doors, move cooling fans to face the wall and reduce the level of cooling
- Try to reduce the level of ambient noise as much as possible. Close windows and doors, switch off mobile phones etc.
- Offer participants a glass of water. Motivate them to drink.
- Be sure the position of the microphone is correct.
- It is possible to modify the instruction below but the bold parts should remain.
- It is necessary that the examiner perform the first two tasks
-

SUSTAINED PHONATION - /a/	Num. of. Repetit.	Perform by exam
- Explain the recording procedure to the patient: "The speech examination consists of 4 speaking tasks. I will firstly explain and show you how to perform the task. Then it will be time for your performance. Some of the tasks will be repeated twice. The duration of the tasks is variable. When the task ends, I will give you a hand-sign to avoid overlap of our speech". - Ask subject: "Now please **draw a deep breath** and try to perform a sustained phonation of the vowel /a/ as **constant and long as possible** on one breath. - Perform the task and continue with the next instruction: "You should keep this as long as possible, but **at least 10 seconds**. I will measure with a timer." - Do not interrupt the participant, let them phonate for as long as possible. The task is performed until the participant is out of breath. The total phonation time is also measured. - In the case that the participant's time is shorter than 6 seconds try to motivate them to better performance. It could be helpful if participant lowers the loudness of voice and use their common pitch of voice.	2X	YES
DDK TASK - /pa-ta-ka/		
- Ask participant: "Now please repeat these syllables /pa/-/ta/-/ka/" - Recite these syllables slowly, emphatically with a short pause among them - After the participant has repeated these syllables correctly, continue with the next instruction: "Before this task **draw a deep breath** and then begin repeating these syllables /pa/-/ta/-/ka/ as quick and accurate as possible until I stop you. Now I will show you this task". - Perform the task. Syllables are pronounced continuously and shortly. - The required number of repetitions is 12 times (12 x pataka triples)	2X	YES

• The accuracy of articulation is more important the velocity. Each syllable should be intelligible. • In the case that participant's performance is not correct, the examiner should refer to mistakes and repeat the instruction. • The typical mistakes are 1. Consonants are changed e.g. /pa-sa-ka/; vowels are omitted e.g. p-t-k-p-t-k, one syllable is doubled /pa-ta-ka-pa-pa-ta-ka/, syllables are not continuous, there are periodic pauses between repetitions.		
READING TEXT • Ask participant: Please now read this short paragraph of text. If you need glasses, please take them now". • Use Rainbow Passage • The recommended number of words for reading passage is about 80 to 120 words printed in 24pt font. The passage should include familiar, up-to-date vocabulary and grammatical structures.	1	No
MONOLOGUE		
• Ask participant: "The aim of the last task is to talk for about one and a half minute. The particular choice of topic is up to you. For example, you can talk about your hometown, childhood, hobbies or family. It should be a monologue, so I will not interrupt you. Think it over for a while and then you can start". • More than one topic might be narrated • The monologue should be composed mostly of **common speech.** No singing, rhymes, strong emotions or imitations of foreign accents should be included. • Use a stopwatch to measure the time of the monologue. If the monologue is short or has poor content (the participant is still repeating the same 2-3 sentences), try to switch to another topic or ask suitable open questions. The real time of the monologue without long pauses or examiner questions should be 90 secs.		

Appendix 7:

Rainbow passage

When the sunlight strikes raindrops in the air, they act as a prism and form a rainbow. The rainbow is a division of white light into many beautiful colours. These take the shape of a long round arch, with its path high above, and its two ends apparently beyond the horizon. There is, according to legend, a boiling pot of gold at one end. People look, but no one ever finds it. When a man looks for something beyond his reach, his friends say he is looking for the pot of gold at the end of the rainbow.

Appendix 8:

Speech analysis instructions using Praat

<u>Sustained vowel task</u>

Measures: MPT and F0SD
On Praat:
- Open > read from file > select audio file
- Annotate > to text grid > create one tier called e.g. duration
- Mark duration of prolonged /a/ including only voiced segment, excluding any audible breathing noise
- Insert boundary 3ms after beginning of sound production and 3ms before the end of the sound production. Use the following steps:
    o Go to the 'Time' tab at the top of the textgrid > select widen or shrink selection > change new width of selections from 0.3 to 0.03 > select left alignment > insert boundary
    o Repeat with the end of the sound production but select right alignment before inserting boundary

Run Hirst Script
- Go to > File > Open editor script
- Load "Hirst script"
- Press Run > Run
- Check pitch changes for every file

Extract data
- Highlight segment
- Go to pulses > voice report
- Enter the following values into excel spreadsheet
- Maximum phonation time (secs), mean pitch and SD
- Close script
- Repeat with next file

1. <u>DDK task</u>

Measures: DDK rate, coefficient of variation
Measuring DDK:
- Load sound file into Praat and create textgrid with one tier named e.g. syllables
- Annotate each syllable with boundaries and letters (p, t, & k). Measure from the burst of one plosive to the next. If participant takes a breath stop there and include only repetitions produced in one breath. Include syllables even if they are not in the correct order.
- Disregard the first and the last syllables as these tend to have a different length from the other syllables (see example below)

Figure 1:

Example annotation for syllable repetition of /ka/
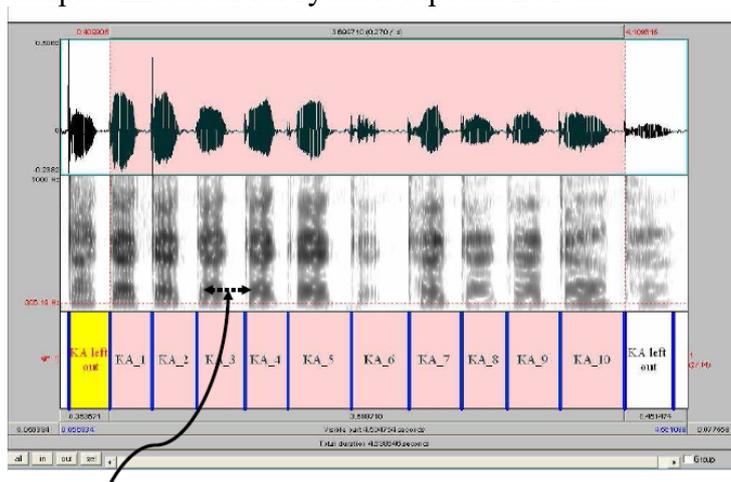
- Count the syllables. This can be done by looking at total syllables on the right side of the screen, making sure you minus any not included e.g. do not include the pause at the beginning and end, and the syllables left out. In the example above, Praat has counted 14 syllables, but we are interested in the highlighted part, so 10 is correct. Enter the number of syllables into excel spreadsheet (attached)
- Enter total duration (**to 2 decimal places**) into the excel spreadsheet. To do this, highlight the segment, not including the first and last syllables. Read from the bottom of the text grid, or from voice report. If the excerpt is particularly long and won't fit on the screen, you can create another tier and mark the first and last boundary to get the total duration of the segment of interest.
- Calculate DDK rate and enter it into the excel spreadsheet. DDK rate = syllables divided by duration. I calculated this manually using a calculator.
- Save textgrid

2. Coefficient of variation (COV):

COV calculates the regularity of the syllable repetitions by using the standard deviation of the duration of the syllables. To calculate regularity, do the following:
- Select annotated textgrid in Praat objects window and select 'down to table'
- Select the table and click 'modify' > 'append difference column'. Fill in the boxes left to right with 'tmax' and 'tmin' respectively. Click Okay.
- Go to save > save as tab-separated file. Here you have to make sure the file is saved in excel format (.xls).
- Go to the folder where you saved the excel spreadsheet and open it. You should see there is a column called 'diff'. This tells you the duration of each syllable repetition.
- We want to convert the syllable durations to syllable repetition rate in an adjacent column called 'syllable repetition rate' by taking the inverse. Use the following formula: =1/(……)   within the brackets, highlight the difference column **making sure to leave out the first and last syllables (which you will have annotated as 'left out').**
- Title the next column 'mean' and work out the mean of the syllable repetition rates. Use the following formula: =(AVERAGE(……))   within the brackets, highlight the cells in the syllable repetition rate column.

- Title the next column 'SD' and work out the standard deviation of the syllable repetition rates using the following formula: =(STDEV.P(…..)) within the brackets highlight the syllable repetition rate column. See example of completed spreadsheet below.
- Enter the mean and SD (**to 2DP**) into the excel spreadsheet and calculate the COV manually. COV = SD divided by mean X 100. Higher numbers mean less regularity of syllable repetitions.
- At this point you may have to save the spreadsheet as an excel workbook (.xlsx) to avoid data losses.

3. Rainbow passage
   Measures: articulation rate
   - Load sound file in Praat and create textgrid with three tiers (e.g. 1, 2, 3)
   - In tier one, add boundaries at the start and the end of the voiced segment excluding any audible breathing.

   - In tier two, annotate pauses longer than 0.2 seconds.
   - The rainbow passage has 127 syllables, so we do not need to annotate every syllable. Ensure the participant is saying all the syllables. If they miss a syllable, take this into account in the total syllable count. If they add extra syllables, exclude these. In tier three annotate any extra syllables/errors (e.g. revisions, additions, false starts) – these will not be included in the syllable count.
   - Fill in the excel spreadsheet with:

   - number of syllables (most, if not all will be 127)
   - total pause duration – add up the duration of all the pauses (do not round up)
   - total speech duration – highlight segment and read from voice report (do not round up)

   - articulation rate – syllables / (speech duration – total pause time)

5. Monologue task

Measures: Articulation rate
- Open the audio file and text grid in Praat. The audio file is the middle 30 seconds of a 1.5 minute monologue produced by participants about a subject of their choice. The textgrid contains the orthographic and phonetic transcription (run through BAS Web services). Use the transcription as a guide but bear in mind that it is not always accurate and the syllables and pauses do not always line up with the audio.
- Add 2 additional interval tiers to the text grid. The first one is for annotating and counting syllables. The second one is for measuring the total duration of the spoken segment and for working out F0.
- Annotate each individual syllable. Label each syllable with it's number e.g. 1, 2, 3,
- Annotate any lexically irrelevant vocalisations but do not include these in the syllable count (e.g. "ehh", "umm", dysfluencies; Rogers t al. 2013). The transcript does not include these anyway. See below.

Figure 2:
Praat textgrid and annotation of monolgue task for articulation rate
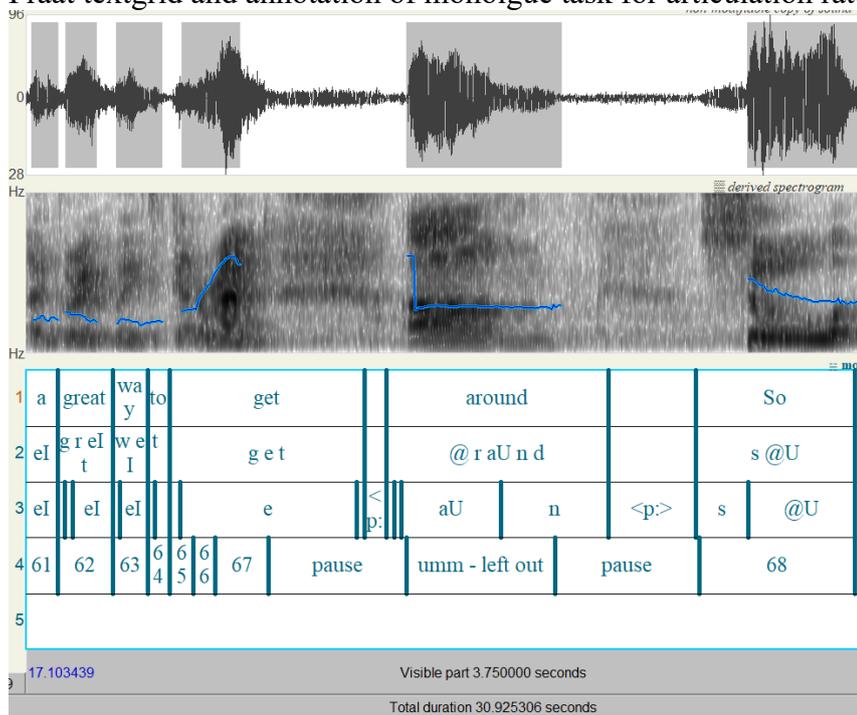
Note: Webmaus (Schiel, 1999) was used for speech to text alignment. Alignment was not always working well. The first three tiers are irrelevant and the fourth tier was used to annotate number of syllables and pauses.

- Annotate pauses longer than 200 ms (Rodgers et al., 2013). Pauses are defined as segments containing silence, breathing or sounds that come from opening or closing the mouth. Filled pauses (e.g. emm, umm) are not to be included in the pause duration.
- In tier 5 mark a boundary at the start and end of the 30 second passage.
- In the attached excel sheet, type in the number of syllables.
- Calculate the total pause time by summing the length of all pauses (I did this in a separate excel spreadsheet). Enter this into the attached excel spreadsheet.
- Get total speech time by highlighting the spoken segment in tier 5. Read the total duration from the voice report. Enter this into the excel spreadsheet and calculate total speech duration minus total pause time.
- Enter articulation rate (no of syllables/speech duration - pause duration).
- Make sure you save the textgrid at this point.
Calculating F0:
- on the annotated textgrid go to file > open: open the Hirst script (attached). Run the script. Open the voice report and copy F0 mean and F0 SD into the excel spreadsheet. Close the script.
- Repeat with the rest.

Appendix 9

Unstandardized coefficients, significance tests and 95% confidence intervals for predictors of motor speech execution

Table 1

Predictors of articulation rate from passage reading

Predictors	Outcomes	N	Unstandardized Coefficients				95% confidence intervals for B	
			B	**SE**	**t**	**p**	**Lower bound**	**Upper bound**
Age	Articulation rate (passage)	87	- 0.01	0.01	- 1.10	0.28	- 0.04	0.01
Gender		87	- 0.14	0.13	-1.04	0.30	- 0.40	0.12
Years of education		87	-0.01	0.03	- 0.23	0.82	- 0.10	0.04
Speech difficulty		87	0.02	0.03	0.74	0.46	- 0.03	0.07
Depression		87	0.02	0.02	1.10	0.28	-0.01	0.05
Anxiety		87	- 0.01	0.02	- 0.33	0.74	- 0.04	0.03
Stress		87	- 0.01	0.01	-0.90	0.37	-0.03	0.01
Activity engagement		87	0.00	0.01	-0.14	0.89	- 0.01	0.01
Hearing ability		87	0.01	0.01	0.36	0.72	- 0.02	0.03
Vision ability		87	- 0.01	0.01	- 0.62	0.53	- 0.01	0.01
Fluid cognition		87	0.01	0.01	0.98	0.33	- 0.01	0.02
Crystallised cognition		87	0.02	0.01	1.85	0.07	- 0.002	0.04

Note. Table contains results from model three with all variables entered

Table 2

Predictors of articulation rate from monologue

Predictors	Outcomes	N	Unstandardized Coefficients				95% confidence intervals for B	
			B	*SE*	*t*	*p*	Lower bound	Upper bound
Age	Articulation rate (monologue)	87	0.01	0.01	0.97	0.34	- 0.01	0.03
Gender		87	0.01	0.13	0.11	0.91	- 0.25	0.27
Years of education		87	- 0.01	0.02	- 0.03	0.60	- 0.6	0.04
Speech difficulty		87	- 0.01	0.03	- 0.28	0.78	- 0.06	0.05
Depression		87	0.01	0.2	0.42	0.68	- 0.02	0.05
Anxiety		87	- 0.03	0.02	-1.80	0.08	- 0.07	0.00
Stress		87	0.02	0.01	1.18	0.07	- 0.00	0.05
Activity engagement		87	0.00	0.00	0.24	0.81	- 0.01	0.01
Hearing ability		87	0.02	0.01	1.22	0.23	- 0.01	0.04
Vision ability		87	- 0.01	0.00	-1.57	0.12	- 0.02	0.00
Fluid cognition		87	0.01	0.01	1.64	0.11	- 0.00	0.03
Crystallised cognition		87	- 0.00	0.01	- 0.12	0.90	- 0.02	0.02

Note. Table contains results from model three with all variables entered

Table 3

Predictors of F0SD from monologue

Predictors	Outcomes	N	Unstandardized Coefficients		t	p	95% confidence intervals for B	
			B	*SE*	*t*	*p*	Lower bound	Upper bound
Age	F0SD (monologue)	87	0.22	0.28	0.77	0.44	-0.35	0.78
Gender		87	11.74	3.35	3.51	<0.001	5.06	18.42
Years of education		87	0.28	0.61	0.46	0.65	-0.93	1.48
Speech difficulty		87	-1.65	0.67	-2.45	0.02	-2.99	-0.31
Depression		87	0.20	0.38	0.52	0.60	-0.56	0.96
Anxiety		87	-0.18	0.44	-0.41	0.68	-1.06	0.70
Stress		87	0.36	0.29	1.26	0.21	-0.21	0.93
Activity engagement		87	0.06	0.09	0.65	0.52	-0.12	0.23
Hearing ability		87	0.50	0.35	1.44	0.16	-0.19	1.19
Vision ability		87	0.02	0.11	0.16	0.87	-0.20	0.24
Fluid cognition		87	-0.22	0.20	-1.10	0.28	-0.61	0.18
Crystallised cognition		87	0.26	0.27	0.97	0.34	-0.27	0.79

Note. Table contains results from model three with all variables entered

Table 4

Predictors of DDK rate

Predictors	Outcomes	N	Unstandardized Coefficients				95% confidence intervals for B	
			B	*SE*	*t*	*p*	Lower bound	Upper bound
Age	DDK rate	87	0.01	0.02	0.34	0.74	- 0.2	0.03
Gender		87	- 0.41	0.17	- 2.46	**0.02**	- 0.75	- 0.08
Years of education		87	- 0.02	0.03	- 0.62	0.54	- 0.82	0.04
Speech difficulty		87	0.06	0.03	1.62	0.11	- 0.01	0.12
Depression		87	- 0.03	0.20	- 1.343	0.18	- 0.07	0.13
Anxiety		87	- 0.30	0.02	- 1.23	0.22	- 0.07	0.02
Stress		87	0.01	0.02	0.69	0.49	- 0.20	0.04
Activity engagement		87	0.01	0.004	1.37	0.18	- 0.003	0.02
Hearing ability		87	0.02	0.02	1.11	0.27	- 0.12	0.05
Vision ability		87	- 0.004	0.01	- 0.80	0.43	- 0.02	0.01
Fluid cognition		87	0.04	0.01	3.75	**< 0.001**	0.02	0.06
Crystallised cognition		87	0.03	0.01	2.27	**0.03**	0.004	0.06

Note. Table contains results from model three with all variables entered

Table 5

Predictors of DDK CoV

Predictors	Outcomes	N	Unstandardized Coefficients				95% confidence intervals for B	
			B	*SE*	*t*	*p*	Lower bound	Upper bound
Age	DDK CoV	85	- 0.27	0.12	- 2.35	**0.02**	- 0.50	- 0.04
Gender		85	0.37	1.133	0.28	0.78	- 2.27	3.02
Years of education		85	0.08	0.25	0.33	0.74	- 0.41	0.58
Speech difficulty		85	- 0.05	0.27	- 0.19	0.85	- 0.59	0.49
Depression		85	0.12	0.16	0.71	0.48	- 0.23	0.47
Anxiety		85	0.10	0.18	0.50	0.62	- 0.27	0.45
Stress		85	- 0.10	0.12	- 0.87	0.39	- 0.34	0.13
Activity engagement		85	0.01	0.04	0.17	0.87	- 0.06	0.08
Hearing ability		85	- 0.10	0.14	- 0.69	0.49	- 0.37	0.18
Vision ability		85	0.04	0.05	0.86	0.40	- 0.05	0.13
Fluid cognition		85	- 0.91	0.08	- 2.48	**0.02**	- 0.34	- 0.04
Crystallised cognition		85	- 0.01	0.11	- 0.11	0.92	- 0.23	0.21

Note. Table contains results from model three with all variables entered

Table 6

Predictors of maximum phonation time

Predictors	Outcomes	N	Unstandardized Coefficients				95% confidence intervals for B	
			B	*SE*	*t*	*p*	Lower bound	Upper bound
Age	MPT	85	0.03	0.11	0.32	0.75	-0.18	0.25
Gender		85	-0.91	1.20	- 0.75	0.45	- 3.31	1.49
Years of education		85	- 0.19	0.22	- 0.83	0.41	- 0.63	0.26
Speech difficulty		85	- 0.53	0.25	- 2.14	**0.04**	- 1.02	- 0.04
Depression		85	-0.13	0.14	- 0.91	0.37	- 0.41	0.15
Anxiety		85	0.15	0.16	0.93	0.35	- 0.17	0.46
Stress		85	0.01	-.11	0.04	0.97	- 0.21	0.22
Activity engagement		85	- 0.06	0.31	- 1.77	0.08	- 0.12	0.01
Hearing ability		85	0.03	0.13	0.27	0.79	- 0.22	0.28
Vision ability		85	0.01	0.04	0.28	0.78	- 0.07	0.09
Fluid cognition		85	- 0.17	0.07	- 2.39	**0.02**	- 0.31	- 0.03
Crystallised cognition		85	0.04	0.10	0.35	0.73	- 0.17	0.24

Note. Table contains results from model three with all variables entered

Table 7

Predictors of F0SD from sustained vowel

Predictors	Outcomes	N	Unstandardized Coefficients				95% confidence intervals for B	
			B	*SE*	*t*	*p*	Lower bound	Upper bound
Age	F0SD (vowel)	87	0.14	0.35	0.40	0.69	- 0.55	0.83
Gender		87	6.62	3.99	1.66	0.10	- 1.32	14.57
Years of education		87	- 0.35	0.75	- 0.47	0.64	- 1.85	1.14
Speech difficulty		87	0.73	0.82	0.89	0.38	- 0.90	2.35
Depression		87	0.46	0.47	0.97	0.34	- 0.49	1.40
Anxiety		87	- 0.56	0.53	- 1.06	0.30	- 1.63	0.50
Stress		87	- 0.004	0.36	- 0.01	0.99	- 0.72	0.71
Activity engagement		87	0.03	0.11	0.29	0.77	- 0.18	0.24
Hearing ability		87	- 0.59	0.42	- 1.41	0.16	- 1.42	0.24
Vision ability		87	- 0.07	0.13	- 0.55	0.58	- 0.34	0.19
Fluid cognition		87	0.01	0.23	0.05	0.96	- 0.44	0.47
Crystallised cognition		87	0.11	0.34	0.31	0.75	- 0.56	0.78

Note. Table contains results from model three with all variables entered