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The application of linear and nonlinear estimators of acoustic variability in the assessment of speech motor control in hypokinetic dysarthria

by

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Declaration of Authenticity and Author's Rights

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

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Abstract

To improve diagnostic and outcome measures in the assessment and treatment of speech disorders, researchers and clinicians are always in search of new techniques to quantify speech impairment. This thesis investigates the relatively unexplored area of linear and nonlinear estimators of acoustic variability and their suitability for assessing the stability of movement patterns of speech organs. In particular, it focused on the estimators' ability to differentiate hypokinetic dysarthria from unimpaired speech, as well as speech of young adults from older adults. In addition, the variability results of hypokinetic dysarthric speakers were compared with the results of standard diagnostic assessments.

Twenty-three speakers with hypokinetic dysarthria and forty neurologically healthy individuals participated in the study. A series of sentence repetition tasks was devised with varying linguistic, cognitive and motor demands. A range of time-varying speech features was extracted from the acoustic signal in order to capture speech motor performance in a number of segmental and prosodic aspects of speech production.

The results showed that acoustic measures of variability were successful in classifying dysarthria and healthy speakers as well as adult speakers differing in age, and correlated with different clinical-based assessments.

The findings of this study indicate that the characterization of complex speech movements during phrase production when evaluating linguistic, cognitive, or motor demands within or between speaker groups cannot be reduced to a single task or speech property, but rather call for a multi-faceted approach in which distinct variability estimators, speech tasks and acoustic properties are evaluated simultaneously.

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Chapter 1

Introduction

1.1 Introduction

The production of speech requires a complex organisation, interaction and execution of motoric, sensory, cognitive and linguistic processes. The characteristics of normal and disordered speech motor control processes have been a well-covered and popular topic of research in the past decades and have been studied by an array of experimental and empirical approaches. As of now, a wide range of experimental instrumentation is available to study speech motor control. In recent years, new methodologies have been developed involving the assessment of consistency and stability of movement patterns of speech organs during speaking. A particularly interesting group of neurogenic speech disorders to put these methodologies into use are the dysarthrias. Dysarthria is *"a collective name for a group of related speech disorders that are due to disturbances in muscular control of the speech mechanism resulting from impairment of any of the basic motor processes involved in the execution of speech."* (Darley, Aronson, & Brown, 1975, p 2). Seven types of dysarthria are distinguished, including hypokinetic, ataxic, hyperkinetic, flaccid, spastic, unilateral upper motor neuron, and mixed spastic-flaccid dysarthria. Each dysarthria type has been hypothesized to be related to a particular lesion site of the neural circuit involved in speech production (Darley, Aronson, & Brown, 1969a, 1969b; Kent, Kent, Weismer, & Duffy, 2000; Duffy, 2000). If one considers the impairment in precise kinematic movement control to be the core deficit in dysarthria, measures of movement stability during speech provide an excellent window into the assessment of speech motor control in dysarthria. While studying speech motor control issues in dysarthria has mostly been useful for clinical purposes, in particular to support identification, assessment and treatment of the disorder, research into disordered or atypical speech also adds to the general knowledge about how motor control processes are governed by the brain during normal, healthy speech production (Kent et al., 2000; Kent, 2000; Chen, Stevens, Kuo, & Chen, 2000).

Relatively new techniques of analysing speech movement stability (and its inverse, variability) are the spatiotemporal index (STI) (Smith, Goffman, Zelaznik, Ying, & McGillem, 1995) and functional data analysis (FDA) (Lucero & Koenig, 2000; Ward & Arnfield, 2001). These data processing techniques enable the analysis of temporal and spatial variability of a repeated continuous signal, and can be applied in the field of speech research to measure variability in the timing and amplitude of speech movements. In research to date, speech movement variability measures have largely been applied to articulatory movement signals captured using direct measurement techniques. For example, studies have applied the STI and FDA to analyse variability in upper lip, lower lip, tongue, and jaw movements collected almost exclusively by means of cantilever/strain gauge systems (Smith et al., 1995), electromagnetic articulography (Ward & Arnfield, 2001), electropalatography (McAuliffe, Ward, & Murdoch, 2003), or electromyography (Wohlert & Smith, 2002). One of the largest drawbacks of these methods is the invasive and complex nature of the technology to collect data, involving intra- and extra-oral attachment of sensors to lips, tongue, palate, velum, and jaw. These methodologies require expensive, large and specialist equipment, making it not easily acceptable to use with participants with motor and sensory impairments. Participant numbers in previous studies involving advanced assessment of speech motor movements have therefore been low and biased, impacting on the statistical power and predictions made by these experiments.

Besides direct external and internal measurements of speech movements, articulatory activity may also be measured indirectly. The speech signal contains several continuous or quasi-continuous acoustic data properties varying in time, including intensity, fundamental frequency, and formants, all corresponding in one way or another to articulatory activity. Recent developments in speech processing have enabled the application of the STI and FDA to assess and quantify variability of these acoustic properties as an indirect measure of speech movement stability, thus circumventing the invasive and technologically demanding nature of directly measured speech movement data. A small number of studies have now applied these speech variability assessment methodologies to acoustic data collected from healthy and speech impaired speakers. Howell, Anderson, Bartrip, and Bailey (2009) demonstrated that variability measures of speech intensity over time obtained from audio recordings are correlating well with directly obtained measures of lower lip movement variability. Anderson, Lowit, and Howell (2008) were able to distinguish between speakers with hypokinetic dysarthria and ataxic dysarthria on the basis of differences in the spatial and temporal variability of amplitude contours extracted from the speech signal. Whilst these studies show promising results of applying the STI and FDA to quantify acoustic variability of healthy and disordered speech, the exploratory nature of these studies made them insufficient to investigate the full potential of variability measures sourced from the acoustic signal as a means to further understand speech motor control in speakers with dysarthria.

1.2 Aim of the study

This study extends previous findings on variability of speech motor control by focussing on the more detailed analysis of speech motor control characteristics in patients with dysarthria as well as young and older healthy adult speakers, by analysing time varying speech properties extracted from the acoustic speech signal. The dysarthrias as a relatively prevalent neurogenic communication disorder are a logical focus of attention with regard to investigating atypical speech motor control behaviour. Of the different types, hypokinetic dysarthria is of particular interest, as this is one of the most prevalent singular dysarthria types (after hyperkinetic dysarthria, which can be divided in four subtypes), and exhibits in general a typical and consistent pattern of speech disorders, enabling the formation and recruitment of a clear-cut participants group (Duffy, 2000, 2013). Therefore, hypokinetic dysarthria is the preferred group to study speech motor control, and will be the focus of this study.

The aim of this study is to undertake a thorough and comprehensive testing of variability measures applied to different continuous acoustic signals, in order to assess their suitability for measuring characteristics of speech motor control in hypokinetic dysarthria, that is, whether these are able to distinguish between hypokinetic dysarthric speech and unimpaired speech. A positive answer entails that this technology can be recommended to be widely adopted in speech motor control research, and potentially be embedded in clinical practice, adding to the instrumentation available to the speech pathologist and speech researcher when assessing this particular type of speech motor disorders.

In this study, the acoustic parameters Sound Pressure Level, Fundamental Frequency, First Formant and Second Formant will be used as audio measures to estimate linear (STI; spatiotemporal variability) and nonlinear (FDA; temporal variability and spatial variability) measures of variability. In addition, different speaking conditions will be employed, in order to observe possible task-related differences in speech motor control for the speakers with hypokinetic dysarthria and healthy control speakers, as well as between healthy speakers differing in age. The speaking conditions will be varied in terms of differences in speaking rate, with longer and more complex sentences, and during a concurrent manual drawing task. In this way, speakers will be challenged by increased linguistic and cognitive complexity, and increased motor load. In order to be able to interpret the acoustic variability results of speakers with hypokinetic dysarthria in a wider clinical context, the results will be compared with established intelligibility ratings, acoustic measures of diadochokinetic performance, and quantifiable details of patient history.

1.3 Thesis outline

In the following Chapter 2, relevant literature is reviewed, starting by examining the nature of hypokinetic dysarthria, including clinical and speech characteristics, particularly highlighting issues in speech motor control. Furthermore, the literature is reviewed with respect to measuring speech motor variability, with an emphasis on the spatiotemporal index and functional data analysis. Literature of speech motor variability of selected acoustic speech parameters is reviewed, along with studies on linguistic, cognitive, and motor factors influencing speech motor variability. The chapter concludes with identifying gaps in the current research, stating the aim of the study, and an overview of the research questions set forth in this study. In Chapter 3, the methodology of the study is laid out, starting with the general design of the study, followed by the characteristics of the participants, a description of the development and testing of the materials used in the study, and the methodology for data collection and data analysis. The results are presented in Chapter 4, starting with an overview of the acoustic analyses, followed by the intelligibility analyses, the variability analyses, and finishing with the results of the correlational analyses. In the final Chapter 5, the results of the various analyses and their correlations are discussed with regard to the aims and research questions set out in this study. Furthermore, an overview of the limitations of this study is given, along with suggestions for further research. The discussion chapter finishes with an evaluation of the suitability of the linear and nonlinear estimators of speech motor variability to be used in clinical research and clinical practice.

Chapter 2

Literature review

2.1 Introduction

In this chapter, the literature is reviewed regarding the assessment of speech difficulties in speakers with dysarthria. In section 2.2, the principles of speech production are briefly discussed. Section 2.3 gives a general definition and description of dysarthria. The nature of hypokinetic dysarthria is examined in section 2.4, including etiology, clinical characteristics, and prominent speech characteristics, with a particular focus on the role of impaired speech motor control in hypokinesia. In section 2.5, literature is reviewed with respect to changes in speech production during normal ageing. In section 2.6, an overview of literature is given with respect to measuring variability of speech in healthy and disordered speakers, specifically by means of the spatiotemporal index and functional data analysis. Research studies concerning the analysis of variability of selected speech properties, including intensity, fundamental frequency, and formants in the speech of speakers with dysarthria and healthy speakers of different age groups are discussed in section 2.7.1 and section 2.7.2, respectively. In section 2.7.3, linguistic and cognitive factors that influence variability of speech motor control are discussed. These factors include speech rate modification, increased sentence length and complexity, and divided attention. The literature review concludes with a summary of findings in section 2.8, and in the final section 2.9, the aim of the study and the research questions are stated.

2.2 The production of speech

The production of speech involves a complex organization of cognitive, linguistic and sensory mechanisms. On a motoric level, speech is governed by the neural system and musculature of the speech organs. Three main components are being governed by motor processes: the subglottal system, the larynx and the supralaryngeal vocal tract (Smith, 1992). During exhalation, the subglottal system generates the air pressure to vibrate the vocal folds. In order to control the sound pressure level of the speech signal (and directly related, the perceived loudness), a high level of muscle control is required. The second component, the larynx, contains vocal folds which produce the voice required for speech. Muscular control involves tensing, relaxing and positioning of the vocal folds, and the resulting vibration frequency is related to the perceived pitch of speech sounds. The tensing and relaxing of the vocal folds together with the air stream generated by the subglottal system thus influence the pitch and loudness of the speech signal. The third component, the vocal tract, filters the voiced sounds coming from the vocal folds, characterizing the nature and identity of speech sounds. The articulators involved in the production of speech are the lips, the mandible (lower jaw), the velum, and the tongue. Lip movements are coordinated by several muscles, to achieve rounding, protrusion and spreading. Opening of the lower jaw is primarily done by gravity. Closing is an active process, involving muscles that are also used for biting. The function of the velum is to close off the nasal passages, necessary to produce the non-nasal sounds. Finally, the tongue as the primary articulator, is a complex system of muscles able to retract, curl, flatten and broaden its shape (Reetz & Jongman, 2009). The muscle contractions are controlled by nerve impulses initiated in the motor areas of the brain and spinal cord (Murdoch, 1990).

A successful execution of these speech production components requires two steps. The first step concerns the *planning and programming* of sensorimotor programs that govern the activation of speech muscles at a specific time, duration and force. The second step concerns the *neuromuscular execution*: the actual activation of the respiratory, phonatory and articulatory muscles by the central and peripheral nervous system, and their subsequent execution of movements. The steps of speech motor planning, programming, control and execution are called *speech motor processes* (Duffy, 2013).

An impairment in each of the steps in the speech motor processes may result in a distinctive speech disorder. When the planning and programming of articulatory movements is impaired, the resulting speech disorder is usually called *apraxia of speech*. An impairment in the neuromuscular activation and movement of articulators usually results in *dysarthria of speech*[1] (Darley et al., 1975; Duffy, 2000).

2.3 Definition of dysarthria

A general definition of dysarthria is provided by Darley et al. (1975, p 2):

> [···] dysarthria is a collective name for a group of related speech disorders that are due to disturbances in muscular control of the speech mechanism resulting from impairment of any of the basic motor processes involved in the execution of speech.

Duffy (2013, p 4) extended this definition and included the neurological nature of the disorder, defined it as a movement disorder, and a possible categorization by dysarthria type.

> [···] a collective name for a group of neurologic speech disorders that reflect abnormalities in the strength, speed, range, steadiness, tone, or accuracy of movements required for the breathing, phonatory, resonatory, articulatory, or prosodic aspects of speech production. The responsible pathophysiologic disturbances are due to one or more sensorimotor abnormalities, which most often include weakness, spasticity, incoordination, involuntary movements, or excessive, reduced or variable muscle tone.

Using this definition it is possible to distinguish dysarthria from non-motor speech disorders, other types of speech motor disorders, as well as differentiate between types of dysarthria. Historically, seven types of dysarthria can be distinguished, including hypokinetic, ataxic, flaccid,

[1] This distinction is becoming slightly blurred, as recent research suggests the presence of a planning issue in some types of dysarthria, see e.g. Spencer and Rogers (2005), Walsh and Smith (2011).

spastic, unilateral upper motor neuron, hyperkinetic and mixed dysarthria (Darley et al., 1969a, 1969b; Duffy, 2013). Each singular dysarthria type is supposed to be related to a specific lesion location of the neural circuit involved in speech production. Whilst the unilateral upper motor neuron dysarthria type has been added later (Hartman & Abbs, 1992; Duffy, 2000), the original distinction between the dysarthria types as defined by Darley et al. (1969a, 1969b) is accepted until today (Kent et al., 2000; Kent, 2000; Duffy, 2000, 2013; Lansford & Liss, 2014). Hypokinetic dysarthria is amongst the most prevalent singular types of dysarthria[2], and exhibits in general a typical and consistent pattern of speech disorders, enabling the formation and recruitment of clear-cut groups of patients (Duffy, 2000, 2013). Therefore, hypokinetic dysarthria is the preferred group to study speech motor control, and will be the focus of this study.

2.4 Hypokinetic dysarthria

Hypokinetic dysarthria is a motor speech disorder involving a reduction in the mobility of speech movements. It is associated with damage in the basal ganglia control circuit. Hypokinetic dysarthria is usually associated with *Parkinson's disease* (PD). An audit by Duffy (2013) of 8101 people with a primary communication disorder diagnosis of a motor speech disorder (of which the dysarthrias accounted for 93% and apraxia of speech for 7%) who were evaluated in the Mayo Clinic, Rochester, USA between 1993 and 2008 showed that hypokinetic dysarthria accounted for around 9% of all motor speech disorders and occurred at a rate comparable to that of other single dysarthria types. Hypokinetic dysarthria is predominantly associated with degenerative diseases, of which idiopathic PD is the most common. PD affects around 1% - 1.5% of individuals aged 60 years and older, but may already manifest in younger individuals in their 20s and 30s (Pringsheim, Jette, Frolkis, & Steeves, 2014; Sapir, 2014). Approximately 3.6% of patients with Parkinson's disease develop symptoms before the age of 45 (Jankovic, 2008; Kilarski et al., 2012).

[2] After hyperkinetic dysarthria, which can be divided into four subtypes according to the specific involuntary movements that underlie them: chorea, dystonia, tremor, and palatopharyngolaryngeal myoclonus (Duffy, 2000)

The following sections will provide a short outline of the etiology of hypokinetic dysarthria, and the role of neural control circuits therein, followed by an overview of the most common clinical characteristics, and an examination of general speech characteristics.

2.4.1 Etiology

Hypokinetic dysarthria is caused by damage to the basal ganglia control circuit, either by damage to the basal ganglia or by damage to neural connections leading from the basal ganglia to other parts of the central nervous system. The basal ganglia control circuit regulates muscle tone, and aids in learning, selecting and initiating movements for goal-directed activities such as speech and arm motion during walking. Furthermore, the control circuit controls postural and speech adjustments, e.g. while speaking with a pen in the mouth (Utter & Basso, 2008). Damage to the basal ganglia control circuit is associated with a reduction of movements, a failure to initiate movements, or a failure to inhibit involuntary movements. The majority of the cases where damage occurs are related to neurodegenerative diseases, of which PD is the most prominent. A nerve cell loss in the basal ganglia and a resulting dopamine decrease in the striatum are related to the pathological changes in PD. Other causes of damage to the basal ganglia control circuit involve vascular and toxic conditions, trauma and infections (Olanow & Tatton, 1999; Israel & Bergman, 2008; Gale, Amirnovin, Williams, Flaherty, & Eskandar, 2008). As one of the degenerative disease of the basal ganglia like Huntington's disease and Wilson's disease, Parkinson's disease is characterized by the presence of cognitive and psychiatric co-morbidities including dementia and depression (Rosenblatt & Leroi, 2000). A series of environmental and behavioural factors have been identify that may increase the risk of developing Parkinson's disease, including exposure to pesticides, consumption of dairy products, history of melanoma, and traumatic brain injury. Reduced risk factors that might be neuroprotective have been reported in association with smoking, caffeine consumption, higher serum urate concentrations, physical activity, and use of ibuprofen and other common medications (Ascherio & Schwarzschild, 2016).

2.4.2 Clinical characteristics

The clinical characteristics of hypokinetic dysarthria are usually based on symptoms found in PD and parkinsonism. The most prevalent non-speech motor characteristics include rest tremor, rigidity, bradykinesia (slowness of movements), akinesia (difficulties initiating movements), and loss of postural reflexes. Other non-speech motor symptoms include hypomimia (loss of facial expression), dysphagia (swallowing difficulties), respiratory difficulties, and laryngeal impairments (Olanow & Tatton, 1999; Jankovic, 2008). Rest tremor is the most common symptom of PD, are usually unilateral and occur at a frequency of around 4 to 6 Hz. The tremor is apparent in the limbs and head, as well as in the primary articulators and the voice (Perez, Ramig, Smith, & Dromey, 1996; Jankovic, 2005). In addition to rest tremor, a subgroup of patients with PD also displays a more prominent and disabling postural tremor (Jankovic, Schwartz, & Ondo, 1999; Fekete & Jankovic, 2011). Rigidity is often present, which is associated with slowness and resistance of passive movement in all directions (Berardelli, Sabra, & Hallett, 1983; Endo, Okuno, Yokoe, Akazawa, & Sakoda, 2009). Bradykinesia is a common non-speech sign in basal ganglia disorders, and refers to slowness during movements. It includes difficulties with planning, initiating, and executing movements. It often manifests as a general slowness in performing daily activities, slow movements, slow reaction times, and difficulties with fine motor control tasks (Berardelli, Rothwell, Thompson, & Hallett, 2001; Jankovic, 2008; Rodriguez-Oroz et al., 2009). Akinesia appears often in conjunction with bradykinesia. Akinesia, or loss or impairment of the power of initiating voluntary movements, might manifest itself in reduced limb gestures and a festinant gait, characterized by short and rapid steps (Giladi, Treves, et al., 2001; Giladi, McDermott, et al., 2001; Berardelli et al., 2001). The final major non-speech motor symptom is loss of postural reflexes, resulting in postural instability. The loss of postural reflexes, leading to a higher risk of falling, generally manifests itself at the late stages of PD, after the onset of other clinical movement features (Morris, Iansek, Smithson, & Huxham, 2000; Bronte-Stewart, Minn, Rodrigues, Buckley, & Nashner, 2002; Horak, Dimitrova, & Nutt, 2005).

Patients with PD may exhibit a number of secondary non-speech motor symptoms that may not be present in all patients, but can be equally or more challenging to cope with as compared to the primary motor symptoms. Dysphagia occur in around 40% - 80% of speakers with PD, usually preceding the presence of dysarthria. Swallowing might be infrequent or impaired, possibly leading to aspiration, pneumonia, malnutrition, dehydration, and asphyxiation (Fuh et al., 1997; Volonté, Porta, & Comi, 2002; Duffy, 2013; Kalf, de Swart, Bloem, & Munneke, 2012). Patients with hypokinetic dysarthria due to PD may show respiratory problems. Chest and abdominal movements during breathing may be reduced, resulting in unusually rapid respiratory rates, with a reduced amplitude of respiration and a restrictive breathing pattern. (Vercueil, Linard, Wuyam, Pollak, & Benchetrit, 1999; Maria et al., 2003; Mehanna & Jankovic, 2010). The ability to alter the automatic respiration rhythm to initiate speaking is often impaired (Kim, 1968; Murdoch, Chenery, Bowler, & Ingram, 1989; Solomon, McKee, & Garcia-Barry, 2001; Moustapha et al., 2013). Laryngeal impairments include a decreased synergy and activation of the laryngeal muscles, glottal incompetence and fatigue (Kent, Vorperian, Kent, & Duffy, 2003; Midi et al., 2008). Due to the reduced glottal efficiency, patients with PD are forced to use a greater respiratory drive, by generating more rib cage volume (Zwirner & Barnes, 1992; Duffy, 2013).

This overview shows that speakers with hypokinetic dysarthria due to PD might display a broad and overlapping spectrum of motor symptoms underlying speech. The general speech characteristics of hypokinetic dysarthria are discussed in the following section.

2.4.3 General speech characteristics

The most salient clinical characteristics affecting speech in patients with hypokinetic dysarthria include rigidity, a hampered initiation of movements (akinesia), a reduced range and speed (bradykinesia) of movements, and tremor. The resulting speech output is sometimes affected by impairment in several speech components simultaneously. The most prominent elements of speech production impaired by hypokinetic dysarthria are phonation, articulation, and prosody (Duffy, 2000, 2013). Studies that have reported on these speech characteristics are briefly summarized below.

2.4.3.1 Phonation

The phonatory characteristics of the speech in speakers with hypokinetic dysarthria are associated with reduced voice quality and impairments in the overall range and variability of fundamental frequency and intensity. Phonatory disturbances in hypokinetic dysarthria are generally considered to be the most perceptually salient, and the initial symptom of the speech impairment (Zwirner, Murry, & Woodson, 1991; Zwirner & Barnes, 1992; Murdoch, Manning, Theodoros, & Thompson, 1997; Duffy, 2000). A formal assessment of vocal impairment might be difficult to perform because the voice problems in dysarthria might interact with other impairments in respiration, resonance, and articulation (Kent et al., 2003). Considerable attention has been paid to phonation impairments in hypokinetic dysarthria in relation to vocal quality, with either qualitative or quantitative descriptions (Darley et al., 1969a, 1969b; Murdoch et al., 1997; Duffy, 2000; Rusz et al., 2011; Tanaka, Nishio, & Niimi, 2011; Constantinescu et al., 2011). Using perceptual, acoustic, endoscopic and stroboscopic measures, a number of studies have confirmed the presence of a vocal tremor (Perez et al., 1996; Gamboa et al., 1997; Holmes, Oates, Phyland, & Hughes, 2000; Kent et al., 2003; Tanaka et al., 2011), a glottal fry (Zwirner & Barnes, 1992; Kent et al., 2003; Manor, Posen, Amir, Dori, & Giladi, 2005), breathiness (Solomon et al., 2001; Solomon, Makashay, Kessler, & Sullivan, 2004; Bunton, Kent, Duffy, Rosenbek, & Kent, 2007), or harshness (Liss, Spitzer, Caviness, & Adler, 2002; Bunton et al., 2007; Skodda, Visser, & Schlegel, 2010) during phonation in patients with hypokinetic dysarthria.

A speech characteristic secondary to the phonatory deficits found in hypokinetic dysarthria is a change in fundamental frequency at the segmental level (Goberman & Coelho, 2002). When analysing vowels in reading and sustained vowel production tasks, several studies have found higher mean fundamental frequency values (Canter, 1963; Metter & Hanson, 1986; Kent & Kim, 2003; Goberman & Blomgren, 2008), as well as a higher degree of variation in cycle to cycle frequency, or 'jitter' (Logemann, Fisher, Boshes, & Blonsky, 1978; Zwirner & Barnes, 1992; Hertrich & Ackermann, 1995; Gamboa et al., 1997; Jiménez-Jiménez et al., 1997; Kent & Kim, 2003; Bunton, 2006; Goberman & Coelho, 2002; Goberman & Blomgren, 2008). The increased jitter values found in speakers with hypokinetic dysarthria is generally attributed to rigidity of the laryngeal muscles, which results in increased stiffness of the vocal folds (Goberman & Coelho, 2002; Kent & Kim, 2003), and seems to be correlated with severity of dysarthria and clinical disability (Metter & Hanson, 1986; Gamboa et al., 1997; de Swart, Willemse, Maassen, & Horstink, 2003; Goberman & Blomgren, 2008).

Underlying phonatory and respiratory deficits are the cause of a third major speech characteristic in in hypokinetic speech: a reduced vocal intensity. Specific impairments include increased chest wall rigidity, and a reduced control over lung muscles and larynx (Metter & Hanson, 1986; Duffy, 2000, 2013; Sadagopan & Huber, 2007). The resulting speech output with respect to vocalization is that overall vocal intensity is found to be reduced during vowel prolongation, alternative motion rate tasks, reading and conversational speech (Canter, 1963; Illes, Metter, Hanson, & Iritani, 1988; Gamboa et al., 1997; Ramig, Shimon, Cynthia, & Stefanie, 2001; Rosen, Kent, & Duffy, 2005; Schulz, Greer, & Friedman, 2000; Schulz & Grant, 2000; Stathopoulos et al., 2014).

2.4.3.2 Segmental articulation

The second element of speech production affected by hypokinetic dysarthria is articulation. The most prominent articulatory changes include a decrease in precision of consonant and vowel production, significantly impacting on speech intelligibility (De Bodt, Huici, & Van De Heyning, 2002; Sapir, Spielman, Ramig, Story, & Fox, 2007). A number of studies reported the imprecise articulation of fricatives and stop consonants (Canter, 1965; Logemann & Fisher, 1981; Yorkston, Hammen, Beukelman, & Traynor, 1990; Goberman & Coelho, 2002; Whitehill, Ma, & Lee, 2003; McAuliffe, Ward, & Murdoch, 2006a; McAuliffe, Ward, & Murdoch, 2006b). A common observation in imprecise articulation in hypokinetic dysarthria is the slurring of stop consonants (Skodda, Visser, & Schlegel, 2011a), and the production of stop consonants as fricatives (Canter, 1965; Logemann & Fisher, 1981). A reduced amplitude, range, and strength of articulators has been suggested to be the common underlying cause, resulting in inadequate constrictions of fricatives and stops (Logemann & Fisher, 1981; Goberman & Coelho, 2002; McAuliffe et al., 2006b).

A reduced movement range and imprecise articulation may also lead to a distortion in the production of vowels. These distortions usually manifest in a reduced vowel length and changes in the mean, range, and variability of formant frequencies (Bunton & Weismer, 2001; Sapir et al., 2007; Wenke, Cornwell, & Theodoros, 2010; Skodda, Visser, & Schlegel, 2011c). Reductions of first formant (F1) and second formant (F2) transition rates in hypokinetic speech in isolated and repeated syllable production tasks were found by Connor, Ludlow, and Schulz (1989) and Flint, Black, Campbell-Taylor, Gailey, and Levinton (1993), indicating a reduced speed of articulator movement. Weismer, Jeng, Laures, Kent, and Kent (2001) carried out a sentence repetition study with speakers with hypokinetic dysarthria, and found a slight reduction in the vowel space of F1 and F2 in individual target words. Walsh and Smith (2012) measured F2 slopes in diphthongs and found similar space reductions, indicating a reduced range of movements. Zwirner and Barnes (1992) and Beverly et al. (2008) found a reduced steadiness of first and second formant trajectories in the speech of speakers with hypokinetic dysarthria, indicating a reduced vocal tract stability.

Articulatory inadequacy may also manifest in oral diadochokinetic (DDK) tasks. Typically DDK tasks involve the production of syllable repetitions containing consonant-vowel combinations with bilabial, alveolar, and velar places of articulation, such as /pʌpʌpʌ/, /tʌtʌtʌ/, /kʌkʌkʌ/, or /pʌtʌkʌ/ (Fletcher, 1972). The DDK tasks are used to examine the speaker's ability to make rapidly alternating or sequential articulatory movements (Kent, Kent, & Rosenbek, 1987). As a result of a possible trade-off between the amplitude of articulator movement and repetition rate, diadochokinetic tasks executed by speakers with hypokinetic dysarthria might show reduced, faster, accelerating, decelerating, or more variable alternative motion rates (Tjaden & Watling, 2003; Rusz, Hlavnicka, Cmejla, & Ruzicka, 2015). Speakers may display unimpaired DDK rates, but possibly at the expense of amplitude and/or regularity of movements (Gurd, Bessell, Watson, & Coleman, 1998; Ackermann, Hertrich, & Hehr, 1995).

2.4.3.3 Prosody

The third element of speech production affected by hypokinetic dysarthria is prosody. Prosody is the term applied to suprasegmental characteristics beyond individual vowels and consonants, and refers to the variation in pitch, intensity, and rhythm occurring during running speech (Reetz & Jongman, 2009). A number of studies reported that speakers with hypokinetic dysarthria display monopitch, monoloudness, and changes in speech rate and pausal behaviour (Darley et al., 1969a, 1969b; Metter & Hanson, 1986; Schlenck, Bettrich, & Willmes, 1993; Le Dorze, Ouellet, & Ryalls, 1994; Le Dorze, Ryalls, Brassard, Boulanger, & Ratté, 1998; Hammen & Yorkston, 1996).

Monopitch in hypokinetic speech is perceived when the fundamental frequency range is reduced at the phrase level (Canter, 1963; Darley et al., 1969a, 1969b; Flint, Black, Campbell-Taylor, Gailey, & Levinton, 1992; Whitehill et al., 2003). For example, it has been found that speakers with hypokinetic dysarthria have difficulties producing the appropriate fundamental frequency differences when forming question-statement pairs (Le Dorze et al., 1994; Le Dorze et al., 1998; Ma, Whitehill, & So, 2010), and have difficulties making fundamental frequency differences when attempting to differentiate noun compounds and noun phrases (Darkins, Fromkin, & Benson, 1988; Tykalova, Rusz, Cmejla, Ruzickova, & Ruzicka, 2014). Monotony is a factor in the increase in the number of lexical boundary errors made by speakers with hypokinetic dysarthria (Liss, Spitzer, Caviness, Adler, & Edwards, 1998; Liss, Spitzer, Caviness, Adler, & Edwards, 2000). The range and variability of fundamental frequency are found to be decreased during reading (Metter & Hanson, 1986; Flint et al., 1992; Jiménez-Jiménez et al., 1997; Skodda, Grönheit, & Schlegel, 2011; Skodda, Visser, & Schlegel, 2011b) and monologues (Anand & Stepp, 2015), possibly reflecting a prosodic deficit.

A reduction in speech intensity and a decrease in variation of intensity, or monoloudness, has been found to play a role in a reduced prosodic accuracy in speakers with hypokinetic dysarthria (Canter, 1963; Darley et al., 1969a, 1969b; Metter & Hanson, 1986; Dromey, Ramig, & Johnson, 1995; Liss et al., 2002; Whitehill et al., 2003; Lansford, Liss, Caviness, & Utianski, 2011). Compared to unimpaired speakers, speakers with hypokinetic dysarthria have been found to produce relatively smaller intensity changes during sentence reading (Metter & Hanson, 1986; Illes et al., 1988; Liss et al., 2002; Rosen et al., 2005), during the production of sentences containing varying emotional content (Caekebeke, Jennekens-Schinkel, Van der Linden, Buruma, & Roos, 1991), and during question-statement contrasts (Ma et al., 2010). Rosen, Kent, Delaney, and Duffy (2006) analysed the standard deviation of average SPL to measure intensity variability in a sentence repetition task, and found that healthy speakers displayed a higher variability compared to speakers with hypokinetic dysarthria.

Changes in speaking rate and pausal behaviour are the third contributing factor to prosodic disturbances found in hypokinetic dysarthria. While some studies found speech rates in mild hypokinetic speech to be similar to unimpaired speech (Canter, 1963; Metter & Hanson, 1986; Ludlow, Connor, & Bassich, 1987), the majority of studies report atypical rate characteristics, with findings of either slowed or perceived and measured accelerated speech rate (Flint et al., 1992; Volkmann, Hefter, Lange, & Freund, 1992; Le Dorze et al., 1994; Hammen & Yorkston, 1996; Duffy, 2000; Tjaden, 2000; Nishio & Niimi, 2001; Skodda & Schlegel, 2008; Blanchet & Snyder, 2009; Blanchet & Snyder, 2010; Skodda, Grönheit, & Schlegel, 2011).

Compared to healthy speakers, speakers with hypokinetic dysarthria have shown faster speech rates (Flint et al., 1992; Whitehill et al., 2003; Duffy, 2013; Tjaden & Wilding, 2004; Tjaden & Wilding, 2011c) and shorter rushes of speech (Darley et al., 1969a; Critchley, 1981; Lansford et al., 2011). A perfunctory execution of articulatory movement, impairments in the timing of motor movements, and a reduced range of chest, larynx, velum, tongue, jaw and lip movements might give rise to a fast or accelerated speech rate (Flint et al., 1992; Ackermann, Konczak, & Hertrich, 1997; Tjaden, 2000). This is partly motivated by listeners' perceptions: a sentence produced at comparable articulation rates by a speaker with hypokinetic dysarthria and a healthy speaker will often be perceived to be faster for the dysarthric speaker (Tjaden, 2008; Duffy, 2013). This is an important characteristic, as hypokinetic dysarthria is the only dysarthria type in which a major feature may be fast or accelerating speech rates (Kent & Rosenbek, 1982; Tjaden, 2000; Duffy, 2000).

Underlining the heterogeneous nature of speech rate characteristics found in hypokinetic dysarthria, a number of studies have also reported slower than normal speaking rates (Caligiuri, 1989; Yorkston et al., 1990; Volkmann et al., 1992; Kent & Kim, 2003; Kim, Kent, & Weismer, 2011; Lansford et al., 2011) and articulation rates (Volkmann et al., 1992; Liss et al., 2009; Liss, LeGendre, & Lotto, 2010; Kim et al., 2011). The underlying causes of slower speech rate are generally considered to be an overall slowness of movement, tremors and difficulties with initiating movements (Jankovic, 2005; Duffy, 2013; Jankovic, 2008; Skodda, Grönheit, & Schlegel, 2011).

The inconsistent findings with respect to speech rate ties in with the deviant pausal behaviour found in speakers with hypokinetic dysarthria. Common findings on pausal characteristics in hypokinetic dysarthria include the production of shorter phrases of uninterrupted speech Illes et al. (1988), Hammen and Yorkston (1996), Rosen et al. (2006), a higher number of silent hesitations per minute (Illes et al., 1988; Hammen, Yorkston, & Minifie, 1994; Rosen et al., 2010), a higher number of abnormally long pauses (Illes et al., 1988; Solomon et al., 2001; Tjaden & Wilding, 2011c), and a lower articulation time versus pause time ratio (Hammen & Yorkston, 1996; Nishio & Niimi, 2001; Harel, Cannizzaro, Cohen, Reilly, & Snyder, 2004; Lowit, Brendel, Dobinson, & Howell, 2006; Skodda & Schlegel, 2008), giving rise to deviant perceptual rhythm characteristics (Skodda & Schlegel, 2008; Liss et al., 2009; Skodda, Flasskamp, & Schlegel, 2010). The prevalence and impact of these characteristics seem to be largely individualized, and might not be consistently present in every impaired speaker with hypokinetic dysarthria (Nishio & Niimi, 2001; Skodda & Schlegel, 2008).

In summary, the clinical characteristics in hypokinetic dysarthria associated with basal ganglia control circuit pathology are rigidity, a reduced range of movement and slowness of movement, and the presence of tremor. The resulting deviant speech dimensions are mainly reported as reduced voice quality, imprecise articulation of consonants and vowels, monopitch and monoloudness at sentence level, a speaker-dependent variable rate of speech, and deviant pausing behaviour. Apart from rate, the literature is relatively consistent in describing these symptoms once differences in speaker severity and task presentation are taken into account. The most variable symptom across speakers appears to be speaking rate, which has been noted as either normal, slower, or faster, compared to healthy speakers.

Parkinson's disease is usually diagnosed in adults of older age, and it is therefore important to understand what changes can occur in speech production in ageing. In the following section, research investigating age-related changes in speech production will be reviewed.

2.5 Age-related changes in speech

It is well documented that ageing brings about physiological changes across the lifespan (Smith, Wasowicz, & Preston, 1987; Sataloff, Caputo Rosen, Hawkshaw, & Spiegel, 1997; Ramig et al., 2000). Physiological studies have shown changes to jaw and tongue muscle anatomy (Weismer & Liss, 1991), an increase of vocal cavity length and volume (Xue & Hao, 2003), a reduction in pulmonary function (Ptacek, Sander, Maloney, & Jackson, 1966), connective tissue changes in the larynx (Kahane, 1987), increased stiffness of the vocal folds (Honjo & Isshiki, 1980; Kahane, 1987), a reduction in vocal fold closure (Ferrand, 2002; Linville, 2002), and a decrease in general oral sensory function (Ikebe et al., 2007; Kawagishi, Kou, Yoshino, Tanaka, & Masumi, 2009). Furthermore, a decrease in muscle activity (Cecilio et al., 2010) and a decrease in tongue strength and movement regularity have been found with increasing age (Crow & Ship, 1996; Butler et al., 2011; VanRavenhorst-Bell, Mefferd, Coufal, Scudder, & Patterson, 2017). These physiological changes have been linked to changes in the production of speech. The following sections review the most important age-related changes in speech production, focusing on accuracy of articulation, speech rate, intensity, fundamental frequency, and formant frequencies. Special attention will be paid to the group characteristics used in the reviewed studies.

2.5.1 Voice and articulation accuracy

Ageing has been associated with changes in voice characteristics and articulatory accuracy.

Acoustic studies have shown that the ageing voice has been associated with increased shimmer (the average cycle-to-cycle variation of intensity during phonation of a sustained vowel). For example, Schaeffer, Knudsen, and Small (2015) compared shimmer values in relatively large groups of young and older speakers. A sustained phonation of the vowel /a/ was produced by 50 participants (25 males, 25 females) between the ages of 60 and 80 (mean age 69.5 years) and 50 participants (26 males, 24 females) between the ages of 20 and 30 (mean age 23.2 years). All participants were selected as non-smokers and had perceptually normal voices, i.e., without strain, trembling, or breathiness. The results showed significantly higher average shimmer values in the older adults group, compared to the young adults. Similar results were reported by Ramig and Ringel (1983) who analysed sustained vowel phonation samples of 48 male subjects divided in three chronological age groupings (25-35, 45-55, and 65-75 years). Individuals with a chronic history of smoking or alcohol use, respiratory problems, speech or hearing pathologies, or professional voice training were excluded from participating. Whilst no differences in shimmer were found between the speakers in the middle-aged group and the other two groups, the group of older adults showed higher shimmer values compared to the young adults. This study also reported increased jitter values (the average cycle-to-cycle variation of frequency during phonation of a sustained vowel) in the older adult group compared to the other two groups (Ramig & Ringel, 1983). Higher jitter values in older speakers were also reported by Benjamin (1981), who compared jitter measurements of a sustained vowel produced by 20 young adults (10 males and 10 females, age range 21 - 32, mean age 29 years) with 20 older adults (10 males and 10 females, age range 68 - 82, mean age 74 years), all without any known pathological voice conditions. Xue and Deliyski (2001) analysed sustained vowel phonations of 21 elderly male speakers (mean age 75.4 years) and 23 elderly female speakers (mean age 74.8) years, all non-smokers and without pathological problems. They found phonatory fundamental frequency range and jitter values to be higher in both older speaker groups, when compared with published norms for young adults. Similar age-related differences were found by Gorham-Rowan and Laures-Gore (2006), who analysed jitter of sustained vowel productions in relative large speaker groups, including 28 young women (mean age 24.7 years), 28 young men (mean age 25.4 years), 28 elderly women (mean age 70.7 years), and 28 elderly men (mean age 69.6 years), and found both older speaker groups to have higher jitter values compared to their younger counterparts. Similar to the methodologies employed in the studies above, the speakers of this study did not have any known pathological conditions; the findings of elevated jitter and shimmer values appear to be a consequence of ageing. Taken together, these studies relatively consistently report increased jitter and shimmer values during vowel prolongations in older adults.

A few studies have found a decrease in perceived accuracy ratings in the speech of older adults compared to younger adults, but speech samples under investigation have mostly been limited to diadochokinetic tasks or individual phonemes, and to relatively small group sizes. For example, Parnell and Amerman (1987) carried out a perceptual judgement experiment of oral diadochokinetic performances with speakers of different age groups, consisting of 10 healthy adult male speakers (age range 21 - 28, mean age 24.5 years), and 10 healthy older male speakers (age range 67 - 81, mean age 73.0 years). Listeners were 20 certified speech-language pathologists, who scored the speech of older adults systematically worse on a series of perceptual dimensions including consonant precision, vowel precision, and voice quality, compared to the speech of younger adults. Similar results have been found by Shuey (1989), who investigated the speech of 5 males and 5 females between 21 and 27 years, and 5 males and 5 females between 72 and 78 years. Listeners were a group of 15 young adult females, who found vowels and final consonants in CVC productions to be perceived less accurately in the older speakers' productions. Whilst measures of perceived accuracy seem to differ across age groups, measures of intelligibility do not. Thus far, just one study has obtained direct measures of intelligibility across age groups. McAuliffe, Wilding, Rickard, and O'Beirne (2012) analysed intelligibility of a series of experimental phrases, all six syllables in length, produced by young (two males and two females, mean age 27 years, SD = 2.1 years) and four of older (two males and two females, mean age 80 years, SD = 5.8 years) speakers. Listeners were nineteen individuals with age-related hearing loss (10 males and nine females, age range 60 - 87, mean age 71.4 years). Intelligibility was measured as the percentage correctly recalled words after stimulus presentation. Although the speaker groups and the listening group had a relatively small sample size, the results showed that intelligibility in this production task was not affected by age: the participants obtained similar speech recognition scores for both the young and older speaker groups, even in adverse listening circumstances.

A small number of instrumental studies on articulatory accuracy across age groups have been carried out, and they reported mixed results. Benjamin (1982) used spectrographic measurements to investigate vowel lengths and silent intervals of stop consonants in sentences containing stop consonants (e.g., ‘He has a blue ball’) produced by relatively small speaker groups differing in age. Speakers were 10 males and 10 females aged 21 to 31 years (mean age 29.4 years), and 10 males and 10 females aged 68 to 82 years (mean age of 74.0 years). She showed that the older adults produce significantly longer vowels and longer silent intervals of stop consonants than young adult speakers, which was interpreted as a reduced control over vocal track closure (Benjamin, 1982). Different results were found by Bilodeau-Mercure and Tremblay (2016), who investigated articulation accuracy of diadochokinetic tasks by means of transcription in 15 young (6 males and 9 females, age range 18 - 39, mean age 27.7 years) versus 15 older adults (8 males and 7 females, age range 66 - 85, mean age 73.9 years). The participants engaged in a series of diadochokinetic tasks with different levels of sequential and articulatory complexity. Accuracy transcriptions of the sequences were used to obtain measures of articulatory accuracy. Whilst most complexity conditions did not yield age-related differences, a significant age-related decline in accuracy was found during the production of nasal vowels embedded in the repetition tasks only. Similarly, Duchin and Mysak (1987) marked the occurrence of disfluencies, including interjections, revisions, repetitions, and arrhythmic phonations during oral reading, picture description, and conversational speech in 75 male speakers aged 21 to 91 years divided in five different age groups, and found no differences across groups, showing that accuracy of speech production did not significantly change in ageing adults. In addition to perceived accuracy, these instrumental studies investigating articulatory accuracy indicate that age-related differences are largely limited to individual vowels and consonants, with most speaking tasks failing to report age-related differences.

The above overview shows that ageing might come with a measurable decrease in voice quality during experimental tasks, even in non-pathological voices. However, acoustic differences were observed only during a specific voice task which required high effort, and these differences were most evident for subtle acoustic characteristics only. A few studies have shown an age-related decrease in perceived articulatory accuracy in a limited set of speech stimuli. There is some evidence of a decrease in articulatory accuracy in older adults when measured instrumentally, although findings were limited to specific vowels and consonants. Overall accuracy during conversational speech does not seem to significantly worsen with age. With respect to overall intelligibility, no studies have reported an age-related decrease in intelligibility during functional speech tasks, indicating that speech production and communication capacities largely remain preserved into older age.

2.5.2 Rate of speech

Studies investigating speech rate as a factor of age generally report a reduced rate of speech and speech movements in elderly speakers. Perceptual studies have shown that read and spontaneous speech produced by older adults appear to be slower. An early study by Ryan and Burk (1974) investigated perceived age estimations of a group of 80 male speakers without speech or hearing problems, and relatively evenly distributed within an age range of 40 to 80 years. A reading passage produced by the speakers was presented to a group of 20 young adult female listeners of unspecified age, who were instructed to make a direct estimation of the speaker's age. The listeners' age estimations were correlated with a series of perceptual correlates scored by a small group of speech pathologists, and the results showed that a slow rate of articulation was a strong predictor of perceived age. However, other variables including air loss, laryngeal tension, voice tremor, and imprecise consonants also contributed as predictors, making it difficult to separate these from the contribution of perceived articulation rate. In addition, no formal acoustic measures of articulation rate across speakers were reported, making it unclear whether the ageing speakers actually slowed down during passage reading. Another perceptual study was carried out by Harnsberger, Shrivastav, Brown, Rothman, and Hollien (2008), who made reading passage recordings produced by 14 young male speakers (age range of 21 - 29, mean age 24 years) and 16 older male speakers (age range 74 - 88, mean age 82 years), and manipulated the speaking rate of the recordings. The speaking rate of the productions of older speakers was increased by 20% and those of the younger speakers were decreased by 20%. Subsequent perceptual judgements were performed by 65 normal-hearing young adult listeners of unspecified age, who were instructed to directly estimate speaker age in years on a 20- to 100-year scale. While for the young male voices no significant shift in perceived age were found, for the older male voices perceived age was found to be lower with an altered speaking rate, indicating that, similar to the results by Ryan and Burk (1974), rate of speech was a perceptually relevant cue in estimating the age of older speakers.

In addition to perceptual analyses, several studies using acoustic observations have found a decrease in speaking rate and articulation rate in older speakers during spontaneous speech, reading, and reciting, when compared to younger speakers. In the same study as cited above, Harnsberger et al. (2008) found that articulation rate of a reading passage was significantly slower in the group of older male adults, compared to their younger counterparts. Smith et al. (1987) found similar results with respect to articulation rate of sentence and word repetitions when comparing 10 healthy young adults (age range 24 - 27, mean age 25 years) and 10 healthy elderly adults without hearing problems (age range 66 - 75, mean age 70 years). Whilst both speaker groups were rather small, it was found that the older adults produced word and sentence durations which were on average 20% to 25% longer than those of the young adults. Brown, Morris, and Michel (1989) found similar results when comparing reading durations during the production of a reading passage by relatively large speaker groups differing in age (25 women aged 20 - 32 years (mean age 27.5 years) and 25 women aged 75 - 90 years (mean age 79.4 years) and without respiratory or neurological diseases). Further evidence of an age-related decrease in speech rate was found by Shipp, Qi, Huntley, and Hollien (1992), who made acoustic measures of one-sentence recordings in three groups of 10 healthy male talkers whose perceived ages were 27 - 35, 53 - 57, and 75 - 85 years. Articulation rate measurements for the three groups revealed that rate slowed with advancing age, although significance was obtained only for the difference in rate between the younger group compared to the middle-aged and older speaker groups; differences between the middle-aged and older speakers were absent. Apart from read sentences and passages, one study systematically investigated speaking rate in conversational speech across age groups. Duchin and Mysak (1987) investigated speaking rate across 75 healthy male speakers between the ages of 21 and 91 years, divided into five age groups. Similar to the findings of the studies above, speaking rates during oral reading, conversation, and picture description were found to decrease from young adult speakers to middle-aged speakers to older males.

Overall, despite small participant groups, the previously discussed studies are consistent in demonstrating that speaking rate and articulation rate decrease with age, both at word level and sentence level, as well as across various speech elicitation tasks. A decreased rate of speech can therefore be assumed to be a generic feature of speech production in ageing, with physiological factors such as visual acuity, processing time and general neuromuscular slowing often cited as the explanation.

2.5.3 Intensity

Both perceptual and acoustic studies have reported age-related changes in average intensity and intensity control during the production of speech.

Perceptual studies of loudness across the age span are sparse. As part of a study discussed above, Parnell and Amerman (1987) carried out a perceptual judgement experiment of oral diadochokinetic performances with a small number speakers of different age groups, and found that the loudness levels and loudness control (assessed as perceived variation across diadochokinetic tasks) of older adults was scored systematically different from young speakers, indicating that listeners were able to distinguish loudness characteristics of speakers of different ages during production of the diadochokinetic tasks.

Studies using acoustic measures of intensity have also reported age-related differences. Morris and Brown (1994b) analysed the speech of 25 women aged 20 - 35 years (mean age 27.5 years) and 25 women aged 75 - 90 years (mean age 79.4 years) in a reading passage and a sustained vowel task at minimum, habitual, and maximum intensity levels. Measurements of intensity showed that the two groups did not show significant differences in intensity for the reading passage or the vowels produced at habitual level, but the older women exhibited significantly higher minimum and significantly lower maximum intensity during sustained vowel production than the younger women, indicating a reduced range of loudness during these tasks. Baker, Ramig, Sapir, Luschei, and Smith (2001) investigated intensity levels in four young adults aged 26 - 28 years and five older adults aged 69 - 79 years. Speakers were asked to produce a series of syllables at soft, comfortable, and loud levels of phonation. Whilst having employed relative small speaker groups, the older speakers showed lower intensity levels compared to young speakers across the three loudness conditions. Relative intensity differences between conditions were similar across groups. The authors interpreted these findings as evidence that in older speakers, the laryngeal mechanism may be more affected than the respiratory system, possibly affecting their vocal loudness levels. In contrast, Huber (2008) did not find overall significant group differences in intensity when evaluating the speech of 28 young adults (15 women of 20 - 33 years; 13 men of 20 - 25 years) and 23 older adults (14 women of 66 - 76 years; 9 men of 66 - 82 years) during a monologue task in habitual and loud speaking conditions. Larger and clearer age-related trends were observed for longer utterances and when participants were speaking loudly, suggesting that older adults might be adversely affected when the speech system is being taxed. In a more recent study, Mazzetto de Menezes, Master, Guzman, Bortnem, and Ramos (2014) found no group differences when asking 30 young (aged 20 - 35, mean age 26.8 years) and 30 elderly (aged 60 - 82, mean age 69.6 years) female Portuguese speakers to produce a sustained vowel at habitual and high intensity. Whilst both speaker groups were able to significantly increase intensity from habitual to loud, differences between age groups were absent in both speaking conditions.

The above studies show that there is limited evidence of age-related changes in speaking intensity and intensity control. The reported results were found to be inconsistent, and largely task dependent: differences found between young and older speakers were mostly limited to intensity of vowel prolongation tasks and individual words. Whilst respiratory kinematic measurements and electromyographic studies have shown lower muscle activity of vocal folds, a reduced chest wall compliance, a reduced pulmonary elastic recoil, and sometimes incomplete laryngeal closure in older speakers (Baker, Ramig, Luschei, & Smith, 1998; Baker et al., 2001; Huber, 2008), these functional changes seem to have little influence on speech intensity.

2.5.4 Fundamental frequency

Fundamental frequency characteristics are usually studied in sustained vowel phonations or reading tasks. Vowel phonation tasks are often used to assess jitter and shimmer, which are probably the most prominently assessed voice characteristics. Relevant studies investigating age differences of jitter and shimmer have been discussed in section 2.5.1. Age-related changes in fundamental frequency during longer stretches of speech have found to be gender specific. Generally, mean fundamental frequency values have been found to increase slightly with age in male speakers (Higgins & Saxman, 1991; Ferrand, 2002; Stathopoulos et al., 2014), whereas mean fundamental frequency values in older females have been found to remain constant or to decrease (Brown et al., 1989; Russell, Penny, & Pemberton, 1995; Ferrand, 2002; Awan, 2006; Stathopoulos et al., 2014). These findings are reported relatively consistently across studies. Findings of age-related differences in variation of fundamental frequency across speech samples, on the other hand, are less coherent. Relevant studies are discussed below.

A few studies have investigated variation in fundamental frequency values across longer stretches of speech. With respect to studies involving reading tasks, Morris and Brown (1994a) analysed fundamental frequency characteristics of twenty-five women aged 20-35 years (mean age 27.5 years) and 25 women aged 75-90 years (mean age 79.4 years) in a reading passage, and found that the standard deviation of mean fundamental frequency was higher in the group of older females, when compared to the younger females. Conflicting results were reported by Goy, Fernandes, Pichora-Fuller, and van Lieshout (2013), who compared the mean and standard deviation of fundamental frequency of a reading passage in 55 young male speakers (age range 18 - 28, mean age 19.4 years) and 51 older male speakers (age range 65 - 86, mean age 73.3 years), as well as 104 young female speakers (age range 18 - 27, mean age 18.9 years) and 82 older female speakers (age range 63 - 82, mean age 71.1 years). Here, no differences in fundamental frequency means and standard deviations were found when comparing the two male speaker groups differing in age. The female speakers did show age-related differences, in which both the mean and standard deviation of fundamental frequency were significantly higher in the group of young speakers compared to the older speakers, directly contrasting the results reported by Morris and Brown (1994a). Finally, Lortie, Thibeault, Guitton, and Tremblay (2015) investigated fundamental frequency means and standard deviations in speech fragments obtained from narrated story tales in 80 adult male and female speakers (aged 20 - 75, mean age 54.6 years) divided into three age groups, and reported no significant differences between the mean fundamental frequency of the three age groups for either men or women. In addition, the standard deviations of fundamental frequency in connected speech were comparable across age groups of both genders. Taken together, these results were largely in accordance with the outcomes reported by Goy et al. (2013).

It can be concluded that the studies discussed above have reported inconsistent findings with respect to fundamental frequency characteristics in connected speech. Whilst underlying age-related changes in the speech production mechanism, including greater stiffness of respiratory and laryngeal structures, and muscle atrophy have been brought forward to explain differences in fundamental frequency characteristics across age groups (Morris & Brown, 1994a; Lortie et al., 2015), it might be that these changes are not large enough to have a functional impact on the physiological characteristics of the vocal folds and control of the larynx musculature.

2.5.5 Formant frequencies

Ageing has been associated with a small decrease in mean vowel formant frequencies, possibly as a result of the lowering of the vocal folds with increasing age, resulting in a longer vocal cavity (Linville & Fisher, 1985; Linville & Rens, 2001; Xue & Hao, 2003; Harnsberger et al., 2008).

Only a few studies have reported on formant frequency variations as a factor of age. Das, Mandal, Mitra, and Basu (2013) calculated the mean and standard deviation for the first three formants in different voiced Bengali vowels in 60 younger (age range 20 - 40) and 60 older (age range 60 - 80) adult speakers. Overall trends of differences in vowel formant variability between young and older speakers could not be identified, and a comparison of vowel formant variability values indicated that age-related changes were strongly dependent on vowel type and formant, e.g., F1 and F2 variability was higher in vowels /a, e, i, o, u/ for the young speakers and higher in /ɑ/ for the older speakers, whilst F3 variability was higher in vowels /a, u/ for the young speakers and higher in vowels /ɑ, e, i, o/ for the older speakers. Hawkins and Midgley (2005) assessed mean first and second formant frequencies of monophthongal vowels extracted from monosyllabic words in 20 speakers divided over age groups of 20 - 25 year, 35 - 40 years, 50 - 55 years, and 65 - 73 years. Whilst group sizes were relatively small, once again, the results across age groups were found to be largely vowel dependent, with the most prominent findings that with increasing age, the first formant frequency tended to decrease in /ɛ/ and /æ/, and that second formant frequency decreased in /uː/. Torre Ill and Barlow (2009) compared average first, second, and third formant frequency values in six English vowels extracted from a carrier phrase, produced by 27 young speakers aged 20 - 35 (mean age 25.5 years) and 59 older speakers aged 60 - 89 (mean age 75.2 years). Age-related trends of average vowel frequencies were found to be largely vowel type dependent: for the vowels /ɪ ɛ æ ʌ/, first formant frequency decreased with age in both women and men, but this decrease was more pronounced in older women, indicating an additional influence of gender. Both second formant and third formant frequencies also showed a decreasing trend with age, fitting with the previous assumption of lower vocal folds in ageing adults. Furthermore, the older adults had on the whole larger standard deviations for the frequency measures compared to the young adults, although only as a trend. As changes in vowel frequencies are associated with altering the dimensions of the vocal tract by varying the articulatory tongue constrictions (Rastatter, McGuire, Kalinowski, & Stuart, 1997), the presence of increased vowel formant variability with increasing age might be associated with decreased tongue movement control, although this would contradict the findings by Bennett, van Lieshout, and Steele (2007), who found lower kinematic variability of tongue movements in older adults, compared to young adults during the production of two- and three-syllabic words.

Overall, these limited number of studies on formant frequencies indicate that measures are often carried out with single vowels, sometimes excised from a carrier phrase prior to formant measurements. Mean formant frequencies tend to decrease with age, but are found to be largely vowel dependent. Variability in formant frequencies tend to increase with age, but the results are not consistent across studies and often reported as trends.

This section gave an overview of research studies investigating general speech characteristics in ageing speakers using physiological, acoustical, kinematic and perceptual measures. Whilst everyday speech does not seem to be affected in ageing speakers, structured speech tasks employed in perceptual and acoustic studies have shown that ageing might come with changes in speech production, including a decrease in articulatory accuracy and a decrease in speech rate. Furthermore, studies have reported age-related changes in vocal intensity, fundamental frequency and formant frequencies during the production of selected speech tasks, however, the results of comparing different age groups have often found to be conflicting across studies. There are a number of possible reasons for this, including small group sizes, differences in speech materials used and measurement methodologies, or because no meaningful and robust differences exist between age groups.

The studies reviewed in the sections above have used an array of experimental paradigms to characterise impaired elements of speech production in speakers with hypokinetic dysarthria, and to assess age-related changes in speech production. Studies have reported on perceptual and acoustic measurements of the average and range of speech parameters including duration, intensity, fundamental frequency and formants applied to individual vowels and consonants, as well as words and phrases. One thing these studies have in common is that the measurements have been carried out across singular speech materials, e.g., the measurement of the average and deviation sound pressure level across a reading passage, or a formant frequency measurement across individual vowels. An additional way of investigating speech production differences between hypokinetic dysarthria and control speakers, or between young and older adults, is to look at variability of speech production across repeated utterances. The following section will focus on the assessment of speech production and speech motor control by means of acoustic measures of variability across different speech parameters and speaking conditions, and review the literature on speakers with motor speech disorders as well as the healthy ageing population.

2.6 Measuring variability in speech

The speech signal lends itself to different measures of variability. One important issue to consider when interpreting variability analyses is the type of data and scope of comparison. That is, if one looks across a speech sequence, then variability in the speech signal is desirable and should be high, otherwise sounds would be difficult to distinguish from each other, with little information provided from suprasegmental aspects. From this point of interest, for example, variability of intensity and fundamental frequency have commonly been investigated across longer phrases and sentences to assess monoloudness and monopitch, typically by extracting the intensity contour or fundamental frequency contour across a single phrase, and calculating the standard deviation of the mean values of the parameter under investigation within that phrase (Metter & Hanson, 1986; Gamboa et al., 1997; Bunton & Kent, 2001; Tjaden & Wilding, 2011a; Bowen, Hands, Pradhan, & Stepp, 2013; Ma, Schneider, Hoffmann, & Storch, 2015).

On the other hand, when the stability of speech production is the focus of investigation, comparisons are drawn between repeated productions of the same element. Repeated productions of phonemes, syllables, words or phrases show small, measurable acoustic variations, which might not be audible to the human ear (Smith et al., 1995; Smith, Johnson, McGillem, & Goffman, 2000; Smith, 2006; Lortie et al., 2015). These variations are induced by differences in the articulatory configuration of the vocal tract, in the coordination between different speech articulators, or in the coordination of the subglottal or laryngeal system. In this instance, a low level of variability between the repetitions is desirable, as this is evidence of a high level of control over speech motor movements (Gracco & Abbs, 1986; Smith et al., 1995). In the presence of higher demands on the speaker, or an underdeveloped, impaired or aged speech mechanism, the level of variability across repeated utterances usually increases, as evidenced by research into second language acquisition (Barcroft & Sommers, 2014), speech production in cross-language contexts (Strange et al., 2007), phonological development (Kehoe, 2002), ageing (Weismer & Liss, 1991), as well as motor speech disorders (McHenry, 2003).

Acoustical and kinematic studies on speech variability have traditionally focused on the analysis of the phoneme and syllable by assuming that a certain set of discrete speech units are the components of speech production. It is theorized that the production of a single word involves the selection and programming of discrete units: the lexical concept and lemma, morphemes, phonological words and phonetic gestures (Levelt, Roelofs, & Meyer, 1999). The production of discrete speech units would then involve unique, discretely produced speech movements with a large stability across different speaking contexts. However, it is difficult to find invariant, stable patterns in single speech movements, like oral opening and closure gestures. In his seminal work on the sequencing of speech sounds, MacNeilage (1970) argues against the notion of invariant motor commands, based on the observation that particular muscle contractions or gestures do not correspond with a discrete linguistic category. The acoustic correlates of such linguistic category, be it a phoneme, syllable, or vocal tract configuration, exhibit large variability due to (amongst others) phonological and phonetic variation, variations in sentence stress, word stress and speaking rate (MacNeilage, 1970; Fowler, 1980; Munhall, Ostry, & Parush, 1985; McClean, Kroll, & Loftus, 1990; Adams, Weismer, & Kent, 1993). Nonetheless, it is possible to produce approximately the same sound with different combinations of vocal tract configurations. This 'motor equivalence' refers to the observation that, across multiple trials, the same acoustic goal is reached in more than one way by means of a trading and compensating relationship between multiple movement actions. This may reflect a motor control strategy to stabilize and reach perceptually acceptable acoustic goals instead of focusing on stabilising individual single speech movements (Perkell et al., 1997; Perkell, 2012).

The difficulties encountered in aforementioned studies in describing stable patterns in single speech movements led Smith et al. (1995) to start a search for stable movement patterns across a longer temporal interval, theorizing that although the patterning of single movements is variable across changes in rate or stress, some aspects of the global patterning of multiple movement sequences may be preserved. To this end, Smith et al. (1995) started looking at the stability and patterning across longer temporal intervals, by expressing this stability as an index of variability in both spatial and temporal directions, called the spatiotemporal index (STI). Subsequently, derivative variability indices were developed by means of functional data analysis (FDA), in which spatial variability and temporal variability of speech movements could be analysed separately, and was first adapted by Ramsay, Munhall, Gracco, and Ostry (1996). The STI and FDA will be reviewed in more detail in the following sections, providing a brief overview of how they are calculated, followed by a review of studies that applied these to measure speech motor control across a variety of speaker populations and speaking conditions. A fuller, more technical explanation of how these measures are implemented and calculated is provided in the methodology chapter (Chapter 3, section 3.6.3.7 (STI), section 3.6.3.8 (temporal variability), and section 3.6.3.9 (spatial variability).

2.6.1 The spatiotemporal index

As mentioned in the previous section, the problem of motor equivalence (the mapping from many-to-one) led Smith et al. (1995) to develop a tool that characterizes the patterning and stability of speech movements over a longer fragment of speech. The calculation of variability by means of the STI assumes that a series of records fit onto a target template. In the area of speech, this template represents the target sequence of speech movements, and in this particular study lower lip movements. The STI quantifies an index of stability by calculating and summing the standard deviations of each of the movement tracks at 2% intervals along the normalized time axis. The first computational step is spatial or amplitude normalization. In this step, the amplitudes of each record is translated and rescaled to obtain a mean of zero and a standard deviation of one, effectively recalculating the records into z-scores. The second step is temporal, or time normalization. This involves the stretching or squashing of the duration of each record to obtain a common length using a linear scale factor. The target movement template is then estimated as the mean displacement amplitude value across records in time. The STI is calculated as the sum of standard deviations in amplitude across records, calculated at regular intervals (usually 2% intervals) along the normalized time axis (Smith et al., 1995; Smith et al., 2000; Smith & Zelaznik, 2004).

In the study by Smith et al. (1995) it was hypothesized that while the patterning of single speech movements varies with rate or stress, the patterning of longer movement sequences might be preserved. In order to study speech movement sequences across longer stretches of speech as a factor of rate, repeated kinematic measurements of the same utterance were obtained at different speech rates. A group of seven young adult healthy speakers was asked to produce the phrase ‘Buy Bobby a puppy’ twenty times at normal rate, fast rate, and slow rate. During articulation, movements of the lower lip were recorded with a strain gauge system. Of the twenty repetitions, eventually fifteen tracks of lower lip movement data were used to calculate the spatiotemporal index (STI) as a measure of speech motor stability. Smith et al. (1995) found that the summed standard deviations of the fifteen lower lip movement tracks for each speaker and each rate condition were very low, resulting in low levels of spatiotemporal variability. This indicated that the lower lip movement tracks converged to a single template. With respect to the actual results, significant higher STI levels were found in the slow rate condition, compared to the normal rate and fast rate conditions. It was suggested that the reason of the presence of higher variability during slow speech was caused by the fact that, when speaking at low rates, speakers move into a less stable and less practised mode of speech motor control, in which a feedback control strategy is used. When comparing the three rate conditions by means of a pattern recognition procedure, it was found that the procedure was able to distinguish the three conditions, indicating that each of the conditions corresponded to an unique movement pattern. Speech rate is therefore hypothesized as being a global parameter, influencing all elements in a motor command sequence (Smith et al., 1995; Smith et al., 2000). The STI was developed as a tool to characterize the patterning of longer movement sequences as a function of speech rate, in an attempt to find invariant speech movement sequences over a longer stretch of speech. The study by Smith et al. (1995) also showed that the computation of the STI of kinematic parameters can provide a useful index to characterize the stability of repeated speech movements under different speaking conditions. This opens up ways to use the STI as a tool to investigate and impaired speech production. This quantification of repeated speech movement patterns may potentially assist in characterization, diagnosis, and the monitoring of progression of speech disorders.

2.6.2 Functional data analysis

A second prominent technique to measure variability is functional data analysis (FDA). FDA uses some of the principles of the spatiotemporal index. The analysis of functional data assumes that the data can be expressed as functions, usually in the shape of smooth curves (Ramsay, 1982; Ramsay et al., 1996; Ramsay & Li, 1998; Ramsay & Silverman, 2006). FDA of the patterning or trajectories through a defined time span has been applied to a range of disciplines and research fields, varying from economics (Ramsay & Ramsey, 2002) and genetic research (Leng & Müller, 2006) to handwriting analysis (Ramsay, 2000).

While there are different approaches towards the methodology of FDA in speech research, assessing variability over time usually involves the following steps. Prior to analysing a spatial displacement data set, a series of smoothing and interpolation steps are applied, similar to steps undertaken during the calculation of the STI. The second step is spatial normalization, also similar to procedures used in the STI calculations, where all records are aligned in the spatial direction. The third step is temporal normalization, where each record is stretched or squeezed to obtain a common length. Unlike the calculations of the STI where records are linearly scaled, the records are nonlinearly scaled in time when applying FDA. The amount of adjustment required between the start point and end point to align all records will vary from record to record, until all records are normalized onto one common template. The nonlinear nature of temporal normalization enables the possibility to extract information about amplitude variability separate from timing variability. Because of this separation, potentially more information on the behaviour of speech movements can be retrieved. For example, by calculating temporal variability, the presumed nonlinear changes in the duration of vowels and consonants during alterations in speech rate can be studied. This has previously been attempted by Gentner (1987), Gracco and Abbs (1986), and Gracco (1988) using traditional methods of variability analysis, in these cases proportional timing analysis and the estimation of the coefficient of variation in the timing of speech events, but this approach may be adapted to FDA as well.

A series of speech studies have used FDA to assess speech motor variability in adult speakers, but compared to studies employing the STI, the number of studies that have used FDA is considerably smaller. In one of the first studies dedicated to the analysis of speech motor movements, FDA was used to assess lip motion variability during speech (Ramsay et al., 1996). An optoelectronic tracking system recorded eight lip positions in three dimensional space of a native English speaker during the repetition of CVC nonsense syllables. The FDA approach showed that potentially complex motions of the three coordinates and eight markers could be reduced to a single coordinate indicating the position along these trajectories, suggesting that during speech, groups of articulators act as coordinative structures with less degrees of freedom than the summed individual group parts (Ramsay et al., 1996). A notable subsequent study involving FDA has been carried out by Lucero, Munhall, Gracco, and Ramsay (1997). In this study, a native speaker of English produced the sentence “Buy Bobby a poppy” 20 times at a slow rate. Lower lip displacement, velocity and acceleration data was recorded using an optoelectronic tracking system. The average kinematic signals were linearly normalized averaged, similar to the approach used in STI analysis. In addition, the data were nonlinearly normalized averaged, as characteristic for FDA analysis. A comparison between the two normalizing methods revealed that nonlinearly normalized averaging preserves the shape of movement patterns to a larger extent, when compared the linear counterpart, while at the same time information regarding temporal variability was still being preserved (Lucero et al., 1997). These studies show the potential of FDA in studying spatial and temporal descriptives of speech motor control.

2.7 Studies investigating speech motor control using variability measures

Thus far, the approach of measuring variability across a series of repeated utterances to investigate aspects of speech motor control has been successfully used in diverse areas of speech motor control research. Three main areas can be identified in this research body: those relating to comparisons of speech impaired versus healthy speakers, research focusing on comparisons between age groups, and research investigating the impact of task condition on speech motor variability. The following sections provide an overview of studies that have used the STI and FDA methodology to investigate speech motor control characteristics in speakers with dysarthria, in comparisons between speakers of different age groups, and during a number of task effects.

2.7.1 Variability in speakers with dysarthria

The first study that used the STI to assess speech motor control in dysarthria was conducted by Kleinow, Smith, and Ramig (2001). The STI was employed to assess the stability of kinematic movements across 15 repetitions of a phrase during rate and loudness manipulations, in order to see whether these conditions affect speech movements in adults with hypokinetic dysarthria differently compared to those in healthy adult speakers. A group of 8 speakers (3 male and 5 female, age range 57 - 78, mean age 70 years) with hypokinetic dysarthria second to idiopathic

Parkinson's disease, and an age- and gender-matched control group (3 male and 5 female, age range 67 - 78, mean age 73 years) participated. During five experimental conditions, the participants repeated the sentence 'Buy Bobby a puppy' during habitual, loud, and soft speaking loudness, and during fast and slow speech rate, while lower lip displacement was recorded using a strain gauge system. The results showed that slow rate was associated with the highest STI for both subject groups; the ability of speakers to produce consistent speech motor patterns over repeated utterances did not improve with increased movement duration. For both groups, speaking loudly was associated with similar STI values compared to the habitual and fast rate speech conditions, but lower compared to the slow rate condition, suggesting that changing only one speech parameter (vocal effort) is easier compared to controlling the velocity and force of multiple articulators during a less practised movement organization. Overall, group differences across conditions were absent, and this was attributed to the presence of relatively mild speech symptoms in the clinical group (Kleinow et al., 2001). Lower lip movement variability in speaker groups with varying dysarthria types, including flaccid, spastic, ataxic, and hypokinetic dysarthria was assessed in two related studies by McHenry (2003) and McHenry (2004). Both studies employed the same speakers: six participants with mild dysarthria (mean age 27.1 years, SD 8.3 years), six participants with severe dysarthria (mean age 27.0 years, SD 7.0 years), and six age and gender matched control speakers. McHenry (2003) compared four speaking conditions: habitual rate, fast rate, a pacing condition by putting short breaks between words, and a pacing condition with prolonged vowels. The STI measurements indicated that healthy controls showed the least variability across all conditions, and STI values for the severe group were significantly larger compared to the mild and normal groups. Similar to the results found by Kleinow et al. (2001), no differences were found between the healthy speakers and the group of speakers with mild dysarthria. Both speaker groups with dysarthria were the least variable in the stretched condition and the most variable in the fast condition, and demonstrated a trend toward slightly higher stability in the stretched condition, compared to the breaks condition. As the stretched speaking condition was explicitly modelled by the experimenter, it might be possible that the specific elicitation procedure contributed to the reduced variability in this condition. In the follow-up study by McHenry (2004), the STI of lower lip movement obtained during phrase repetition at habitual rate was correlated with the coefficient of variation of voice onset time (VOT), but no significant correlation was found between the two measures of variability. A potential explanation might be that the STI in this study was concerned with the articulation of only one articulator, while VOT represents a measure of variability across physiological systems, including coordination between respiration, larynx and velopharynx action, indicating that correlating variability of a single articulator with variability across physiological systems might be problematic (McHenry, 2004). The first, and thus far only other study to use FDA to measure temporal and spatial variability in dysarthric speech, is the exploratory study by Anderson et al. (2008). In this study, four speakers with hypokinetic dysarthria (age range 46 - 64 years) resulting from PD and three speakers with ataxic dysarthria (age range 39 - 55 years) resulting from Friedreich's ataxia participated, as well as age and gender matched control speakers. Participants repeated the phrase "well we'll will them" at their habitual rate, and twice as fast as normal. The intensity contour was extracted from ten fluent repetitions, and subjected to FDA to extract spatial and temporal variability. The results showed that the two dysarthria types could be distinguished on the basis of relative differences in the spatial and temporal variability of amplitude contours: the speakers with hypokinetic dysarthria showed higher spatial variability whilst the ataxic speakers displayed higher temporal variability.

This overview shows that, thus far, no more than a handful of studies have investigated variability of speech motor control in dysarthria, and the employed group sizes were mostly small, varying between three and eight speakers per group. The results of these studies generally showed that dysarthric speech was characterized by higher variability values compared to healthy speakers. Altered speaking conditions including manipulations of rate and loudness also appear to have an influence on variability. Findings across studies were sometimes conflicting, e.g., Kleinow et al. (2001) found higher STI values in the slow rate condition whilst the study by McHenry (2003) did find lower STI values in the paced slow condition. The effects of different speech tasks on variability will be explored in detail in section 2.7.3, where possible contradictory findings of altered speaking conditions across studies will be discussed further.

2.7.2 Variability across age groups

In addition to comparing speech motor variability in healthy versus dysarthric speakers, a number of studies have also investigated aspect of variability across age groups. This section will focus on those that investigated young and older adult populations.

The first study investigating lower lip movement variability by means of the STI in older adult speakers was employed by Wohlert and Smith (1998). In this study, a group of older adults (5 men and 5 women, age range 76 - 83 years, mean age 79 years), and a group of younger adults (5 men and 5 women, age range 20 - 35, mean age 24 years) repeated the sentence ‘Buy Bobby a puppy’ during habitual, slow, and fast rates. It was found that in the habitual rate condition, variability of lower lip movements was higher in the group of older adults, while no differences were found in slow rate and fast rate conditions. Concurrently measured perioral strength was weaker and tactile acuity was poorer in older adults than in young adults. These combined findings led the authors to conclude that, as sensorimotor abilities change in older age, speakers are less consistent in the spatiotemporal organization of speech movements, reflecting decreased stability of speech motor control. In a subsequent study by Kleinow et al. (2001) were lower lip and jaw variability assessed by means of the STI in a group of older speakers (three male and 5 female, age range 67 - 78, mean age 73 years) and a group of younger speakers (4 male and 4 female young adults, age range 21 - 28, mean age 26 years). The two groups repeated the sentence ’Buy Bobby a puppy’ during habitual, loud, and soft speaking intensity, and during fast and slow speech rate. Across all speaking conditions, the STI values for the group of older speakers were found to be significantly higher compared to the STI values for the younger speaker group, demonstrating a robust decline in speech motor stability, and these findings were in line with the results reported by Wohlert and Smith (1998). Dromey, Boyce, and Channell (2014) investigated the effect of age on lower lip and upper lip variability in young (age range 20 - 30, mean age 23.0 years), middle-aged (age range 40 - 50, mean age 45.3), and older adults (age range 60 - 70, mean age 63.2 years), and each group containing 10 men and 10 women. Sentence stimuli included four different phrases with varying syntactic complexity levels. In contrast to the results reported in the studies above, the group of younger speakers in this study showed higher STI values across conditions, compared to the older speakers. Utterance durations across the different speaking conditions were found to be longest in the group of older speakers, and it was suggested that the older adults relied on a slower speech rate to maintain consistency and precision in articulator movements across utterance repetitions to compensate for declining articulatory control. Changes in linguistic complexity did not lead to increased STI values: the results did not show evidence of increasing articulatory instability due to changes in linguistic complexity. It was concluded that not much linguistic creativity was required of the participants of this study, and thus the used phrases may not have been reflective of the processing demands encountered in everyday language and speech interactions (Dromey et al., 2014).

This overview shows that, similar to the research studies on variability in dysarthria, only a few studies have employed the STI to measure variability of speech motor control as a function of age. In addition, the studies by Wohlert and Smith (1998) and Kleinow et al. (2001) employed relatively small speaker groups, with respectively 10 and 8 participating speakers per age group. These studies assessed the effect of speaking conditions with varying rate, loudness, and syntactic complexity on speech motor control across age groups, and reported results were not always clear-cut or consistent: where Wohlert and Smith (1998) and Kleinow et al. (2001) found higher variability in older speakers, Dromey et al. (2014) reported higher variability in young speakers.

The research reviewed in the previous two sections highlight that, in addition to comparing different speaker groups, often a range of different task conditions is employed in these studies, in order to assess the effects these might have on speakers' variability, and investigate whether the various groups respond in similar ways to these task changes. The following section will therefore focus more closely on the potential behavioural changes that can be attributed to the nature of the speech task. Due to the relatively limited number of research studies that have been conducted using the STI and FDA to date, this review will consider the wider literature on task effects, whilst maintaining the focus on studies on impaired versus healthy speaker groups and different age ranges as much as possible.

2.7.3 Task effects on speech variability

The speech system is capable of producing fluent and intelligible speech under different speaking circumstances. However, instrumental analysis techniques have revealed that altering speaking conditions affect speech motor control, and might invoke changes in variability across productions. The main linguistic and cognitive factors that have been known to influence speech motor control are speech rate alterations (Adams et al., 1993; Logan & Conture, 1995; Dromey & Ramig, 1998; Smith & Kleinow, 2000; Wildgruber, Ackermann, & Grodd, 2001; Dromey & Benson, 2003; Tasko & McClean, 2004), increased sentence lengths (Logan & Conture, 1995; Melnick & Conture, 2000; Maner, Smith, & Grayson, 2000; Dromey & Bates, 2005; MacPherson & Smith, 2013; Allison & Hustad, 2014), increased syntactic complexity (Melnick & Conture, 2000; Maner et al., 2000; Dromey & Benson, 2003; Dromey & Bates, 2005; MacPherson & Smith, 2013; Allison & Hustad, 2014; Dromey et al., 2014), and divided attention (Dromey & Benson, 2003; Dromey & Bates, 2005; Dromey & Shim, 2008). These areas will now be explored in greater detail in the sections below.

2.7.3.1 Speech rate modification

Research on the effects of rate changes on speech motor control has found that slowing down speech rate might decrease the stability of speech movements, with potentially detrimental effects to speech intelligibility for both healthy speakers and impaired speakers. For example, Smith et al. (1995) analysed STI variability of lower lip movements under different rate conditions in a group of seven young adults (four male, three female) of unspecified age, and without speech or hearing problems. A comparison across rate conditions showed that the STIs for habitual and fast speech rate were significantly lower compared to slow rate. The authors suggest that deviating from the preferred rate of speech production means moving into a less stable mode, with higher variability of repeated productions as result. A possible explanation brought forward by the authors is that a slower speech rate is less practised, and therefore less skilled (Smith et al., 1995). The effect of speech rate reduction on the variability of speech movements has also been investigated in speakers with hypokinetic dysarthria and healthy age-matched control speakers in a previously discussed study by (Kleinow et al., 2001). Participants repeated the phrase 'Buy Bobby a puppy' at their habitual, fast, and slow rate at a comfortable loudness, while lower lip and jaw movements were recorded. The results showed that all groups were successful in modulating speech rate. No significant differences in variability were found between the habitual and fast rate conditions, but the slow speaking condition was associated with the highest STI for both speaker groups, possible because the speakers moved away from their 'stable' speech mode into a more effortful portion of their operating range (Kleinow et al., 2001). In a very similar study, McHenry (2003) assessed lower lip stability in speakers with varying dysarthria types as a factor of speech rate. Participants were six individuals with mild dysarthria, six with moderate-to-severe dysarthria and six healthy speakers, who engaged in four experimental conditions: habitual speech rate, twice habitual rate (fast condition), paced by prolonging vowels (stretched condition) and paced by inserting breaks between words (breaks condition). Across groups, the duration of utterances differed significantly across rate conditions. Sentence durations were the shortest in the fast rate condition, whereas in the breaks condition durations were the longest. The severe group showed no significant increase in speech rate from the habitual to the fast condition, indicating that patients with dysarthria were near the upper limits of maintaining speech rate in the habitual rate condition. The STI values for the severe group were significantly higher compared to the mild and healthy groups, but no significant differences were found between the normal and the mild group. Across groups, the STIs were generally lower in the stretched condition, but again no significant effect was found here. The STI values for the fast conditions were significantly higher than the other three conditions. From these results, the authors concluded that individuals with dysarthria benefit from a reduced speaking rate (McHenry, 2003), contradicting the results found by Kleinow et al. (2001), who found higher variability values in the slow rate condition. Possible explanations for these different results might be that the speakers in the two studies used different strategies to reduce speech rate, differed in severity of dysarthria, or participant groups lacked homogeneity. The effects of increased articulation rate on temporal and spatial variability of intensity contours in dysarthric speech was assessed by Anderson et al. (2008) in their exploratory study. Four speakers with hypokinetic dysarthria resulting from PD (age range 46 - 64 years) and three speakers with ataxic dysarthria resulting from Friedreich's ataxia (age range 39 - 55 years) participated. The two groups were comparable in relation to dysarthria severity, and speakers within each group presented with similar speech symptoms. Each participant was matched with a healthy control participant of the same gender and similar age. Participants repeated the phrase "well we'll will them" at their habitual rate, and twice as fast as normal. When comparing the rate conditions, it was found that the speakers with hypokinetic dysarthria showed significantly higher spatial temporal variability in the fast rate, compared to the habitual rate condition, in line with the results by McHenry (2003), but again contradicting the results by Kleinow et al. (2001). No differences were found with respect to temporal variability. No significant differences across rate conditions were found for the speakers with ataxic dysarthria or the control speakers. The particularly small group sizes might have contributed to the absence of further rate-related differences.

The above studies investigating the influence of rate changes on variability in dysarthric speakers are characterized by small speaker groups, ranging from three to eight participants per group. The small group sizes may have had an influence on the mixed results reported across the studies, as heterogeneity within small groups might have become an issue. Whilst speakers with dysarthria generally showed lower variability values during sentence repetition at their habitual rate, findings with respect to variability changes during increasing and decreasing speech rate showed conflicting results: Kleinow et al. (2001) reported significantly higher STIs in slow rate conditions while McHenry (2003) reported (non-significantly) lower STIs, compared to habitual rate conditions. With respect to fast rate, McHenry (2003) and Anderson et al. (2008) reported significantly higher variability in fast rate compared to habitual rate conditions, while in contrast Kleinow et al. (2001) did not find differences between fast and habitual rate conditions. Additional reasons for these contradicting results across studies might lie in different group make-ups, with differences in dysarthria severity, as well as in different pacing styles: Kleinow et al. (2001) instructed speakers to speak twice as slow, whilst McHenry (2003) asked speakers to prolong vowels and insert slight pauses between words respectively. These pacing styles might have helped speaker maintain speech motor stability during slower rates, underlining the importance of instruction in experimentation.

Only two studies have compared the movement variability of young and older adults speakers as a factor of rate. The first study was employed by Wohlert and Smith (1998), in which young adults (5 men and 5 women, age range 20 - 35, mean age 24 years) and older adults (5 men and 5 women, age range 76 - 83 years, mean age 79 years) repeated the sentence ‘Buy Bobby a puppy’ during habitual, slow, and fast rates. Variability of lower lip movements was found to be higher in the group of older adults compared to the group of younger adults, but only significantly so in the habitual rate condition. When comparing speaking conditions separately for each group, it was found that participants of both groups tended to show greatest variability at slow rate, less variability at fast rate, and least variability at habitual rate. Concurrently measured perioral strength and tactile acuity were poorer in older adults than in younger adults. The results led the authors to conclude that, as sensorimotor abilities change in older age, speakers were becoming less consistent in the spatiotemporal organization of speech movements, reflecting decreased stability of speech motor control (Wohlert & Smith, 1998). Kleinow et al. (2001) also investigated the effects of speech rate on lower lip movements as a function of age. Young healthy speakers (4 men and 4 women, age range 21 - 28, mean age 26 years) and older healthy speakers (3 men and 5 women, age range 67 - 78, mean age 73 years) were asked to repeat a sentence at habitual, fast, and slow rate. For both age groups, STI values of lower lip movement were significantly higher at slow rates, compared to habitual and fast rates, while no differences were found between the habitual and fast rate conditions. Across all speaking conditions, the older speakers displayed higher STI values, compared to the younger speakers, largely supporting the results found in the study by Wohlert and Smith (1998).

The small number of studies and their relatively small group sizes notwithstanding, the above results showed that, similar to speakers with hypokinetic dysarthria, changing rate has an effect on speech motor control in ageing speakers. However, results were found to be more clear-cut in healthy ageing speaker group than speaker groups with hypokinetic dysarthria. As indicated by the results of Wohlert and Smith (1998) and Kleinow et al. (2001), speech motor stability was unanimously found to reduce when intentionally slowing down speech rates, whilst increasing rate did not show an discernible effect on variability.

2.7.3.2 Increased sentence length and complexity

In addition to the studies demonstrating changes in speech rate to affect speech motor stability, a growing body of research has reported a deterioration in speech motor control and articulatory stability during the production of longer sentences or sentences with increased linguistic complexity. Studies have shown that speech motor control in specific speaker populations is adversely affectedby demands imposed by increased sentence length and complexity, for example in children (Maner et al., 2000; Sadagopan & Smith, 2008), in people with apraxia of speech (Strand & McNeil, 1996), or in people who stutter (Kleinow & Smith, 2000).

Thus far only one study employed variability measures to investigate speech motor stability in dysarthria as a factor of linguistic complexity. Walsh and Smith (2011) investigated the effects of increased syntactic complexity and utterance length demands on speech variability in a group of 16 speakers with hypokinetic dysarthria secondary to Parkinson's disease (11 men, 5 women, age range 62 - 82, mean age 73 years), and in a group of age- and gender-matched control speakers (11 men, 5 women, age range 63 - 80, mean age 73 years). The speakers participated in a sentence repetition task, with a series of six different stimuli varying in sentence length and complexity. The sentences were presented in 15 blocks of six sentences, pseudo-randomized within each block. Lower lip and upper lip displacement movements were recorded using an optical motion tracking system, and merged into lip aperture tracks. Oral motor coordination variability was measured by calculating the STI of the lip aperture tracks obtained from displacement movements measured during repetition of the sentences. The results showed that, across speaking conditions, lip aperture variability was higher in speakers with hypokinetic dysarthria, indicating a higher variability in oral motor coordination. Increasing length and syntactic complexity led to an increase in lip aperture variability for both the group of speakers with hypokinetic dysarthria and the control group, but an interaction effect of group by complexity was absent, showing that the speakers with hypokinetic dysarthria were not disproportionately affected by the demands of increased sentence lengths and complexity. The authors suggest these findings might have been due to the heterogeneity of speech motor performance within the hypokinetic speaker group, and due to the particular reading paradigm used; as the sentences were available on the computer screen throughout the trial, this could have reduced programming and formulation demands for the complex sentences (Walsh & Smith, 2011).

Only a few studies have investigated the effects of increased syntactic complexity and utterance length demands on speech motor control in elderly adults. The above discussed study by Walsh and Smith (2011) reported that healthy older speakers, who acted as control speakers to a group of speakers with hypokinetic dysarthria (both groups with a mean age of 73 years), were less stable in their articulatory movements during longer and more complex utterances, compared to the baseline sentence, although they were not directly compared with younger speakers. Dromey et al. (2014) analysed the effect of utterance length and grammatical complexity on articulatory stability in unimpaired young (age range 20 - 30, mean age 23.0 years), middle-aged (age range 40 - 50, mean age 45.3), and older adults (age range 60 - 70, mean age 63.2 years). Each of the three speaker groups was made up of 10 male and 10 female speakers. Speech tasks included the repetition of five different stimuli with different grammatical contexts, while lower lip, jaw, and upper lip movements were recorded. Articulatory stability was calculated by means of the STI. The results showed that across all tasks, the group of young adults had the highest STI values as compared to the other two groups, leading the authors to conclude that speech motor control matures beyond young adult speaker characteristics. For all speaker groups, higher STI values were found in the longer and complex conditions, compared to the shorter speech task. Utterance durations were significantly longer in the older adults group when compared with productions of the other two age groups. Taken together with the higher STI values for the younger speakers, it is possible that the older adults relied on a slower speech rate to maintain consistency and precision in articulator movements across repetitions of the utterance. Another interpretation brought forward by the authors was that, rather than viewing lower STI values as optimal, they could be interpreted as evidence of reduced flexibility or plasticity, suggesting more rigid control strategies employed by the elderly adults. Furthermore, differences between sentences with varying grammatical complexity levels but with equal length were absent, indicating that changes in linguistic complexity in a repetitive task do not appear to have a consistent effect on measures of speech movement variability. The variability measurements where characterized by high within-group and within-task variation, and might have contributed to the absence of significant differences across complexity tasks. In addition, the authors speculate that linguistic complexity might not have placed sufficient demands on the available resources to negatively influence articulator movement. The repetitive nature of producing the stimuli resulted in utterances that were not representative of typical conversational speech (Dromey et al., 2014).

This overview shows that only a handful of studies have investigated the effect of increased sentence length and linguistic complexity on speech motor stability in speakers with dysarthria and in ageing speakers. Thus far, one study investigated variability in hypokinetic dysarthria, and reported that increased sentence length and complexity led to higher STI values in both hypokinetic speakers and unaffected controls. Although the average variability values of the hypokinetic speakers were higher across all speaking conditions compared to the control speakers, they did not seem to be adversely influenced by the demands of increased sentence length and complexity conditions, suggesting a general disease factor impacting speech production. The two studies investigating variability in younger and older healthy adults indicated that longer and more complex sentences influence speech motor stability for both groups, with evidence of age-related effects.

2.7.3.3 Divided attention

Research in the field of cognitive psychology has observed that executing tasks in situations that require divided attention are subject to measurable changes in performance. Typically, results show that the execution of two simultaneous tasks leads to a performance decrease in either or both tasks. In addition, if performance on one task increases, it usually declines for the concurrent task, indicating a trade-off relationship in resource allocation between the two concurrent tasks (Leclercq, 2002; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). Dual tasks paradigms have been used to study the effect of divided attention on speech performance in healthy populations, showing that either speech performance declines during the execution of a concurrent task, the concurrent task is executed slower or less accurately during speech production, or that the performance on both the speech production tasks and the concurrent task is lower, compared to when these tasks are executed separately (Hiscock, Kinsbourne, Samuels, & Krause, 1985; Simon & Sussman, 1987; Tun, Wingfield, & Stine, 1991; Feyereisen, 1997; Pashler, Johnston, & Ruthruff, 2001; Plummer-D'Amato, Altmann, & Reilly, 2011). Dual-task paradigms to study interference effects on cognition have also been applied to patients with neurological disorders (Camicioli, Howieson, Oken, Sexton, & Kaye, 1998; McCulloch, 2007; Keintz, Bunton, & Hoit, 2007; Plummer-D'Amato et al., 2008; Holmes, Jenkins, Johnson, Adams, & Spaulding, 2010; Plummer-D'Amato & Altmann, 2012; Rogalski, Altmann, Plummer-D'Amato, Behrman, & Marsiske, 2010).

While no studies to date have used variability measures to assess the influence of dual tasks on speech motor control in dysarthria, other methodologies have been used to identify changes in speech motor stability or speech motor performance under the influence of divided attention. Ho, Iansek, and Bradshaw (2002) used a dual-task paradigm to examine the role of attention in speech motor control of speakers with hypokinetic dysarthria due to Parkinson's disease. Fifteen (11 male, 4 female) hypokinetic speakers (mean age 67.3 years, SD = 11.5), and 15 healthy age- and sex-matched controls (mean age 66.7 years, SD = 13.9) engaged in a spontaneous conversation task and a numerical recitation task while performing a visuo-manual tracking task. Speech intensity, speech intensity decay, counting duration, and counting latency were measured during the speech tasks. For all groups, the results showed a reduction in speech intensity and an increase in speech intensity decay during the concurrent speech task. In addition, for the group of speakers with hypokinetic dysarthria, counting duration was lowered and counting latency was increased during the concurrent task. The results suggest that dividing attention between two concurrent tasks might be more difficult for speakers with Parkinson's disease due to an inability to perform complex and well-trained movement sequences in an automatic manner (Ho et al., 2002). The effects of executing a dual-task on speech rate, fundamental frequency variation and intelligibility in the speech of speakers with dysarthria related to Parkinson's disease were investigated in study by Bunton and Keintz (2008). In this study, a group of 4 speakers with hypokinetic dysarthria and 4 unimpaired speakers (mean age 67.3 years, age range = 62 - 71, SD=2.4 combined for both groups) engaged in a series of speech tasks in single-task and dual-task conditions. The dual-task condition consisted of a motor task, in which participants were instructed to turn a nut on a bolt. Whilst for the unimpaired speakers there were no noticeable differences in intelligibility between the single-task and dual-task conditions, the speakers with Parkinson's disease had lower intelligibility scores in the dual task as compared to the single task. Across both speaking conditions, variation in fundamental frequency was found to be lower in the group of impaired speakers, compared to the healthy speakers. When comparing speaking conditions within the group of impaired speakers, it was found that fundamental frequency variation was lower, speech rate was higher, and speech intelligibility scores were lower in the dual-task condition compared to the single-task speaking conditions. The competition for resources created by the dual-task condition forced speakers to sacrifice performance on one task to adequately complete the other task. The authors suggested that the deterioration in speech performance found in the dual-task condition could indicate that could be used to obtain measures of intelligibility in a clinical or laboratory setting that is more representative of functional communication abilities in speakers with hypokinetic dysarthria (Bunton & Keintz, 2008). Although speaker groups employed in this study were rather small, these results support the findings of the study by Ho et al. (2002) that allocation of attention across different tasks does affect speech production performance in speakers with Parkinson's disease. Dromey et al. (2010) examined dual task interference between speaking and postural stability in a group of 9 speakers with Parkinson's disease (mean age 68.7 years, SD = 9.2) and an unimpaired age-matched control group made up of 7 speakers (mean age 70.5 years, SD = 11.9). An utterance repetition task and a rise-to-toes task were performed, while selected acoustic (F1 and F2 range and slope) and postural variables (centre of pressure and centre of mass) were measured. The results showed that during the single task, measures of speech parameters were not worse or better in the group of speakers with Parkinson's disease compared to the healthy control speakers, but during the dual task, speakers with Parkinson's disease showed a reduced diphthong range and slope, along with smaller, slower, and less stable postural movements. These results indicated, similar to the findings by Bunton and Keintz (2008) that the concurrent performance of speech and postural control might impair speech as well as the concurrently executed task in speakers with Parkinson's disease.

Only a small number of studies have assessed speech motor stability of repeated utterances during the execution of a dual task, and the majority of these studies have investigated young adult speakers only. For example, Dromey and Benson (2003) investigated the influence of three types of concurrent tasks on speech motor performance in a group of ten male and 10 female young adult (mean age 22.7 years, SD = 1.69), unimpaired speakers. The concurrent tasks included a motor task (putting together washers, nuts, and bolts), a linguistic task (transforming nouns to verbs during utterance repetition), and a mental arithmetic task (generating numbers during utterance repetition). A group of young adults repeated a series of sentence during the distractor tasks and in isolation. During the experimental conditions, lower lip and upper lip movement data were recorded, and speech motor stability was assessed by the STI. The results showed a decrease in displacement and velocity of the lower lip during the concurrent motor task. During the concurrent linguistic and cognitive dual tasks, the STI of lower lip movements was significantly higher as compared to the single-task condition. In addition, the coordination between upper lip and lower lip movements was less stable during the dual tasks. As linguistic and cognitive, but not motoric dual-task conditions had a significant influence on lingual kinematics and coordination during speech, the authors concluded that resource allocation to speech production depends on situational demands, and that the cognitive and linguistic challenges were more alike than either was to the manual task Dromey and Benson (2003). In a related study, Dromey and Bates (2005) examined variability of lower lip movements during a series of speaking conditions involving sentence repetitions in a group of 10 females (mean age 22.4 years, SD = 2.2) and 10 males (M = 24.5 years of age, SD = 1.8). Sentence repetitions were concurrently executed with a linguistic, cognitive, or visuomotor challenge task. The results on variability showed that, partly in line with the results reported by Dromey and Benson (2003), the concurrent task involving the linguistic challenge resulted in an increase in the STI, while the visuo-motor and cognitive challenges did not result in a change in speech motor stability. Dromey and Shim (2008) examined in a follow-up study the effects of manual motor tasks on lower lip variability in a group of ten right-handed men (mean age 22.8 years) and 10 right-handed women (mean age 21.0 years). The speakers were subjected to a sentence repetition task in isolation as well as during a motor task in which speakers were instructed to placing pegs and washers in a pegboard with either their right or left hand. Lip and jaw movement data were recorded during the sentence task, and selected speech parameters and the STI were derived from lower lip displacement data. The results showed that during concurrent performance of manual tasks, the lip displacement and peak velocity decreased, while sound pressure increased. The STI increased significantly when participants concurrently performed the left-handed pegboard task, while for the right-handed task no differences were found. The authors speculate that speech motor patterns are more unstable as the complexity of the tasks increases, indicating that the overall attentional demands of left-handed fine motor performance were greater than the demands for the equivalent right-handed task. In addition, the fact that the STI increased during the execution of the motor task with the non-dominant hand confirmed findings of earlier studies that manual motor performance and speech motor performance are possibly subject to the accessibility of similar neural resources (Dromey & Shim, 2008).

A number of studies have compared the speech performance of speakers of different age groups during dual task paradigms. The general consensus is that with increasing age, the production of speech is disproportionally affected during the execution of a dual task, possibly due to reduced processing capacities, and loss of sensory and sensory-motor functions (Li & Lindenberger, 2002). During the execution of a dual task, linguistic changes associated with ageing have found to be multi-faceted, including a decrease in fluency (Kemper, Herman, & Nartowicz, 2005; Kemper, Schmalzried, Herman, Leedahl, & Mohankumar, 2009), a decrease in grammatical complexity (Kemper et al., 2005; Kemper et al., 2009), a smaller vocabulary (Kemper, Schmalzried, Hoffman, & Herman, 2010), and decreased sentence length (Kemper et al., 2010). Only one study reported on the effects of divided attention in speech motor variability across different age groups. Bailey and Dromey (2015) analysed the effect of three non-speech tasks on concurrent speech motor performance in speakers of three different age groups. The age groups included younger adults (age range 20 - 28, mean age 23.0 years), middle-aged adults (age range 40 - 50, mean age 45.6 years), and older adults (age range 58 - 70 years, mean age 63.2 years). The speakers completed a sentence repetition task in isolation and concurrently with each of the non-speech tasks, a semantic decision task, a quantitative comparison (cognitive) task and a manual motor task. Sound pressure level, sentence duration and the STI of lower lip movements were extracted from the sentence repetition task. During the concurrent linguistic and cognitive tasks, a higher STI was found during the speech task across all age groups, and the linguistic and cognitive tasks showed a decrease in performance. However, no age-related differences in speech motor stability were found, possibly due to a compensatory strategy in older speakers to reduce speaking rate, as evidenced by longer durations (Bailey & Dromey, 2015). This finding of older adults reducing their speech rate during divided attention contrasts the results reported by Bunton and Keintz (2008) in their study with PD speakers, where higher speech rates were found in the dual-task condition compared to the single-task conditions, suggesting that speech tasks with divided attention may tax older unaffected adults different than patients with Parkinson's disease. For example, differences in performance could be related to the reduced availability of attentional resources in patients with Parkinson's disease, forcing them to adopt a different strategy in completing multiple tasks. The results of the study by Bailey and Dromey (2015) reflect the results of previous studies with respect to findings related to bi-directional interference between speech and other concurrent tasks (both tasks suffer, see e.g., Dromey and Shim (2008)), as well as the findings of possible compensatory strategies between rate and accuracy in ageing speakers (decrease rate to maintain accuracy, see e.g., Dromey et al. (2014)).

The overview above of studies investigating aspects of speech motor stability in dysarthria and ageing speakers indicates that modifying speech rate, sentence length and complexity, and divided attention have an influence on speech performance in speakers with dysarthria and across age groups of healthy speakers. With respect to the effects of modifying speech rate on speech motor stability, the reported results were found to be ambiguous, and results were largely dependent on the speech tasks employed. Slowing down is usually associated with an increase in variability, while both higher and lower variability values are found with increasing speech rates. With respect to speaking conditions involving increased linguistic complexity and divided attention, the results are more clear-cut, at least in speakers with dysarthria, i.e., these conditions are typically associated with an increase in motor speech variability. On the other hand, results for the ageing population under these conditions are more diverse, as some studies fail to find differences when compared with optimal speaking conditions.

The literature review above also shows that only a few studies have attempted to assess the effect of rate changes, increased linguistic complexity, or divided attention on speech motor control in dysarthria, and variability measures employed in these studies were mostly limited to STI measures of lower lip and upper lip movements.

The following section compares the use of the STI and FDA in speech research, and discusses advantages and disadvantages between the two measurement methodologies.

2.7.4 Comparing STI and FDA

As briefly mentioned before, the calculation methods of the STI and FDA both have advantages and disadvantages when applied to analysing variability in the domain of speech. Advantages of using the STI include the following. The STI is more widespread in research, enabling comparison across studies. Algorithms to calculate the STI are more readily accessible, and computationally easier, making it more accessible to implement as a signal processing tool (Smith et al., 1995; Howell et al., 2009; Howell, Anderson, & Lowit, 2011). In addition, as the STI is a composite measure of spatial and temporal variability, this method might be more sensitive when discriminating disordered speakers and healthy speakers, as differences in variability in both dimensions will be aggregated (Howell, Anderson, & Lucero, 2010). A large limitation of using the STI is that errors in timing are confounded with errors in articulator displacement. This is especially critical with regard to nonlinear speech events. When using STI, the averages of the set of functional observations are usually linearly time-normalized. This reduces the effects of differences in the duration of events, while the distortions due to underlying nonlinear factors are not eliminated. Differences in nonlinear lengthening due to differences in pausing behaviour and different combinations of vowels and consonants within a set of observations will add temporal variability after normalization. The total measured variability is then a sum of different factors, including nonlinear differences in phonetic make-up and variations in speech motor control. This complicates the interpretation of the results, as nonlinear factors can obscure linearly time-scaled behaviour (Ward & Arnfield, 2001; Howell et al., 2011). Ward and Arnfield (2001) compared findings from linear and nonlinear normalization procedures in the analysis of lower-lip displacement of phrase-length utterances for a group of 8 unaffected speakers (age range 18 - 42, mean age 29 years), across habitual, fast, and slow speaking rate conditions. Nonlinear spatiotemporal indices revealed lower and more homogeneous values within groups, compared to linear spatiotemporal indices, and thus showed that the use of nonlinear STI variability measures are more sensitive to rate-dependent movement data as compared to linear STI variability measures. The authors suggest that nonlinear analyses can therefore potentially reveal more about underlying speech motor control structures that are associated with speech stability. Finally, when employing linear STI measures, it is essential to prevent the introduction of unwanted nonlinear factors, and the acquisition of data needs to be severely controlled. This includes using shorter time spans per observation, strict pausal control, and ideally an identical phoneme make-up of observations within a trial (Lucero et al., 1997).

When looking at FDA, advantages are mainly concerned with the increased richness of data, as compared to the STI. Firstly, the process of nonlinearly normalized averaging of the time scale used in FDA removes the problem of using the STI in the presence of nonlinear variability in event durations. In contrast, FDA turns this into a feature by enabling the quantification of this nonlinear temporal variability (Howell et al., 2011). Secondly, to obtain an estimate of the average speech trajectory and its deviations, prominent speech events across different contours should be synchronized. With FDA, the time-distorted events are aligned before averaging, and thus minimizes phase differences. When using the STI, the time-distorted events are aligned together with the spatial excursions into one common template during the averaging step, possibly introducing inaccurate phase variability estimations. The approach used with FDA removes variations in time from the average template, and become available as a separate measure of temporal variability, along with a measure of spatial variability, enabling the study of the underlying pattern of speech movements into two dimensions (Lucero & Koenig, 2000). The disadvantages of using FDA mirror the advantages of the STI to a certain extent. The application of FDA in healthy and disordered speech research is, as of yet, less widespread compared to the STI, impacting on the comparability across research studies. In addition, the algorithms are more difficult to implement, and require more skills in terms of signal processing. Finally, the choice and selection of optimal parameter settings are opaque and depend on the data under investigation. The length of the records should be taken into consideration when fitting the records. It is furthermore necessary to vary and test parameter settings to obtain reliable normalization results, e.g., by defining a suitable fitting criterion for the alignment of the records, and by defining a term for a roughness penalty if some degree of smoothing is desired (Lucero et al., 1997).

In conclusion, the aforementioned studies indicate that the use of linear and nonlinear variability measures may be a promising approach in investigating aspects of the speech production mechanisms in healthy and unimpaired speaker populations. So far, only a few studies have combined the STI or FDA with audio data. The differences between STI and FDA, and their respective advantages and disadvantages, warrant a side-by-side comparison when studying speech motor variability in different speaker groups.

2.7.5 Indirect measurements of articulatory movements

The majority of the studies reviewed thus far have used directly obtained movement patterns, for example by means of cantilever / strain gauge systems (Smith et al., 1995), electromagnetic articulography (Ward & Arnfield, 2001), electropalatography (McAuliffe et al., 2003), or electromyography (Wohlert & Smith, 2002) to calculate articulatory variability. In recent years new techniques and methods have been developed to investigate speech motor control, and one of these techniques involves the measurement of variability of speech movements based on the extraction of acoustic properties in the speech signal (Anderson et al., 2008; Howell et al., 2009; Howell et al., 2010; Howell et al., 2011). The speech signal contains several continuous or quasi-continuous acoustic data properties varying in time, including intensity, fundamental frequency, and formants, all corresponding in one way or another to articulatory activity. An approach in which speech motor control is investigated through these acoustic properties would thus avoid the invasive and technological demanding nature of directly measured speech movement data. A small number of studies have now applied the STI and FDA to acoustic data (Anderson et al., 2008; Howell et al., 2009; Howell et al., 2010). In comparison with kinematic data collection, the collection of acoustic data has some important advantages. Specialized and expensive devices are unnecessary; only a high quality microphone and sound recorder are required to collect data. Acoustic recordings are non-invasive, and therefore easier to collect, especially when recording speakers which have hypersensitive or abnormal oral structures. In addition, the equipment is portable and easy to set up, and data collection can be carried out at different locations, including health centres, speech and language clinics, support group locations, and participants' homes. This potentially enables the use of acoustic variability measures in clinical practice (Howell et al., 2011). Thus far, only a few studies have applied the analysis of speech variability by means of STI and/or FDA to acoustic data. The first notable study in using FDA based on audio data has been carried out by Anderson et al. (2008). In this exploratory study, Anderson et al. (2008) were able to distinguish between speakers with hypokinetic dysarthria and ataxic dysarthria on the basis of differences in the spatial and temporal variability of amplitude contours extracted from the speech signal, showing the potential of using audio recordings in the assessment of speech variability. In a study by Howell et al. (2009), the STI was used to analyse variability of kinematic lower lip movements and speech intensity profiles extracted from the concurrently recorded audio signal. Strong significant correlations were found between STI variability measurements of the lower lip contours and STI variability measurements of speech intensity profiles, indicating that the audio signal also can be used to provide a signal for estimating variability by means of the STI (Howell et al., 2009). In a subsequent extended analysis, Howell et al. (2010) used FDA to assess speech motor control by analysing spatial and temporal variability of concurrently recorded lower lip movement contours and speech intensity profiles. Temporal variability measurements of the lower lip contours were correlated with temporal variability measurements of speech intensity profiles. Similar to the results for the STI, strong significant correlations between the two FDA measures were found. In short, this study demonstrated that FDA variability measures obtained from indirect acoustic recordings potentially provide similar speech movement characteristics and potentially have similar explanatory value when compared to direct kinematic recordings (Howell et al., 2010).

The following section gives a summarized overview of the findings of the relevant literature, identifies contradicting results and competing interpretations, and identifies gaps in the current knowledge.

2.8 Summary

The production of fluent and intelligible speech requires quick, precise, and coordinated articulator movements. Impairments of the speech systems and increased cognitive or linguistic demands of the spoken output may have an impact on the control of speech motor movements. The dysarthrias as a relatively prevalent neurogenic communication disorder are a logical focus of attention with regard to investigating atypical speech motor control behaviour. Of the different types, hypokinetic dysarthria is of particular interest, as this is a common dysarthria type, and exhibits in general a singular, distinctive and consistent pattern of speech disorders. Damage to the basal ganglia control circuit underlying hypokinetic dysarthria may affect respiratory, phonatory, resonatory, articulatory, and prosodic aspects of speech production. Furthermore, a series of experimental tasks employed in perceptual and acoustical studies have shown that functional and anatomic changes to the speech system associated with ageing may affect aspects of speech production and articulatory accuracy.

One way to investigate atypical speech motor control behaviour is by analysing speech variability over a series of repeated utterances. The measurement of speech variability has shown to be successful in investigating motor control aspects of speech, both in unimpaired and clinical speaker populations. In the presence of an impaired or non-typical speech mechanism, levels of variability usually increase, as evidenced by kinematic studies into lower lip stability of speakers with hypokinetic dysarthria. Relatively new techniques of analysing speech movement variability are the spatiotemporal index and functional data analysis, enabling the composite and separate measurement of temporal and spatial variability of speech movements. This approach has the potential to provide more insights into the impairment of speech motor control in hypokinetic dysarthria, as well as into changes in speech motor control as a factor of ageing. In research to date, the majority of speech movement measures are based on direct kinematic input, with its associated invasive and complex nature of data collection. In recent years, new techniques and methods have been developed to investigate speech motor control, involving the measurement of variability of speech movements based on extracted acoustic and kinematic properties in the speech signal. The use of the acoustic signal has several benefits, and opens up new possibilities in the assessment of speech motor control, especially in disordered populations. Audio-based signals are cheaper, less invasive and easier to record and analyse compared to kinematic signals, lowering the usability threshold for speech-language pathologists. Acoustic properties extracted from audio signals are related to different aspects of articulation including voicing, prosody and articulator position, and may therefore be as informative about speech motor control behaviour as directly obtained kinematic movement data. Acoustic data can also be captured in combination with other scanning and imaging systems used in analysing the production of speech. These factors facilitate a greater freedom in experimental set-up, such as the choice of speech tasks and flexibility of recording environments.

Instrumental analysis techniques have revealed that altering speaking conditions affects speech motor control, and might invoke changes in variability across productions. In parallel, several studies have been in search of the optimum assessment task when comparing speech motor control across different speaker groups. Using variability estimators, studies have investigated the effects of speech rate alterations, sentence length and grammatical complexity, and divided attention on speech motor control in healthy and impaired speaker populations. A general finding is that intentionally slowing down decreases speech motor stability. Conflicted results have been reported in studies investigating the effect of increasing speech rate. Some studies reported a small decrease in speech motor stability, while in other studies effects were absent altogether. Few studies have investigated the effect of increased length and complexity of linguistic stimuli on speech motor variability in speakers with dysarthria and ageing speakers. Increased length and grammatical complexity of speech tasks come with a decrease in speech motor stability for virtually all speaker groups investigated. Speakers with hypokinetic dysarthria seem to be equally affected compared to healthy control speakers, while in their turn ageing speakers have shown a disproportionally larger decrease in stability compared to younger speakers. Studies investigating dual-task paradigms have not yet used variability estimators to monitor speech motor performance in dysarthria. Nonetheless, other measures of speech performance suggest that divided attention does adversely affect speech production in speakers with hypokinetic dysarthria. Results of studies of speech motor stability in ageing speakers have been conflicted, with some studies reporting a larger increase in variability during a dual task compared to younger adults, while other studies were not able to find age-related differences.

Apart from the conflicting results reported across studies, a further consideration in discussing differences in spatiotemporal, spatial, or temporal variability when comparing speaking conditions is the interpretation of these measures. A common interpretation is that low variability values reflect greater stability. For example, low STI values of lower lip movements were usually found during well-practised habitual rate conditions, and reflect the presence of stable underlying processes involved in movement planning and execution. Findings of higher variability values for speakers with hypokinetic dysarthria suggest that larger movement variability is a feature of disordered speech motor control, as speakers are using multiple solutions to reach task goals, that is, they may be using more of the available movement space. However, another perspective could be taken when interpreting variability values. Rather than viewing lower variability values as optimal, they could be interpreted as evidence of reduced flexibility or plasticity, suggesting the usage of more rigid control strategies. In the face of prosodic disturbances, orofacial rigidity, and bradykinesia present in speakers with hypokinetic dysarthria, manifestations of monoloudness and monopitch might translate into findings of reduced variability of sound pressure level and fundamental frequency contours. A further point to consider is that due to the presence of physiological changes associated with ageing, older speakers might choose to pay more attention to speech production accuracy, intelligibility, and naturalness at the cost of speaking rate. With slower speaking rates, speakers move away from a habitual rate, which may not involve the same trained motor control processes, inadvertently introducing a source of articulatory variability. Accordingly, a measure of variability cannot be interpreted at face value, as the underlying source and explanation thereof are not always clear-cut. A comprehensive assessment of speech motor performance in hypokinetic dysarthria therefore warrant a side-by-side comparison of variability measures under different speaking conditions and in different age groups.

In conclusion, only a few studies have attempted to assess the effect of rate changes, increased linguistic complexity and divided attention on speech motor variability in hypokinetic dysarthria by means of the STI or FDA, and these studies often reported inconsistent results. The use of variability estimators has been mostly limited to measurements of the STI of directly obtained lower lip kinematics. Novel methodologies in measuring speech motor stability based on acoustic properties enable more flexible experimental conditions. However, whilst the analysis of variability of speech properties of the acoustic signal is a promising tool in research on speech motor disorders, this paradigm has been used in only one exploratory study so far, and research to date failed to provide a conclusive answer on whether linear and nonlinear estimators can be used in the assessment of speech difficulties in hypokinetic dysarthria and ageing speakers. A positive answer entails that this technology may potentially be adopted in speech motor control research, and possibly be embedded in clinical practice, adding to the instrumentation available to the speech-language pathologist and speech researcher when assessing this particular type of speech motor disorders.

2.9 Aim of the study and research questions

In view of the above mentioned gaps in knowledge, this study aims to investigate to what degree acoustic linear and nonlinear estimates of variability hold their promise in being valuable for clinical research and clinical practice. Given that previous research highlighted many factors that may affect speech motor performance, this study will take a comprehensive approach to capture these variables.

To this end, a range of speech parameters including sound pressure level, fundamental frequency, first and second formant frequency will be investigated in order to capture speech motor performance in a number of segmental and prosodic aspects of speech production. This study will also be distinctive in the wide selection of speaking conditions under which these aspects will be observed, including slower and faster speaking rate, increased sentence length, increased sentence complexity, and divided attention, thus enabling the assessment of increased cognitive and motor loads on speech motor stability. Finally, several speaker groups are investigated, i.e., speakers with hypokinetic dysarthria and their age-matched control group, and two groups of unimpaired speakers in which the effect of age on speech motor variability will be investigated, in order to provide a better understanding of the neuromotor factors affecting performance in the various conditions and parameters.

The results of the variability measures of the hypokinetic speakers will be related to established outcome measures of intelligibility ratings, a series of maximum performance tasks, and quantifiable details of their medical history. The direct comparison of linear and nonlinear estimators, speaking conditions and speech parameters allows for investigating which variability measures, conditions and parameters are most promising in distinguishing speaker groups. In addition, by investigating the relationship between the variability measures and other outcome measures it is possible to evaluate the suitability of variability measures in assessing speech motor control in the domains of clinical research and clinical practice. This approach results in the following three research questions.

The first research question is concerned with the discriminatory value of the variability measures with respect to hypokinetic dysarthric and unaffected speech. In the assessment of hypokinetic dysarthria, it is important to establish whether disordered speakers react similarly to different task demands as unimpaired participants.

> Research question 1: Can the variability estimators be used to differentiate speakers with hypokinetic dysarthria from age-matched healthy control participants?

Parkinson's disease is usually diagnosed in adults of older age. As previous research showed the presence of age-related differences in speech motor control, the effects of ageing on variability will also be investigated.

> Research question 2: Can the variability estimators be used to distinguish between healthy young speakers and healthy older speakers?

Finally, it is important to know how the measures of variability relate to standard assessments of disordered speech and quantifiable details of treatment history, in order to be able to interpret the results of the variability assessment in a wider clinical context. Therefore, the third research question is:

> Research question 3: What is the relationship between variability estimators and clinical assessments of disordered speech?

The methodology to answer the research questions set out in this study is described in the following chapter, Chapter 3.

Chapter 3

Methodology

3.1 Introduction

In this chapter, the methodology for this research study is laid out. First, an overview of the study design is given (3.2), followed by a description of the participants involved in the study (3.3), and the materials used (3.4). Finally, the methodologies of data collection (3.5) and data analysis (3.6) are described.

3.2 Study design

This research study was designed to investigate variability of speech motor control in speakers with hypokinetic dysarthria compared to age-matched healthy participants, as well as young adult speakers compared to older adult speakers. Accordingly, participants were recruited to four speaker groups, including patients with hypokinetic dysarthria due to Parkinson's disease (group one) and healthy age-matched control speakers (group two). In addition, groups of speakers younger than 40 years of age (group three) and speakers older than 60 years of age (group four) were formed to assess the effects of age on changes in speech motor control independent from the effects of possible changes due to dysarthria. The speakers of group four formed a subgroup of the speakers in the age-matched control group.

A variety of sentence repetition tasks was designed to investigate the impact of speaking condition on variability in speech motor control, including differences in speaking rate and cognitive load, in order to answer research questions one and two. In addition, a series of speech tasks including diadochokinetic performance, tasks to measure intelligibility, and quantifiable information of the patients' medical history were correlated with the results of the variability assessment to answer research question three. The speech tasks used to measure intelligibility were also used to characterise the dysarthria type in the first speaker group.

The following sections contain detailed descriptions of the participants who were involved in the study, the materials used in the cognitive assessment and the speaking tasks, data collection and data analysis.

3.3 Participants

Four groups of speakers participated in this study. The first study group consisted of twenty-three speakers with varying degrees of hypokinetic dysarthria due to Parkinson's disease. All participants in this group were diagnosed with having hypokinetic dysarthria by their speech and language therapist, or had self-reported speech problems. The second group was made up of twenty-four age-matched healthy adults who served as control speakers. To investigate the effect of ageing on variability, young adult and older adult healthy speaker groups were formed. The literature discussed in section 2.5 was considered with respect to establishing age cut-offs of young and older adults (e.g., Wohlert and Smith, 1998; Kleinow et al., 2001; Bilodeau-Mercure and Tremblay, 2016; Das et al., 2013; Kemper et al., 2009; Dromey et al., 2010; Mazzetto de Menezes et al., 2014; Schaeffer et al., 2015). In order to establish clearly distinct age groups, the age range was set as 18-40 for the young adult speaker group, and above 60 for the older group. The latter was formed by selecting speakers of appropriate age from the age-matched control group already recruited for comparison with the speakers with hypokinetic dysarthria. For the young adult group, additional data had to be collected.

3.3.1 Ethical approval

All participants gave written consent prior to participating in the study. Permission for the study was granted by the University Ethics Committee of Strathclyde University, and the National Health Service (NHS) West of Scotland Research Ethics Committee. Permission to recruit participants at Speech and Language Therapy clinics was obtained from the Research and Development departments of NHS Greater Glasgow and Clyde, NHS Forth Valley, NHS Lothian and NHS Ayrshire and Arran. All procedures adhered to ethics guidelines issued by the National Health Service (NHS) (NHS, 2010) and the National Research Ethics Service (NRES) (NRES, 2010).

3.3.2 Selection criteria

The participants of the four study groups all complied with the following inclusion and exclusion criteria. Inclusion criteria were the following.

- **The participants were capable of giving full informed consent.** In accordance with guidelines on clinical trials and medical research issued by the National Health Service (NHS) (NHS, 2010) and the National Research Ethics Service (NRES) (NRES, 2010), prospective participants gave consent to participate before actual data collection was initiated. The capacity to give informed consent was determined during the discussion of the participant information sheet, and where applicable, based on reports from their associated speech and language therapist or healthcare professional.
- **They were native speakers of English.** In order to ensure that task performance was not adversely affected by language skills, only participants who were native English speakers were selected, allowing for a direct comparison within and across participant groups.
- **Their vision and reading abilities were sufficient to participate in the study.** In order to be able to follow written instructions and to engage in reading and writing tasks as part of the cognitive assessment and speech assessment, only participants with sufficient vision capable of reading and writing were selected. When prescribed, participants were

using glasses or contact lenses during the experiment. None of the prospective participants were excluded because of insufficient visual or reading abilities.

- **Their hearing abilities were adequate.** As hearing loss might influence speech, adequate hearing abilities were required. During personal interviews prior to the study it was established that participants displaying no hearing problems beyond mild age-related hearing loss. When hearing aids were prescribed to participants, they were worn during the experiment. None of the prospective participants were excluded based on insufficient hearing abilities.

The following exclusion criteria were established for the speakers of the clinical group. These criteria were listed in the recruitment letters sent out to the managers of NHS Speech and Language Therapy centres and Parkinson's disease support groups.

- **They did not have a clinical diagnosis of depression.** Depression is associated with changes in speech production, including reduced voice onset times, decreased second formant transitions and increased spirantization (Flint et al., 1993), reduced speaking rate (Cannizzaro, Harel, Reilly, Chappell, & Snyder, 2004; Mundt, Snyder, Cannizzaro, Chappie, & Geralts, 2007), and changes in fundamental frequency variation and range (Alpert, Pouget, & Silva, 2001; Möbes, Joppich, Stiebritz, Dengler, & Schröder, 2008). Depression might also influence fine non-speech motor movements including a decrease in the speed and accuracy of drawing (Sabbe, Hulstijn, Van Hoof, & Zitman, 1996; Schröter et al., 2003; Mergl et al., 2004). For the participants who were not referred from SLT centres, information about a current diagnosis of depression was obtained during an interview prior to the study. None of the recruited participants were excluded due to depression.

- **They did not have a history of speech and language problems unrelated to hypokinetic dysarthria.**

The presence of cognitive problems was not an exclusion criteria as long as participants were able to participate in the assessments. All participants were able to understand and remember instructions and execute the relative straightforward speech and language tasks employed in the study. This was established at the start of the recording session during the informal interview with the participant. None of the volunteers had to be excluded on the basis of this criterion.

3.3.3 Participants excluded from the study

A number of SLT services helped with the recruitment of participants with PD. The relevant SLTs received information about the inclusion and exclusion criteria, and identified and referred suitable participants accordingly. None of the participants referred by SLTs were excluded from the study. Two persons (one speaker with hypokinetic dysarthria and one young adult speaker) who were recruited through a support group and a posted advert respectively, were not entered into the study as it emerged at the initial interview that they were not native English speakers. Furthermore, the data of one participant with hypokinetic dysarthria and one healthy young speaker were not included, as the recordings were of insufficient quality due to technical difficulties.

3.3.4 Participant characteristics

The characteristics of the four participants groups are summarized in tables 3.1 to 3.4, including participant number, gender, age and the Addenbrooke's Cognitive Examination - Revised (ACE-R) test score (see section 3.4.1 for details on the test). For participants with hypokinetic dysarthria, additional information was obtained, including the neurological diagnosis of Parkinson's disease, the number of years post diagnosis, their history of speech and language therapy, and medication use.

3.3.5 Group 1: Patients with hypokinetic dysarthria

Twenty-three participants a medical diagnosis of idiopathic Parkinson's disease were recorded. Eighteen males and five females participated. The participants ranged in age from 40 to 81 years (mean = 66.8 years, SD = 10.6 years). The participants were recruited from four NHS

Speech and Language Therapy centres and two Parkinson's disease support groups based in the West of Scotland. The presence of hypokinetic dysarthria was established by their speech and language therapists, or participants had self-reported speech problems. To further confirm the presence of hypokinetic dysarthria, two experienced speech and language therapists working in the Speech and Language Therapy unit at the University of Strathclyde, one of which was independent of the study, were provided with two contextual speech samples obtained from each speaker, i.e., fragments of a monologue and a read text. The SLTs evaluated qualitatively whether at least one of the speech characteristics typically associated with hypokinetic dysarthria was present, including monopitch, monoloudness, reduced loudness, fast rate, imprecise consonants, or rapid rushes of speech. They established the presence of hypokinetic dysarthria in the speakers of this group independently of each other. All participants were capable of communicating independently with the experimenter in order to discuss the purpose of the study, to give consent, and to follow instructions. On this basis it was assumed that they had the ability to fulfil the demands of the study, i.e., to be able to repeat a series of sentences and engage in a battery of reading and conversation tasks.

An overview of the participants with hypokinetic dysarthria can be found in table 3.1.

3.3.6 Group 2: Age-matched control speakers

The second group of participants were twenty-four unimpaired speakers, age-matched to individuals from the group of speakers with hypokinetic dysarthria. A maximum age difference of 3 years was allowed. Fifteen males and nine females participated. The speakers ranged in age from 41 to 80 years (mean = 60.1 years, SD = 12.3 years). The participants were recruited through acquaintances, local social clubs and service organizations, and as spouses of participants with dysarthria. All participants were born in the United Kingdom, and either native Scottish speakers or living in Scotland for at least 15 years, without a reported history of speech, language, hearing, or neurological disorders. Information regarding the selection criteria was obtained directly from the speakers during the recruitment phase and prior to conducting the study. When hearing aids were prescribed for participants, they were worn during

TABLE 3.1: Participant information: speakers with hypokinetic dysarthria. A: Ropinirole, B: Sinemet Controlled Release (carbidopa/levodopa), C: Madopar Controlled Release (levodopa/benserazide), D: Sinemet-Plus (carbidopa/levodopa), E: Sinemet (levodopa), F: Entacapone, G: Stalevo (carbidopa/levodopa/entacapone), H: Simvastatin, I: Pramipexole, J: Amantadine, K: Rasagiline, L: Atenolol, M: Selegiline.

Subject	M/F	Age	Years post-onset	Speech therapy	Medication (daily dosage)	ACE-R
HD01	M	40	3	No	A 1x16mg; K 1x10mg	99
HD02	F	55	11	LSVT in 2009	A 4x6mg; E 6xXmg	86
HD03	M	48	2	No	A 1x4mg	90
HD04	M	56	5	2008, LSVT in 2010	A 6x2mg; B 4x25/100mg; D 4x12.5/50mg; F 4x200mg	97
HD05	F	76	15	No	D 4x25/100mg	74
HD06	M	66	2	2009, 2010	E 3xXmg	79
HD07	M	76	13	2010	B 1x150mg; E 2x25mg; G 3x25/100/200mg; H 1x40mg; L 1x25mg	79
HD08	M	70	14	LSVT in 2009	A 5x6mg; G 6x25/100/200mg	88
HD09	M	54	16	LSVT in 2010	C 8x50/12.5mg; G 8-10x50/200/200mg	93
HD10	M	64	12	LSVT in 2010	A 3x7mg	98
HD11	M	75	7	2010	C 3x50/12.5mg; D 6x25/100mg	90
HD12	M	73	4	2007	B 1x50/200mg; D 6x25/100mg	88
HD13	M	78	6	No	B 3x25/100mg; C 2x100/25mg	89
HD14	F	75	6	2005-2011	A 3x8mg; B 1x50/200mg; E 3x62.5mg	80
HD15	M	75	7	No	C 2x100/25mg; D 3x25/100mg; I 3x0.7mg and 3x0.18mg	83
HD16	M	67	5	LSVT in 2010	A 3x4mg; B 1x50/200mg; D 3x25/100mg	86
HD17	M	60	8	LSVT in 2007, 2008	A 3x8mg; B 3x25/100mg; C 1x100/25mg; D 4x50/200mg; J 1x100mg; K 1x1mg	96
HD18	M	73	4	2010, 2011	G 3x37.5/150/200mg; H 2x40mg; I 3x0.125mg	74
HD19	M	74	8	LSVT in 2005	C 5x100/25mg	100
HD20	F	65	2	LSVT in 2010	D 4x25/100mg	98
HD21	M	71	18	2008, LSVT in 2011	C 5x100/25mg; J 1x100mg; M 1x10mg	96
HD22	M	62	22	LSVT in 2011	C 5x200/50mg; F 4x200mg; I 3x0.7mg	60
HD23	F	81	8	LSVT in 2006	C 4x100/25mg	80
Mean (SD)		66.8 (10.6)	8.6 (5.6)			87.1 (10.0)

the experiment. Some participants reported a mild age-related hearing loss, but were not prescribed hearing aids. Prior to data collection, however, it was established during a personal interview about the speakers' background that they had no obvious hearing problems or signs of impact on their speech. In addition, based on results reported in previous research, it was not expected that minor hearing loss would have led to speech production or communication-specific problems in a way that could have influenced experimental results (Dalton et al., 2003; Bowen et al., 2013; Stepp, 2013).

An overview of participant information of the group of age-matched control (AMC) speakers can be found in table 3.2.

TABLE 3.2: Participant information: age-matched control speakers. Shared membership of the older adult group is indicated by the alternative subject ID.

Subject	Gender	Age	ACE-R	Alternative subject ID
AMC01	M	45	93	
AMC02	F	41	100	
AMC03	F	50	95	
AMC04	M	41	90	
AMC05	M	48	97	
AMC06	F	48	100	
AMC07	F	41	98	
AMC08	M	73	99	OA01
AMC09	M	71	91	OA02
AMC10	F	71	94	OA03
AMC11	M	73	89	OA04
AMC12	M	62	99	OA05
AMC13	M	80	91	OA06
AMC14	M	75	94	OA07
AMC15	F	63	94	OA08
AMC16	M	73	97	OA09
AMC17	F	62	98	OA10
AMC18	M	66	100	OA11
AMC19	F	57	99	
AMC20	F	70	94	OA12
AMC21	M	66	93	OA13
AMC22	M	51	96	
AMC23	M	65	92	OA14
AMC24	M	50	97	
Mean (SD)		60.1 (12.3)	95.4 (3.4)	

Since the speakers of the AMC group were not completely matched in gender with the group of dysarthric speakers, the possible effect of gender was investigated in a selected representative proportion of the experimental data, and reported in section 3.7.2. The results of the gender comparison showed that differences in gender proportions between the two groups were limited, indicating that the speakers of this group were suitable for matching with the speakers of the clinical group.

3.3.7 Group 3: Young adult speakers

The third group of participants were sixteen young adults. Of the sixteen speakers, twelve were female and four of them were male. All speakers in the group of younger adults were younger than 40 years of age. Subjects ranged in age from 19 to 37 years (mean = 26.3 years, SD = 6.5 years). The participants were recruited as students of Strathclyde University or through acquaintances. All were native Scottish speakers, without a reported history of speech, language, hearing, or neurological disorders. Information regarding the assessment of selection criteria was obtained directly from the speakers during the recruitment phase and prior to conducting the study.

An overview of participant information of the group of young adult (YA) speakers can be found in table 3.3.

3.3.8 Group 4: Older adult speakers

The fourth group of participants were fourteen older adults, all of them aged 60 or above. Four speakers were female and ten were male. Subjects ranged in age from 62 to 80 years (mean = 69.3 years, SD = 5.4 years). All 14 speakers were sourced from the age-matched control group.

An overview of participant information of the group of older adult (OA) speakers can be found in table 3.4.

TABLE 3.3: Participant information: young adults.

Subject	Gender	Age	ACE-R
YA01	F	32	100
YA02	F	36	92
YA03	F	20	97
YA04	M	23	98
YA05	F	19	92
YA06	M	21	92
YA07	F	20	95
YA08	F	20	87
YA09	F	27	95
YA10	F	28	100
YA11	M	28	97
YA12	F	24	94
YA13	F	32	93
YA14	M	35	99
YA15	F	19	97
YA16	F	37	99
Mean (SD)		26.3 (6.5)	95.4 (3.6)

TABLE 3.4: Participant information: older adults.

Subject	Gender	Age	ACE-R
OA01	M	73	99
OA02	M	71	91
OA03	F	71	94
OA04	M	73	89
OA05	M	62	99
OA06	M	80	91
OA07	M	75	94
OA08	F	63	94
OA09	M	73	97
OA10	F	62	98
OA11	M	66	100
OA12	F	70	99
OA13	M	66	93
OA14	M	65	92
Mean (SD)		69.3 (5.4)	94.8 (3.8)

3.4 Materials

As indicated briefly above, a number of tasks and measures were undertaken in this study, i.e., the experimental tasks used to evaluate variability and background measures, as well as information collected to form a clinical picture of the participants with hypokinetic dysarthria. The following sections will provide more details on each of these.

3.4.1 Evaluation of cognitive status

A range of cognitive functions are known to be impaired in Parkinson's disease, of which the executive functions are the most prominent (Klepac, Hajnsek, & Trkulja, 2010; Parker, Lamichhane, Caetano, & Narayanan, 2013). As a decline in cognitive function may have an impact on speech production, it was important to establish the participants' cognitive state, and correlate this with information about their speech production. Within the limitations of the study, it was not possible to assess cognitive function in detail. Instead, the Addenbrooke's Cognitive Examination - Revised (ACE-R) was used for this purpose (Mioshi, Dawson, Mitchell, Arnold, & Hodges, 2006). The ACE-R contains 5 sub-scores, each one representing one cognitive domain: attention/orientation (18 points), memory (26 points), fluency (14 points), language (26 points), and visuospatial (16 points). The ACE-R maximum score is 100, composed by the addition of all domains, with higher scores indicating better cognitive functioning. The authors of the ACE-R define a cut-off score of 82/100, with scores below indicating cognitive impairment (Mioshi et al., 2006). However, in the current study, the ACE-R score was not used as a selection criterion. Although it is only a screening tool, it has been used extensively in speakers with Parkinson's disease, and has been found to be patient friendly, easy to apply, and to have an excellent diagnostic accuracy of detecting cognitive decline affecting speech and language skills (Larner, 2007; Robben et al., 2009; Reyes et al., 2009). It was therefore deemed appropriate to provide a general overview of the participants' cognitive state as required for this study.

In order to prevent recall from previous assessments, three versions of the ACE-R have been developed. The versions differ in the content of the name and address of the repetition task which is used to test memory abilities. In this study, version A was used throughout, unless participants indicated to be familiar with this assessment version. In these cases, version B was administered. The ACE-R test (version A) can be found in Appendix A.

3.4.2 Speech assessment tasks

A series of commonly used clinical speech assessment tasks was applied as experimental tasks in order to correlate these measures with variability of speech motor control in the clinical speaker group. The assessment tasks consisted of a series of diadochokinetic tasks, reading a short story, reading a list of unpredictable sentences, and engaging in a monologue. The diadochokinetic tasks were used to obtain maximum syllable repetition rates, variation in syllable duration and variation in peak vowel intensity. The short story and the monologue task were used to obtain intelligibility ratings by means of a Likert scale, and the unpredictable sentences were used to obtain a proportion of correctly identified words by means of a transcription task. An overview of the speech tasks and their measurements is displayed in table 3.5.

TABLE 3.5: Overview of speech assessment tasks.

Articulation and speech tasks	Measurement
Diadochokinetic tasks	Syllable repetition rate
	Variation in syllable duration
	Variation in peak vowel intensity
Reading passage	Intelligibility ratings using a 9-point Likert scale
Monologue	Intelligibility ratings using a 9-point Likert scale
Reading unpredictable sentences	Intelligibility ratings using percentage correctly identified words

3.4.2.1 Diadochokinetic tasks

Diadochokinetic (DDK) tasks are designed to measure articulation rate and regularity of syllable repetitions, and considered to be an indication of the severity of dysarthria (Ackermann et al., 1995; Tjaden & Watling, 2003; Duffy, 2013). In this task, alternating motion rates and sequential motion rates were analysed. Alternating motion rates (AMRs) were measured with the syllable repetition tasks /pʌ/, /tʌ/, and /kʌ/. Sequential motion rates (SMRs) were elicited with /pʌtʌkʌ/. The results of the diadochokinetic tasks were analysed for all speaker groups.

The participants were instructed as follows:

> Take a breath and repeat /pʌ/-/pʌ/-/pʌ/-/pʌ/ as fast and steadily as you can, until I give a signal that you can stop.

The instruction was followed by a 2-3 second example by the experimenter. The aim was to obtain at least 10 repetitions. Some of the speakers were unable to reach 10 repetitions. The participants were allowed three attempts, and the longest syllable repetition sequence was used for analysis.

3.4.2.2 Reading passage

To assess intelligibility in connected speech, a reading task was employed (Bunton et al., 2007; Van Nuffelen, De Bodt, Wuyts, & Van de Heyning, 2009). For the reading task, the 'My Grandfather' reading passage was used (Van Riper, 1963). This story has a length of 130 words, contains most English phonemes and consonant clusters, and is the most widely used in the assessment of people with dysarthria (Bunton et al., 2007; Duffy, 2013; Patel, Usher, Kember, Russell, & Laures-Gore, 2014). Therefore, normative acoustic and perceptual data for this passage are abundant. The 'My Grandfather' reading passage can be found in Appendix B.

The reading passage was printed on paper and given to the participants. The participants were allowed to read the passage in silence before reading it aloud, allowing them to get familiarized with the text. The participants read the passage aloud only once.

3.4.2.3 Reading unpredictable sentences

In addition to reading a standardized reading passage, a series of unpredictable sentences was read by all participants. The use of sentences with unpredictable content ensured that predictable elements of contextual information that facilitate comprehensibility, i.e., syntactic, semantic, and pragmatic cues were eliminated. From the perspective of perceptual assessment, rating intelligibility will be more accurate by removing these cues (Yorkston, Strand, & Kennedy, 1996; McHenry, 2011; Beijer, Clapham, & Rietveld, 2012).

McHenry and Parle (2006) developed a corpus of 50 sentences, each with a length of seven words. The sentences are grammatically correct but are semantically unusual or illogical, making the identity of upcoming words during reading unpredictable. The set of unpredictable sentences used for intelligibility testing in the current study was adopted from McHenry and Parle, 2006, and can be found in Appendix C. To minimize reading errors, the following words spelled in American English were changed to British English before presenting them to the participants: ‘flavored’ to ‘flavoured’ and ‘favorite’ to ‘favourite’.

A list of 10 unpredictable sentences was prepared for each participant. The sentences were randomly selected from the corpus of 50 sentences. The participants were instructed to read the sentences once. To prevent recall, participants were not allowed to read the sentences to themselves beforehand. Reading errors made by the participants were ignored.

3.4.2.4 Monologue

To investigate intelligibility of speech obtained from a more natural speech style, all participants engaged in a monologue (Preminger & Tasell, 1995; Tjaden, 2000; Tjaden & Wilding, 2011b). The participants were asked to talk about their experiences of a holiday they enjoyed in the past or to describe a future ideal holiday they would like to undertake. The following instruction was given:

> Can you say something about one of the following situations: Imagine you are having an unlimited amount of money to spend on a holiday. Where would you go, why would you go there, and what activities would you undertake there? Alternatively, can you talk about your experiences during a holiday you really enjoyed. Where did you go, what activities did you undertake, and why did you enjoy it so much?

It was ensured that for each participant, at least one minute of speech was recorded. When participants stopped talking before the required amount of speech was collected, they were prompted to elaborate more on one or more elements they had mentioned during their monologue.

3.4.3 Sentence repetition task

3.4.3.1 Introduction

To assess variability in speech, a sentence repetition task was devised. The application of the STI and FDA to acoustic data requires a continuous audio signal, without interruptions in voicing. In a large number of studies on speech variability, the STI has been calculated from lip movement data by using the sentence "Buy Bobby a puppy" (Smith et al., 1995; Kleinow et al., 2001; Sadagopan & Smith, 2008; Huber & Spruill, 2008, amongst many more). The bilabial closures in this sentence interrupt the voicing throughout the sentence, and is therefore unsuitable for acoustic variability analysis. Anderson et al. (2008) used the nonsense sentence "Well we'll will them" in their variability analysis to counter these problems. However, this sentence is limited in the number of different consonants and vowels used. To introduce movement and differences in formant frequency movements across the extracted contours, it is desirable to use different vowel-consonant combinations, ensuring variation in first and second formant excursions. Therefore, a new sentence was developed to fulfil the criteria of both sustained voicing and vowel variation.

3.4.3.2 Development of speech materials

A pilot study was carried out to develop and test the suitability of speech materials to be used in the sentence repetition task. The pilot study was designed for three purposes: (1) to develop a phrase that was suitable for the extraction of speech parameters from the acoustic signal, (2) to assess whether the selected phrase could be used in different speaking conditions, that is, whether rate changes or embedding would be problematic for the fluency and the perceived well-formedness of the phrase, and (3) to assess to what extent these different speaking conditions were able to induce differences in variability across a group of healthy young to middle-aged speakers.

Two experiments were carried out to fulfil the objectives of the pilot study. The first experiment was concerned with the selection of suitable speech material, and the second experiment was to evaluate the suitability of the selected speech materials to be used in a range of speaking conditions, as well as to evaluate the effect of varying speaking conditions on measures of variability.

To select suitable speech materials, eight sentences were created with different phonemic make-up and syllable count. See table 3.6 for an overview of the stimulus materials. The sentences were produced at habitual rate and fast rate in series of around 20 repetitions by a 32 years old female speaker of Scottish English. The data were recorded in a quiet room, using a wave recorder (Edirol R-09HR) connected to a head-mounted condenser microphone (AKG C420). Data were sampled at 44.1 kHz/16 bits. The head-mounted device allowed for a constant distance between the speaker's mouth and microphone during recording.

A preliminary qualitative perceptual evaluation was carried out to see to what extent the sentences contained possible problems with fluency or pronunciation. Based on this evaluation, sentences 1, 3, and 6 were used for further quantitative acoustic evaluation, which involved visual inspection using Praat version 5.2 (Boersma & Weenink, 2010) and Speech Filing System version 4.7 (Huckvale, 2010). The fundamental frequency contours were examined to estimate the number of discontinued phonations and miscalculations. In addition, the sentences were analysed perceptually, to estimate the occurrence of fluency breakdowns, hesitations and articulation errors. The results are summarized in table 3.7. In order to be able to compare the sentences, the average number of articulation errors, fundamental frequency breaks and miscalculations were summed and calculated for each sentence. The average number of errors across rate conditions were for sentence one: 14, sentence three: 31.5, and sentence six: 14. The number of errors relative to sentence length (5 syllables vs 9 syllables) were the lowest

TABLE 3.6: Initial test sentences for stimulus selection.

Stimuli	Words	Syllables	Morphemes
1. Two will win new wood	5	5	5
/tuː wɪl wɪn njuː wʊd/			
2. Then all men won one walnut	6	7	6
/ðen ɔːl men wʌn wʌn wɔːl.nʌt/			
3. The nanny will yell in Leeds	6	7	6
/ðə næn.i wɪl jel ɪn lidz/			
4. But none knew you yawned	5	5	6
/bʌt nʌn njuː ju jɔːnd/			
5. Paul will lean on my neon light	7	8	7
/pɔːl wɪl lɪːn ɒn maɪ niː.ɒn laɪt/			
6. Tony knew you were lying in bed	7	9	8
/təʊ.ni njuː ju wɜːʳ laɪ.ɪŋ ɪn bed/			
7. Donna won money in Miami Beach	6	10	6
/dɒn.ə wʌn mʌn.i ɪn maɪ.æm.i biːʧ/			
8. The mailman in Alloa won my land	7	8	10
/ðə meɪl.mæn ɪn æl.əʊ.ɑ wʌn maɪ lænd/			

in sentence six: "Tony knew you were lying in bed", and this phrase was therefore used in subsequent analyses.

3.4.3.3 Selection and testing of speaking conditions

The objective of the second experiment in the pilot study was to evaluate the suitability of the selected speech materials to be used in a range of speaking conditions, and to evaluate the effect of varying speaking conditions on measures of variability in a group of young to middle aged healthy adult speakers. Specifically, it was investigated whether the selected phrase could be used in different speaking conditions. Firstly, the effects of rate changes and embedding on fluency and perceived well-formedness of the phrase were evaluated. Secondly, it was investigated to what extent these different speaking conditions were able to induce differences in

TABLE 3.7: Number of errors in three test sentences.

Sentence	Speaking rate	Articulation errors	F0 breaks	F0 miscalculations	Total
1	Hab	3	4	9	16
	Fast	4	3	5	12
				Average	14
3	Hab	15	17	16	48
	Fast	6	2	7	15
				Average	31.5
6	Hab	2	9	7	18
	Fast	1	7	2	10
				Average	14

variability across a group of healthy young to middle-aged speakers.

Speaking conditions

The phrase "Tony knew you were lying in bed" was used in six different experimental conditions. The speaking conditions are listed in table 3.8 and discussed in detail below.

In the first speaking condition, the sentence was repeated at habitual speech rate. This sentence was used as a baseline to be compared to the other conditions. The speakers were instructed to repeat the sentence at their self-chosen comfortable speech rate and normal loudness.

To assess the effect of speech rate changes on variability, a fast speech rate condition was introduced, following Smith et al. (1995), Wohlert and Smith (1998), Kleinow et al. (2001), McHenry (2003, 2004), and Anderson et al. (2008). The participants were instructed to repeat the baseline sentence twice as fast as their habitual speech rate.

Additionally, a slow rate condition as introduced, following Smith et al. (1995), Wohlert and Smith (1998), Kleinow et al. (2001), McHenry (2003), and Mefferd and Green (2010). The participants were instructed to repeat the baseline sentence half as fast as their habitual rate.

To assess the effects of sentence length and increased syntactic complexity on variability, two utterance conditions were developed, in line with Kleinow and Smith (2000), Maner et al. (2000), Dromey and Bates (2005), and Sadagopan and Smith (2008). To increase sentence length without increasing syntactic complexity, the baseline sentence was modified by adding cardinal numerals. The following sentence was used: "One two three Tony knew you were lying in bed five six seven".

To increase sentence length and syntactic complexity, a dependent clause and an adverbial phrase were added to the baseline sentence: "I heard that Tony knew you were lying in bed this Sunday morning". Participants were instructed to repeat these sentences at their habitual rate.

To investigate the effect of concurrent motor tasks on variability, a dual task was devised involving tracing spirals (Dromey, 2003; Dromey & Bates, 2005; Dromey & Shim, 2008). The spiral drawing task allowed participants to execute a continuous dual task along the speech task to assess the additional cognitive effect of a manual motor task on speech variability (Dromey, 2003). In the dual task, participants were instructed to repeat the utterance at their normal speech rate, while at the same time using a regular pen to trace the line of an Archimedean spiral. The spirals were printed on a A4-size paper, with a maximum outside diameter of 80 mm. Participants were instructed to start at the center point of the spiral, tracing the line until the outer end, and then trace it back towards the center at a self-paced velocity and as accurately as possible. When finished with one spiral, participants continued with the next spiral, until the desired number of sentence repetitions was obtained.

TABLE 3.8: Six speaking conditions used in sentence repetition task.

Condition	Stimulus	Speech rate
Habitual	Tony knew you were lying in bed	Habitual
Fast	Tony knew you were lying in bed	Twice habitual
Slow	Tony knew you were lying in bed	Half habitual
Increased length	One two three Tony knew you were lying in bed five six seven	Habitual
Increased complexity	I heard that Tony knew you were lying in bed this Sunday morning	Habitual
Dual task	Tony knew you were lying in bed	Habitual

Speakers

Seventeen speakers participated in this pilot study. The speakers were recruited in the Faculty of Education of the University of Strathclyde, after permission for the study was granted by the Departmental Ethics Committee of the University of Strathclyde. The seventeen speakers ranged in age from 18 to 45 years (mean = 27.2 years, SD = 8.6 years), and four of them were male and thirteen of them were female. All were native Scottish speakers, without a reported history of speech, language, hearing, or neurological disorders.

Data collection

The participants' voices were recorded in the speech laboratory of the Speech and Language Therapy department. Audio recordings were taken using a wave recorder (Edirol R-09HR) connected to a head-mounted condenser microphone (AKG C420). The data recorder supplied phantom power to the microphone. Data were sampled at 44.1 kHz at 16 bits. The head-mounted device allowed for a constant distance between the speaker's mouth and microphone, eliminating any distance-related variation in amplitude during the recording. This ensured that amplitude was as constant as possible within and between speech conditions in the sentence repetition task, allowing a direct comparison between sentence repetitions and speaking conditions. The microphone to mouth distance was approximately 4 cm.

Each recording session lasted approximately 20 minutes. Each session was started with a short interview to obtain background information of the speakers including their age, gender, and their history of speech or hearing problems. The data collection of the sentence repetition task always started with the repetition of the baseline sentence, i.e., the Habitual Rate task. The remaining speaking conditions were recorded in randomized order. The participants were instructed to repeat the baseline sentence, the sentence with Increased Length, the sentence with Increased Complexity, and the Dual task sentence at their habitual speech rate. In the Fast Rate task, participants were asked to repeat the sentence at double their habitual rate, and in the Slow Rate task speakers were ask to repeat the sentence at half their habitual rate. During the Dual task, participants were instructed to repeat the utterance at their normal speech rate, while at the same time using a regular pen to trace the line of an Archimedean spiral. The spirals were printed on a A4-size paper, with a maximum outside diameter of 80 mm. Participants were instructed to start at the center point of the spiral, tracing the line until the outer end, and then trace it back towards the center at a self-paced velocity and as accurately as possible. When finished with one spiral, participants continued with the next spiral, until the desired number of sentence repetitions was obtained. The number of repetitions was monitored by the experimenter, ensuring that at least 20 reasonably fluent and uninterrupted repetitions were recorded per speaking condition.

Participants were instructed to try to keep their intonation and loudness characteristics as similar as possible throughout the sentence repetition. To ensure continuous voicing throughout each of the target sentences and the execution of uniform pacing strategies, participants were instructed to try to avoid pauses, but instead ‘stretch the words’ as much as possible. This was demonstrated by the experimenter. The sentence repetition task was practised beforehand, paying to mastering continuous voicing. Three sentences made up with words containing only sonorants were used to practice sentence repetition in slow rate, habitual rate, and fast rate conditions. The sentences used for practice were “Two will win new wood”, “The nanny will yell in Leeds” and “The mailman in Alloa knew my land”.

Data analysis

The spatiotemporal index and temporal and spatial variability were calculated for speech parameters sound pressure level (SPL), fundamental frequency (F0), first formant frequency (F1) and second formant frequency (F2), following the methodology outlined in section 3.6.3, with the following notable changes.

Around 20 phrases were selected and annotated for each speaking condition, ensuring that each phrase did not contain any obvious disfluencies based on the spectrogram. There was no a-priori data selection based on the quality of the contours of the four speech parameters, i.e., all annotated phrases were used for variability analyses, regardless of fundamental frequency / formant frequency interruptions or miscalculations that may have appeared in the contours.

Sentence durations were explored by means of a one-way ANOVA with duration (in seconds) as dependent variable and speaking condition as independent variable. The equality of variances was tested by Levene's test. A significance level of $p < .05$ was maintained. The variability results were analysed by means of a series of univariate ANOVAs with the spatiotemporal index, spatial variability and temporal variability as dependent variables, and speaking condition and speech parameter as fixed factors. With respect to factor speech parameter, no direct comparisons were made amongst them. The reported results were pooled over all speech speech parameters. When exploring post-hoc effects, the Bonferroni correction was applied to compensate for multiple comparisons.

Results

Group averages and standard deviations of the measures sentence duration, spatiotemporal index, spatial variability, and temporal variability are displayed in table 3.9.

The results are explored further below, separately by outcome measure.

Sentence durations:

The sentence durations of the six speaking conditions in the pilot study are displayed in Figure 3.1 and Appendix E.

The statistical analysis across the six speaking conditions showed the following results. Variances across speaking conditions were not homogeneous: $F(5, 96) = 7.76$, $p < .001$, and Tamhane's T2 test was applied to correct for multiple comparisons that do not assume equal variances. A main effect of speaking condition was significant: $F(5, 101) = 18.04$, $p < .001$. Post-hoc analysis showed longer durations for the Habitual Rate condition compared to the

TABLE 3.9: Group averages and standard deviations of variability measures in pilot experiment.

Measure	Slow	Habitual	Fast	IL	IC	Dual
Dur	2.21 (0.89)	1.35 (0.20)	1.10 (0.15)	1.19 (0.17)	1.23 (0.15)	1.33 (0.14)
STI - SPL	26.92 (4.07)	20.82 (4.61)	20.30 (4.93)	22.55 (4.97)	24.99 (6.22)	20.76 (4.35)
STI - F0	21.43 (7.25)	13.90 (5.24)	14.45 (4.86)	17.44 (6.49)	20.85 (5.42)	15.93 (7.34)
STI - F1	31.20 (5.51)	25.31 (6.41)	24.44 (6.45)	25.01 (6.02)	27.31 (6.06)	26.98 (5.11)
STI - F2	31.87 (5.98)	28.91 (6.59)	31.07 (7.05)	28.26 (8.21)	29.50 (7.79)	29.44 (6.66)
SV - SPL	0.390 (0.067)	0.328 (0.062)	0.320 (0.075)	0.359 (0.077)	0.391 (0.100)	0.333 (0.070)
SV - F0	0.333 (0.118)	0.220 (0.081)	0.222 (0.075)	0.285 (0.117)	0.326 (0.099)	0.247 (0.117)
SV - F1	0.486 (0.126)	0.377 (0.124)	0.350 (0.121)	0.358 (0.117)	0.414 (0.127)	0.412 (0.096)
SV - F2	0.504 (0.105)	0.445 (0.113)	0.500 (0.158)	0.447 (0.165)	0.449 (0.160)	0.459 (0.139)
TV - SPL	0.0216 (0.0068)	0.0176 (0.0059)	0.0190 (0.0042)	0.0187 (0.0057)	0.0190 (0.0054)	0.0193 (0.0052)
TV - F0	0.0266 (0.0072)	0.0218 (0.0092)	0.0276 (0.0104)	0.0289 (0.0132)	0.0296 (0.0098)	0.0269 (0.0132)
TV - F1	0.0240 (0.0072)	0.0255 (0.0105)	0.0252 (0.0079)	0.0239 (0.0090)	0.0265 (0.0078)	0.0299 (0.0095)
TV - F2	0.0253 (0.0076)	0.0249 (0.0063)	0.0317 (0.0093)	0.0275 (0.0086)	0.0309 (0.0145)	0.0279 (0.0066)

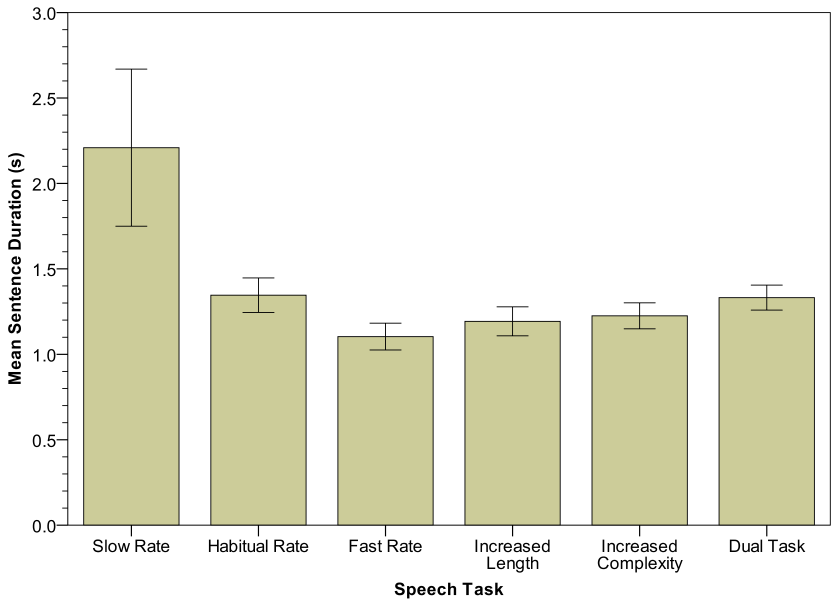

FIGURE 3.1: Sentence durations of the six speaking conditions in the pilot study.

Fast Rate condition (p = .017), and shorter durations compared to the Slow Rate condition (p = .005). Durations in the Slow Rate conditions were longer compared to all other conditions: Fast Rate (p = .002), Increased Length (p = .004), Increased Complexity (p = .005), and Dual task (p = .014). Finally, durations in the Dual task condition were longer compared to the Fast Rate (p = .001).

The variability results are discussed below, separately for each variability measure and displayed in Figure 3.2

The spatiotemporal index:

Raw data for the spatiotemporal index are displayed in Appendix F. The spatiotemporal index showed a significant main effect of speaking condition: $F(5, 384) = 8.70$, $p < .001$. The post-hoc analysis of the speaking conditions showed that pooled over speech parameters, compared to the Habitual condition, variability was higher in the Slow Rate condition ($p < .001$) and in the Increased Complexity condition ($p = .016$). Variability in the Slow Rate condition was also higher compared to the Fast Rate, Increased Length, and Dual task conditions (all $p < .001$). Finally, variability in the Increased Complexity condition was higher compared to the Fast Rate condition ($p = .047$).

Spatial variability:

Raw data of spatial variability values are listed in Appendix G. The spatial variability results largely followed those of the STI, with a significant main effect of speaking condition: $F(5, 384) = 5.74$, $p < .001$. The post-hoc analysis of the speaking conditions showed that variability was higher in the Slow Rate condition compared to the Habitual condition ($p < .001$), the Fast Rate condition ($p = .001$), the Increased Length condition ($p = .010$), and the Dual task condition ($p = .011$). Further comparisons were non-significant.

Temporal variability:

The temporal variability data are displayed in Appendix H. The main effect of speaking condition was non-significant: $F(5, 384)$, $= 1.93$ $p = .087$, and the post-hoc analysis did not show significant differences between speaking conditions.

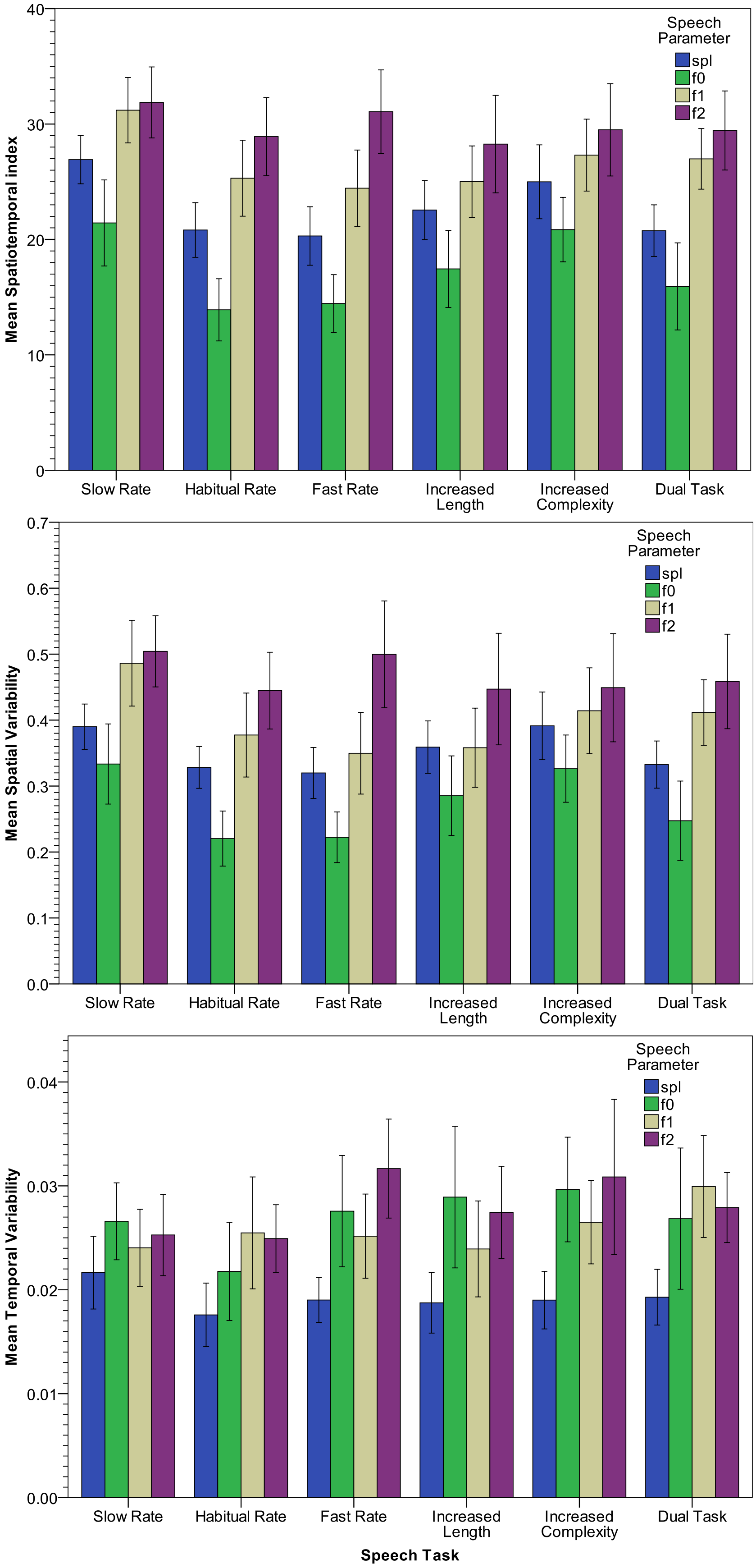

FIGURE 3.2: Variability results of the six speaking conditions in the pilot study.

Discussion

When assessing the mean durations of the phrases used in the pilot study, it was found that participants were able to increase and decrease their speech rate when asked to do so, as evidenced by significantly slower articulation rates in the slow rate condition and significantly faster articulation rates in the Fast Rate condition, as compared to the Habitual Rate condition. These results reflect other studies employing sentence repetition tasks at varying rate Smith et al. (1995), Wohlert and Smith (1998).

The general trends of the variability results are discussed by considering the results pooled over the four speech parameters. It was found that the spatiotemporal index and spatial variability estimator showed differences across the six speaking conditions. Differences usually involved the Slow Rate condition, with a higher spatiotemporal and higher spatial variability values compared to all other conditions. Furthermore, differences between the baseline condition and Increased Complexity were observed. For temporal variability, no significant differences between speaking conditions were found.

Another purpose of this pilot study was to assess whether the test sentence could be used in a variety of speaking conditions, and fluency and perceived well-formedness of the phrase would not be affected. Based on speakers' feedback and the perceptual and visual inspection of the recordings, it was found that these sentence conditions were suitable to use in further experimentation. Based on the findings of the variability results and the successful application of the phrases in different contexts, it was decided to include all tested speaking conditions.

In conclusion, the results of the pilot study showed that the speaking conditions were in general suitable to be used in the main study, as well-formedness and fluency were found to be adequate. In addition, the results of the participants in the pilot group yielded significant differences between the tested speaking conditions. Therefore it was decided to include all six speaking conditions. However, the pilot study also revealed obstacles with respect to obtaining reliable contours. A complication encountered in this pilot study was the occurrence of fundamental frequency breaks. These breaks were predominantly present in the slow speech rate condition, where voicing was interrupted. These interruptions in the fundamental frequency contours were interpolated by the acoustic processing software, in which unvoiced gaps were joined with a simple, straight line, possible affecting variability calculations. Breaks in voicing also affects the calculation of formant frequency contours. Visual inspection of the first and second formant contours revealed the presence of formant frequency miscalculations and jumps around unvoiced regions, with the second formant contours especially affected. Section 3.6.3.2 addresses how this problem was dealt with in the main study.

3.4.3.4 General instructions for the main study

The methodology of data collection of sentence repetitions in the main study was largely similar to the methodology used in the second experiment of the pilot study, described in section 3.4.3.3. Notable differences between the methodology of the pilot study and the main study were the following.

The breaks in voicing encountered in the pilot study were addressed by giving speakers explicit instructions with respect to pacing their speech, and by dedicating more time to train avoiding pauses and stretching words, until the experimenter deemed the participant to be able to carry out the repetition task and the pacing instructions.

During the Dual task, the participants were instructed to trace an Archimedean spiral using a stylus pen on an electronic tablet while repeating the baseline sentence at habitual speech rate. The spiral was slightly larger than the one used in the pilot study, with a maximum outside diameter of 100 mm, and involved four complete cycles with an incremental distance of 14 mm in diameter between turns. The spiral template was printed on A4-sized paper and centered on an electronic drawing tablet. A template of the spiral used in the spirography task can be found in Appendix D. The spiral line was traced from the center of the template outwards, in anti-clockwise directions. The tablet was turned 180 degrees for left-handed participants. Participants were allowed to rest their hand on the tablet, but were not allowed to support or hold their writing hand with the other hand. The start of each recording was paced by an electronic double beep generated by a computer connected to the electronic tablet. Participants were instructed to trace the spiral as accurate as possible, while maintaining a reasonable speed of drawing. Upon finishing one spiral, the participants immediately started drawing a consecutive spiral.

In the unlikely case where participants inserted a long pause (≥ ~10 seconds) between sentences during the repetition of one series, only sentences in the part before the pause were selected for further analysis, as the long pause might have initiated a stabilizing recovery occurrence. If the number of obtained repetitions were not sufficient, participants were asked to execute the speech task again.

The number of repetitions was monitored by the experimenter, ensuring that at least 20 reasonably fluent and uninterrupted repetitions were recorded per speaking condition. One speaker in the HD group (speaker HD05) was unable to complete the Dual task due to severe hand motor movement problems.

3.5 Data collection

3.5.1 Introduction

Each recording session lasted approximately 60 to 90 minutes. Each session was started with an interview to obtain background information of the speaker. In the case of participants with a speech disorder, information was also gathered concerning their disease history, disease progress, medication, and details of previous and current speech and language therapy details. The session was continued with the ACE-R test. Then, the speech assessment tasks were administered in the order: diadochokinetic tasks, reading of the 'My Grandfather' passage, reading of the unpredictable sentences, and the contextual speech task. The session was continued with the sentence repetition task, which was started with the baseline sentence and followed by the remaining speaking conditions administered in random order. The speaking conditions of the sentence repetition task are listed in table 3.8. Audio recordings were taken throughout the recording session.

3.5.2 Location

The participants were recorded in a quiet room on different locations. All participants of the younger adult control group and some participants of the older adult control group were recorded at the University campus. All other older adults from the control group were recorded at their homes. The participants with dysarthria were either recorded at the University campus, at their homes, in their out-patient clinic, or in an associated support group building.

3.5.3 Equipment

Audio recordings were taken using a wave recorder (Edirol R-09HR) connected to a head-mounted condenser microphone (AKG C420). The data recorder supplied phantom power to the microphone. Data were sampled at 44.1 kHz at 16 bits. The head-mounted device allowed for a constant distance between the speaker's mouth and microphone, eliminating any distance-related variation in amplitude during the recording. This ensured that amplitude was constant within and between speech conditions in the sentence repetition task, allowing a direct comparison between sentence repetitions and speaking conditions. The microphone to mouth distance was approximately 4 cm.

3.6 Data analysis

This section describes the analyses of the diadochokinetic tasks, the analyses of the intelligibility assessment tasks, and the analyses of the sentence repetition tasks, and finishes with a description of the methodology of the statistical analyses.

3.6.1 Diadochokinetic tasks

The acoustic analyses of the DDK tasks were performed with Praat 5.2 (Boersma & Weenink, 2010). A series of analyses were performed, with the aim to correlate the results with the variability measures. The following analyses were performed:

- Mean syllable repetition rate (syllables per second)
- Syllable duration variability (Coefficient of Variation of syllable duration)
- Peak intensity variability (Coefficient of Variation of peak intensity)

Syllable repetition rate was calculated by measuring the timed interval between two successive vowel off-sets, based on information in the oscillogram and spectrogram displayed in Praat. An example of the analysis of the DDK task of syllable /pʌ/ produced by a speaker with Parkinson's disease is displayed in Figure 3.3. The variation of syllable duration was calculated by dividing the standard deviation (SD) of mean syllable duration by the mean syllable duration, yielding a Coefficient of Variation (CoV), expressed as a percentage. The Coefficient of Variation is a relative measure of dispersion that enables the comparison of measurements with a wide spread of means across groups and tasks, and as such preferred to the standard deviation.

The peak intensity was measured at the highest intensity region of each vowel. Variation in maximum intensity was calculated by dividing the SD of mean maximum intensity by the mean maximum intensity, yielding a CoV expressed as a percentage. For task /pʌtʌkʌ/, the single highest vowel intensity of one complete repetition was used.

The first syllable of each repetition task was discarded, as it has been found that speakers often produce these at a longer duration and higher amplitude than the succeeding syllables. The last syllable in a repetition task is usually longer due to final lengthening, and was also discarded (Ackermann et al., 1995).

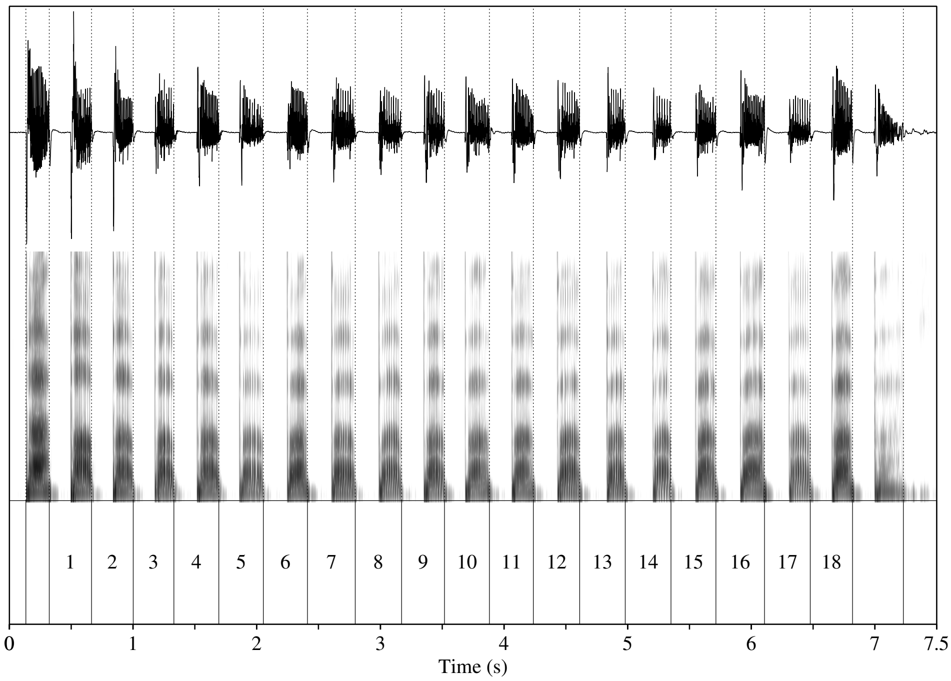

FIGURE 3.3: Example of syllable duration analysis of a DDK task in Praat. Upper panel: oscillogram. Middle panel: spectrogram. Lower panel: annotation grid with numbered syllables.

3.6.2 Intelligibility ratings

3.6.2.1 Introduction

A series of listening experiments was designed to obtain intelligibility ratings of the speakers with hypokinetic dysarthria, with the purpose to correlate these outcome measures with the variability measures. As intelligibility ratings in unimpaired speakers under optimal speaking conditions and listening conditions have generally been reported to level off towards maximum scores (Markham & Hazan, 2004; Volberg, Kulka, Sust, & Lazarus, 2006), it can be expected that listeners in the experiments perform near ceiling level for the groups of unimpaired speakers. When correlated with measures of variability, such typical high intelligibility ratings can be expected to result in a null effect (Hammen et al., 1994; Ferguson, 2004). It was therefore decided to not include material of unimpaired speakers in the listening experiments. In addition, including participants with dysarthria only kept the intelligibility experiments at a reasonable length while being able to obtain a sufficient number of observations.

The listening experiments involved the orthographic transcription of the unpredictable sentences, the intelligibility scaling of fragments of the reading passage, and the intelligibility scaling of fragments of a monologue fragment.

3.6.2.2 Listeners

Fifteen native Scottish listeners participated in the listening experiments. None of the listeners reported a history of hearing, speech, or language problems. Thirteen listeners were female and two were male. Listeners ranged in age from 22 to 29 years (mean = 22.7 years, SD = 3.0 years). They were recruited as undergraduate Speech and Language Therapy students in the University of Strathclyde. The students were unconnected to the study, but had some experience in listening to disordered speech. All listeners had completed a course about dysarthria, but none had extensive experience with this speaker group in everyday life. The relatively inexperienced listeners were chosen instead of professional speech therapists, as a familiarity with dysarthric speech might overestimate intelligibility scores (Beukelman & Yorkston, 1980), possibly reducing the range of intelligibility ratings.

3.6.2.3 Presentation of stimuli

During the intelligibility assessment, the listeners were seated in a quiet room. The participants used a laptop and enclosing headphones, and the experiments were designed and executed in Praat.

In the transcription experiment, a series of unpredictable sentences was presented which were recorded as part of the speech and language assessment tests. The stimuli were binaurally presented to the listeners in randomized order. All sentences were converted to a peak intensity of 75 dB to ensure a roughly equal and comfortable loudness level. The listeners were instructed to orthographically transcribe the sentences on paper. They heard each sentence only once.

Since all sentences were only seven words long, listeners were able to remember and transcribe the sentences without repeated listening. The experiment was self-paced; i.e., speakers pushed a button after finishing transcription of a sentence, to be presented with the next sentence. The stimuli consisted of the unpredictable sentences recorded with the 23 speakers from the hypokinetic dysarthric group. Every speaker produced ten sentences, yielding a total of 230 sentences. All fifteen listeners were presented with a pseudo-random selection of 70 sentences from the pool of 230 sentences, ensuring that each stimulus was transcribed at least three times.

In the intelligibility scaling experiment listeners were presented with a fragment of the reading passage and a short fragment of the monologue task, produced by the 23 speakers with dysarthria. The fragments of the reading task were presented first, followed by the monologue speech fragments.

Of the reading passage (see Appendix B), sentence three to six were used:

> "A long, flowing beard clings to his chin, giving those who observe him a pronounced feeling of the utmost respect. When he speaks, his voice is just a bit cracked and quivers a trifle. Twice each day he plays skilfully and with zest upon our small organ. Except in the winter when the ooze or snow or ice prevents, he slowly takes a short walk in the open air each day."

Of the monologue task, representative fragments with a length of around 30 seconds were used.

A scaling experiment was designed to obtain intelligibility scores, following Zyski and Weisiger (1987), Folker et al. (2010). The stimuli were binaurally presented in randomized order over headphones. All sentences were converted to a peak intensity of 75 dB to ensure a roughly equal and comfortable loudness level. Intelligibility scores were obtained from both the reading task and the spontaneous speech task. The listeners were seated in a quiet room, and the audio signal was presented binaurally by enclosing headphones at a comfortable loudness level. After presentation of a stimulus, listeners had to indicate the level of intelligibility and listener effort using a nine-point Likert scale (Dobinson, 2007) that has proven to be successful in assessing intelligibility in monologue speech of patients with Parkinson's disease (Lowit, Dobinson, Timmins, Howell, & Kröger, 2010). The Likert scale ratings are detailed in table 3.10. All stimuli were presented once. Listeners were encouraged to use the whole scale while making their judgements.

TABLE 3.10: Nine-point scale used for rating intelligibility and listener effort, c.f. Dobinson (2007).

Intelligibility	Effort	Rating
Able to fully understand what the person was telling you	Easy	9
	Pay a little attention	8
Able to fully understand what the person was telling you, but had to take extra care in listening	Listen carefully	7
	Concentrate hard	6
Able to understand part of what the person was telling you	Nearly all (75% or more)	5
	Most (over 50%)	4
	Not much	3
Able to understand some individual words, but unable to understand what the person was telling you		2
Able to understand nothing at all		1

3.6.2.4 Calculating intelligibility scores

The mean number of correctly transcribed words per stimulus was calculated for each speaker to obtain a measure of intelligibility (Yorkston & Beukelman, 1978; Hustad, 2008; Tjaden & Wilding, 2011b). The intelligibility scores were obtained by calculating the mean percentage of words transcribed correctly for each speaker. The transcriptions of each listener were scored by marking the number of correctly identified words. A word was identified as being correct when there was an exact phonemic match to the corresponding word in the target utterance. In situations where possible orthographic errors resulted in a lexical item distinct from the target word, the answer was marked as incorrect. Each correct word earned one point. For each sentence, seven points were possible, one for each target word. The total number of correctly identified words was divided by the total number of words possible, and multiplied by 100 to yield the percentage of words identified correctly for each speaker (Neel, 2009).

Mean intelligibility scores were obtained for each speaker and used for further statistical analysis (Hustad, 2007; Hustad, Dardis, & Kramper, 2011).

3.6.3 Variability analysis

3.6.3.1 Annotation of sentence repetitions

The digital audio recordings were first processed in Speech Filing System (SFS) version 4.7 (Huckvale, 2010).

The sound pressure level (SPL) envelopes, fundamental frequency (F0) envelopes, first formant (F1) envelopes, and second formant (F2) envelopes were extracted. The start and end of the voiced parts of each repetition were marked in the oscillogram. The beginning of the phrase "Tony knew you were lying in bed" was marked at the onset of /o/, at the point where voicing started, based on information in the oscillogram calculated by SFS. The end of the phrase was marked at the endpoint of the nasal preceding the onset of /b/. Phrase durations were defined as the time between the marked onsets and offsets. To evaluate whether speakers decreased or increased their rate of speech in the different speech tasks relative to the Habitual Rate condition, the percentage change from Habitual rate was calculated for each speaker by: $\frac{duration\ habitual\ rate\ -\ duration\ speech\ task}{duration\ habitual\ rate}\ x\ 100$.

An example of annotation in SFS is displayed in Figure 3.4. The upper panel shows the oscillogram of the utterance "Tony knew you were lying in bed" articulated by speaker HD01 in the Fast Rate condition. The second panel shows the sound pressure level contour. The third panel shows the original formant tracks for F1-F5. The fourth panel displays the annotation grid, with start marks and end marks indicated. The fifth and sixth panel display the corrected first and second formant contours (see section 3.6.3.3 for details on contour corrections), and the seventh panel displays the smoothed fundamental frequency contour.

3.6.3.2 Selecting and optimizing acoustic contours

The pilot study revealed obstacles with respect to obtaining reliable contours of speech parameters. Complications were encountered with fundamental frequency contours, where slow rate conditions in particular resulted in contour breaks, which were crudely interpolated. Breaks in voicing also affected the calculation of formant frequency contours. Visual inspection of

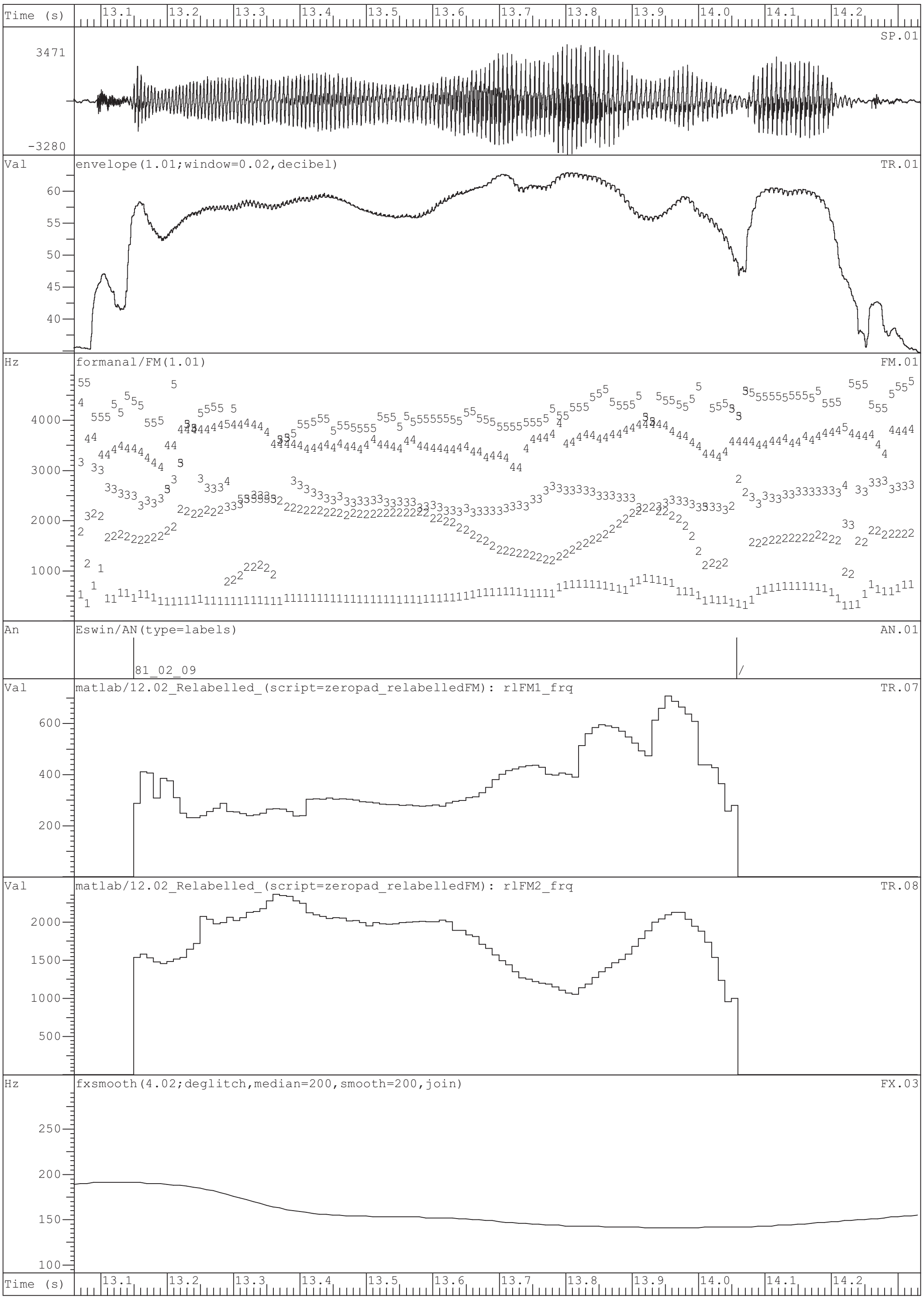

Figure 3.4: Annotation in Speech Filing System. One repetition of "Tony knew you were lying in bed" articulated by speaker HD01 in the Fast Rate condition. Panel 1: oscillogram, panel 2: sound pressure level contour, panel 3: original formant tracks F1-F5, panel 4: annotation grid, panel 5: corrected first formant contour, panel 6: corrected second formant contour, panel 7: smoothed fundamental frequency contour.

the first and second formant contours revealed the presence of formant frequency miscalculations and jumps around unvoiced regions, with the second formant contours especially affected.

Three steps were undertaken to optimize the accuracy of contour estimation across the four speaker groups, the six speaking conditions, and the four speech parameters:

- The quality of the contours were improved through the optimisation of smoothing, interpolation, and stabilisation parameters in Speech Filing System. Specifics of these optimizations are detailed in section 3.6.3.3, separately for each speech parameter.
- After optimisation, all annotated contours were visually inspected for interruptions, miscalculations and other systemic artifacts. Contours with visible miscalculations, pauses, and sudden and unnatural jumps were manually excluded from further analysis. In order to perform accurate analyses of variability, a requirement of a minimum of 10 valid phrase repetitions per trial was maintained, c.f., Nip and Blumenfeld (2015). Trials with less than 10 viable contours were excluded from further analysis. Characteristics of acoustic contours and associated measurement challenges are detailed in section 3.6.3.4.
- In the third step, prior to the actual variability analyses, the contours that were included in further analysis were resampled, filtered, and normalised. The filtering function removed individual spikes left in contours after selection. Details of the filtering step can be found in section 3.6.3.6.

Visualised examples of the three optimisation steps for each of the four parameters are displayed in section 3.6.3.5.

3.6.3.3 Optimizing acoustic contours

Sound Pressure Level

The sound pressure level contours were generally extracted and calculated in a reliable manner. The envelope program within Speech Filing System produced a smoothed amplitude envelope of a speech pressure waveform. The envelope is calculated from the sum-squared sample values in a given time window and represented in dB. Processing parameters may be varied between rectangular (default) and hamming smoothing window, as well as the window width. Experimentation with different processing parameters yielded negligible differences between smoothing techniques. Window sizes between 1 ms and 50 ms produced the most sensitive contours, with largely inconsequential differences within this range. The rectangular window with a width of 20 ms was used in further experimentation.

Fundamental Frequency

Reliable extraction of contours of fundamental frequency was often hampered by disfluencies and devoicing events, resulting in interruptions and frequency jumps (either half or double the correct frequency). Speech Filing System provides a number of techniques to smooth a fundamental frequency contour, including an interpolation function that joins up the voice regions to obtain a continuous curve; a de-glitch algorithm to remove sudden jumps in the contour; a median smoother that replaces each F0 value by the median of the values found in a window symmetrically placed around the sample; and a linear smoother that applies a raised cosine window symmetrically around each voiced value. The interpolation and deglitch functions were used throughout all analyses. Experimentation with different window sizes for the smoothing algorithms indicated optimal window widths of 200 ms for both the median smoothing and linear smoothing options on contours with varying phrase lengths, and these parameter settings were used in further experimentation.

Formant Frequencies

The extraction of first formant and second formant frequency contours was complicated by miscalculations of the formant tracker. Formant contours were misplaced and confused when spectral energy bands were close together. This may happen in back vowels where F1 and F2 are close together, or in high front vowels where F2 and F3 are close together. In order to decrease the number of miscalculations, computational steps were applied to stabilise the calculation of formant contours. The contours were reassigned and corrected within the annotated regions by iterative calculation of the mean formant frequencies and velocities until the means stabilised. Remaining slim spikes in formant contours were ignored as they were removed during further normalising and filtering steps in the process of calculating variability.

3.6.3.4 Overview of eligible contours in repetition tasks

After the optimization steps, all annotated contours were visually inspected on interruptions, miscalculations and other systemic artifacts across the four speaker groups, the six speaking conditions and the four speech parameters. All contours with obvious pauses, and miscalculations in fundamental frequency, first formant frequency and second formant frequency were discarded. A few aberrant sound pressure level contours were present after optimising, and related to the presence of pauses in the phrases which went unnoticed during the annotation process. With respect to fundamental frequency it was found that despite the application of extensive smoothing steps, a small number of contours still contained irregularities. With respect to first formant and second formant contours, a substantial number of contours showed miscalculations and jumps between energy bands, and these were especially present in second formant contours.

Table 3.11 lists the number of eligible speakers for each group, split by speech parameters and speaking condition, along with the average number of phrase repetitions for each speaker used for analysis. Recall that repetition tasks eligible for further variability analysis were those with at least 10 repetitions, and that one speaker in the HD group was unable to complete the Dual task, and associated data was absent (see section 3.4.3.4 for further details). The overview shows that extraction of contours of sound pressure level and fundamental frequency contours was usually performed correctly, irrespective of speaker group or speaking condition. The number of eligible repetition tasks involving first formant frequency contours was on average somewhat lower, especially in the slow rate conditions. Furthermore, the average number of eligible contours for each task was lower compared to these of SPL and F0. However, in view of comparing groups, at least 10 eligible speakers per group were available for first formant variability analyses. Substantial problems were encountered for second formant contours, where a large portion of the data had to be discarded. This became most apparent in the smaller YA and OA groups, possibly impacting on statistical power when making comparisons between them. However, participant numbers were still in line with earlier studies assessing variability in Parkinson's disease which, in comparison, have used group sizes as small as six speakers (McHenry, 2003, 2004).

TABLE 3.11: Number of eligible speakers per group for each speaking condition and speech parameter.

Group	Parameter	Speaking condition					
		Slow	Hab	Fast	IL	IC	Dual
HD (n = 23)	SPL	23 (21.3)	23 (20.8)	23 (21.0)	23 (20.3)	23 (20.4)	22 (23.0)
	F0	23 (20.6)	23 (20.3)	23 (21.0)	23 (20.1)	22 (20.6)	21 (23.2)
	F1	20 (18.7)	23 (17.7)	23 (18.6)	23 (18.6)	22 (17.0)	22 (19.8)
	F2	10 (13.9)	16 (14.5)	20 (14.1)	16 (14.2)	15 (12.9)	11 (16.5)
AMC (n =24)	SPL	24 (19.3)	24 (21.0)	24 (21.6)	24 (20.3)	24 (20.5)	24 (26.3)
	F0	24 (19.0)	24 (20.2)	24 (20.7)	24 (20.3)	24 (20.3)	24 (23.8)
	F1	22 (17.5)	22 (16.1)	24 (18.6)	21 (16.2)	24 (14.9)	21 (19.0)
	F2	9 (12.4)	13 (11.9)	16 (13.1)	11 (13.4)	11 (12.2)	11 (16.7)
YA (n = 16)	SPL	15 (20.5)	16 (20.8)	16 (21.2)	16 (19.7)	16 (21.4)	16 (25.9)
	F0	16 (19.6)	16 (19.9)	16 (20.9)	16 (19.9)	16 (20.8)	16 (25.8)
	F1	10 (16.7)	13 (14.9)	14 (14.9)	12 (15.3)	11 (16.9)	14 (17.5)
	F2	4 (13.3)	8 (12.3)	9 (12.8)	8 (12.0)	9 (15.3)	8 (14.1)
OA (n = 14)	SPL	14 (19.8)	14 (21.1)	14 (21.6)	14 (20.7)	14 (20.7)	14 (26.9)
	F0	14 (19.4)	14 (20.1)	14 (20.1)	14 (20.9)	14 (20.1)	14 (24.5)
	F1	10 (19.0)	13 (17.1)	14 (19.4)	13 (17.8)	14 (16.4)	13 (19.6)
	F2	3 (12.5)	6 (12.0)	9 (12.8)	5 (12.6)	6 (13.2)	6 (16.2)

3.6.3.5 Visualisation of optimisation steps

Sound pressure level

Examples of optimisation of sound pressure level contours of two speakers (left: speaker HD11 in Habitual Rate task, and right: speaker HD23 in Dual task) are given in Figure 3.5. The upper panels display the contours before data selection, the middle panels display the contours after data selection, and the lower panels display the contours after filtering and normalising.

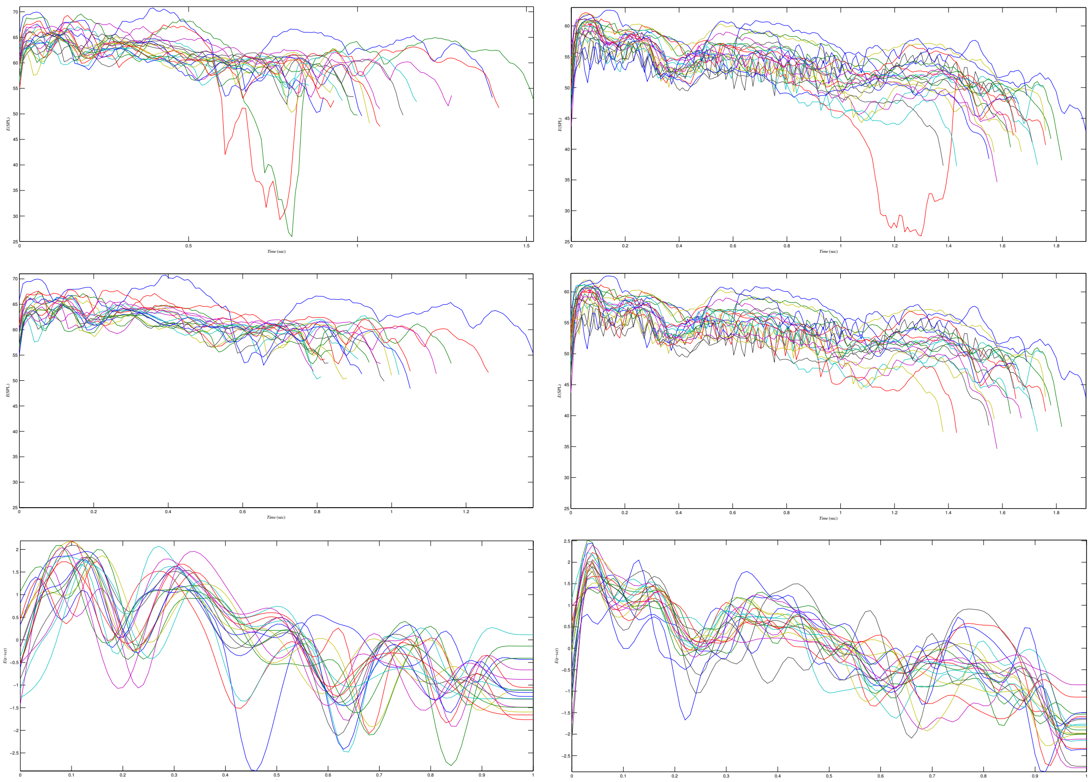

FIGURE 3.5: Contours of sound pressure level: examples of data selection. Left side panels: speaker HD11 in the Habitual Rate condition; right side panels: speaker HD23 in the Dual task condition. Upper panels: original data contours; middle panels: contours after data selection; lower panels: contours after filtering and normalisation.

Fundamental frequency

Examples of contour smoothing and data selection of fundamental frequency contours of two speakers (left panels: speaker HD03 during the Habitual rate condition, and right panels:

speaker HD08 during the increased length condition) are displayed in Figure 3.6. The upper panels display the contours before smoothing and data selection, the middle panels display the contours after smoothing and data selection, and the lower panels display the contours after filtering and normalising.

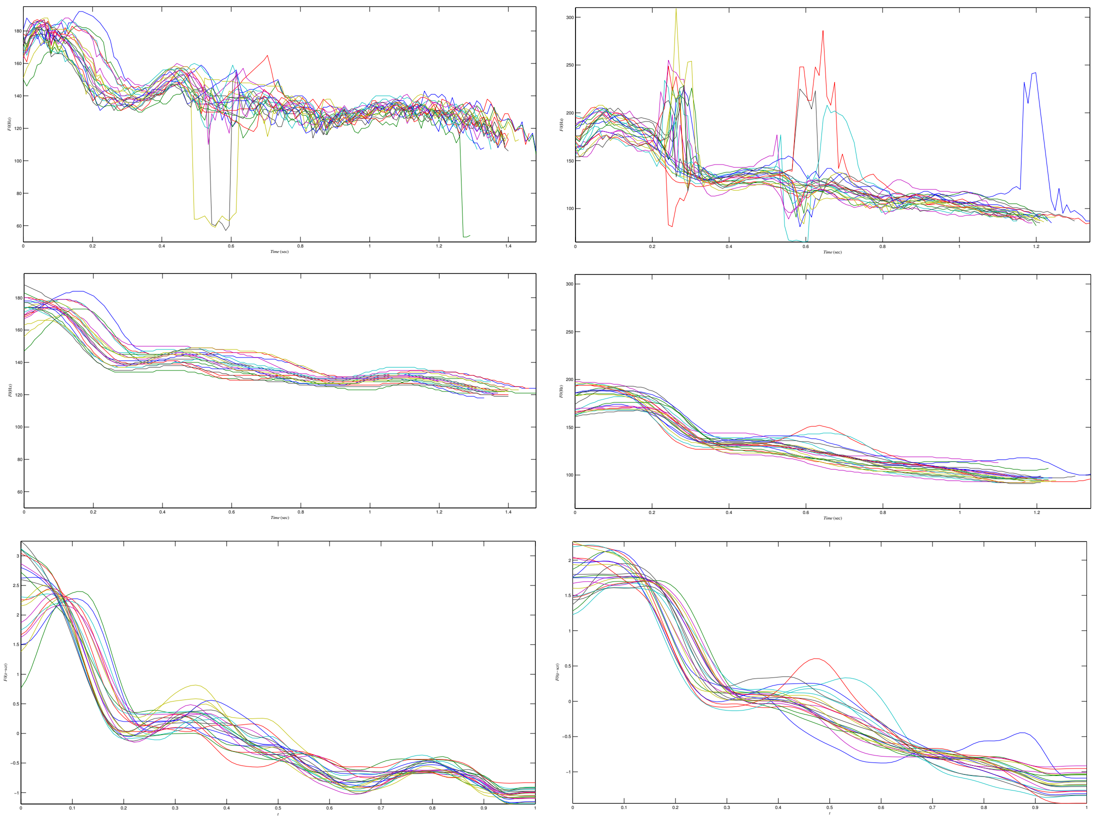

FIGURE 3.6: Contours of fundamental frequency: examples of contour smoothing and data selection. Left side panels: speaker HD03 in the Habitual Rate condition; right side panels: speaker HD08 in the Increased Length condition. Upper panels: original data contours before smoothing; middle panels: contours after data selection and smoothing; lower panels: contours after filtering and normalisation.

First formant frequency

Examples of data selection and stabilising of first formant frequency contours of two speakers (left side panels: speaker HD05 in the Increased Complexity condition, and right side panels: speaker HD09 in the Habitual rate condition) are displayed in Figure 3.7. The upper panels display the contours before stabilising and data selection. The middle panels display the contours after stabilising and data selection. The lower panels display the contours after filtering and normalising, with eliminated spikes (e.g., spikes at 0.5 seconds for speaker HD05).

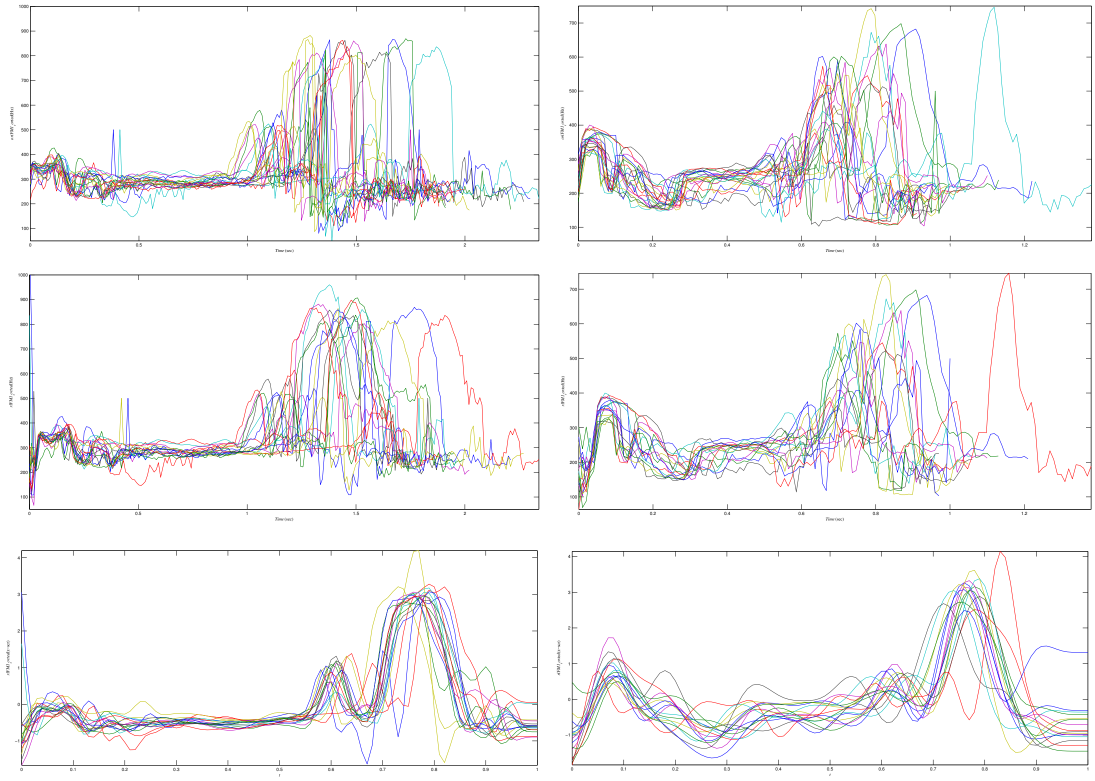

FIGURE 3.7: Contours of first formant frequency: examples of contour smoothing and data selection. Left side panels: speaker HD05 in the Increased Complexity condition; right side panels: speaker HD09 in the Habitual rate condition. Upper panels: original data contours before contour stabilising; middle panels: contours after data selection and contour stabilising; lower panels: contours after filtering and normalisation.

Second formant frequency

Examples of data selection and stabilising of second formant frequency contours of two speakers (left side panels: speaker HD02 in the Habitual rate condition, and right side panels: speaker HD17 in the Increased Length condition) are displayed in Figure 3.7. The upper panels display the contours before stabilising and data selection, the middle panels display the contours after stabilising and data selection, and the lower panels display the contours after filtering and normalising.

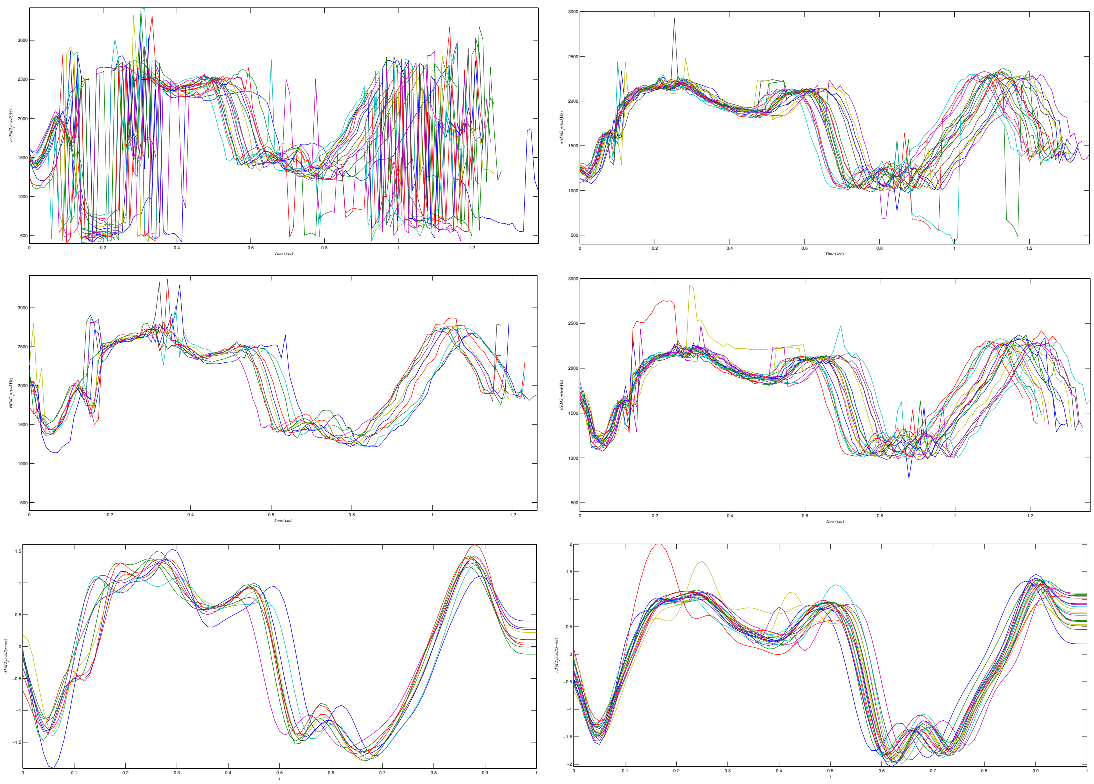

Figure 3.8: Contours of second formant frequency: examples of contour stabilising, data selection, and contour smoothing. Left side panels: speaker HD02 in the Habitual rate condition; right side panels: speaker HD17 in the Increased Length condition. Upper panels: original data contours before contour stabilising; middle panels: contours after data selection and contour stabilising; lower panels: contours after filtering and normalisation.

3.6.3.6 Initial processing steps of variability measures

The annotated audio recordings were used to calculate the spatiotemporal index and spatial and temporal variability by functional data analysis (FDA) using Matlab version 7.8 with customized FDA registration software (Ramsay, 2009; Ramsay, Hooker, & Graves, 2009; Howell et al., 2010).

The first steps to calculate the spatiotemporal index, spatial variability, and temporal variability were identical across the three variability measures, and are detailed below.

A graphical representation of the first steps in the analysis procedure is displayed in figure 3.9, where the sound pressure level contours of twenty-one repetitions of the sentence “Tony knew you were lying in bed” were analysed. The annotated phrases served as the analysis window for the contours. The unprocessed contours are displayed in the top panel.

In the following processing step, the sound pressure level contours were resampled to 8000 Hz, and filtered using a 6th order Butterworth filter with a cut-off frequency of 10 Hz. The contours were normalised by calculating the *z*-scores (middle panel), and time-scaled to fit on a similar time frame (lower panel). The normalised contours were used to calculate both the spatiotemporal index, and temporal and spatial variability by means of functional data analysis.

3.6.3.7 Calculating the spatiotemporal index

The spatiotemporal index was obtained by calculating the overall mean and standard deviation of the linearly time-stretched contours in the lower panel of figure 3.9. The sum of standard deviations at every 2% of the arbitrary time interval, which are effectively 50 points, is the spatiotemporal index (Smith et al., 1995; Smith et al., 2000; Ward & Arnfield, 2001). Figure 3.10 shows the mean of all contours (black line), the median (blue line), and the standard deviations around the mean (green lines).

3.6.3.8 Calculating temporal variability

Temporal variability was calculated by expanding or compressing the SPL contours nonlinearly, based on prominent peaks, valleys, and zero-crossings. These transformations were applied in a registration step with the aim to minimize distance between each contour and the overall mean contour (Lucero & Koenig, 2000; Lucero, 2005). Figure 3.11 shows the graphs displaying the steps towards calculating temporal variability. The graph in the upper panel shows the x-axis as the linear scaling of time plotted against the y-axis as the nonlinear deformation of the x-axis resulting from FDA registration. If the records were identical, this would be a series of lines with a slope of 1. The second panel shows the differences in the temporal dimension for each contour (the relative error). The bottom panel shows the mean of all contours in the temporal dimension (black line), the median (blue line), and the standard deviation of the mean (green lines). Temporal variability is defined as the summed standard deviation over all intervals at every 2% along the contour of temporal differences.

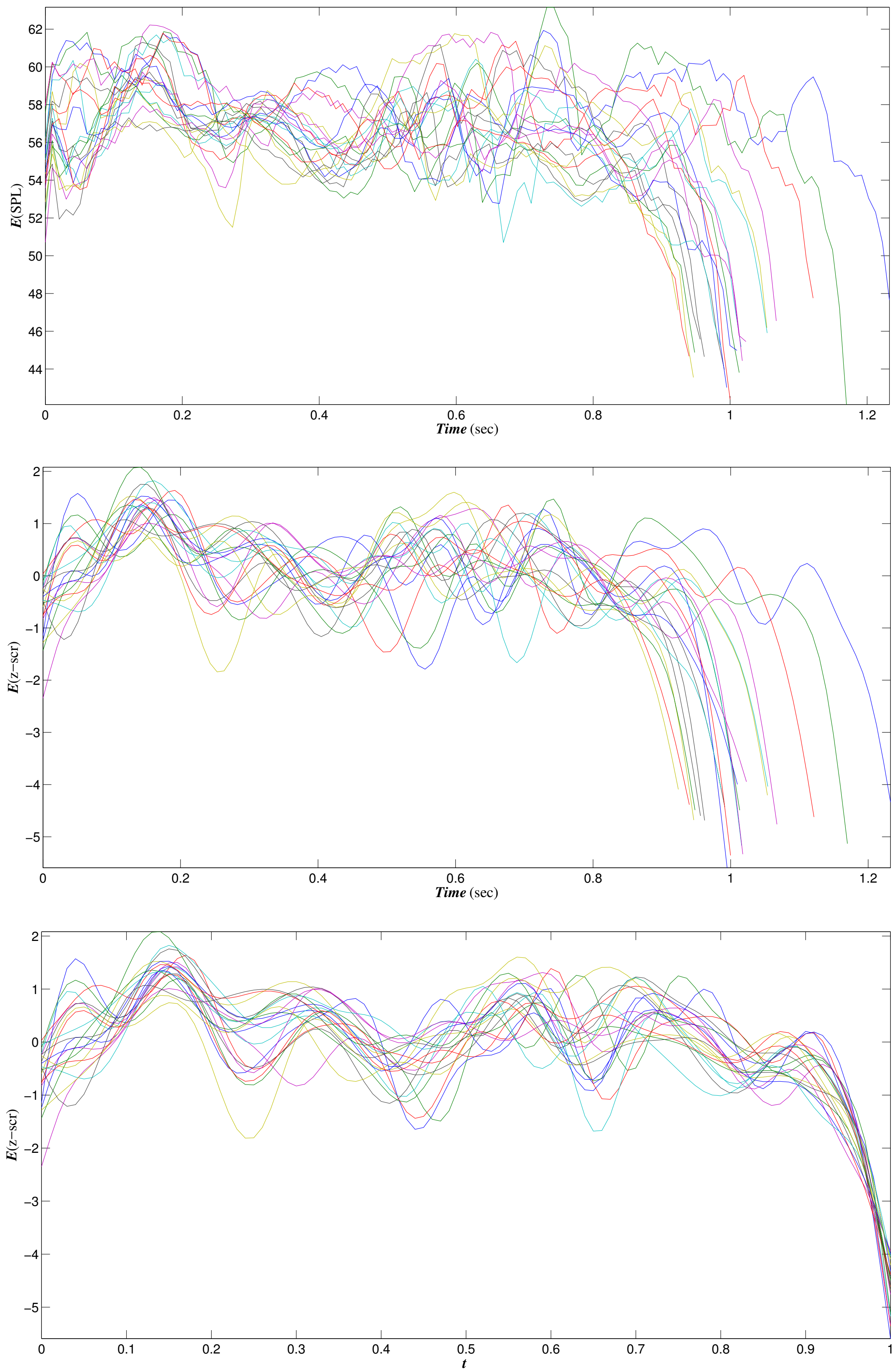

FIGURE 3.9: Processing the SPL contours. The upper panel shows the raw SPL contours of 21 repetitions of "Tony knew you were lying bed" repeated at fast speech rate. In the middle panel, the contours are resampled, filtered and normalised. In the bottom panel, the contours are time-scaled to fit on a similar time frame.

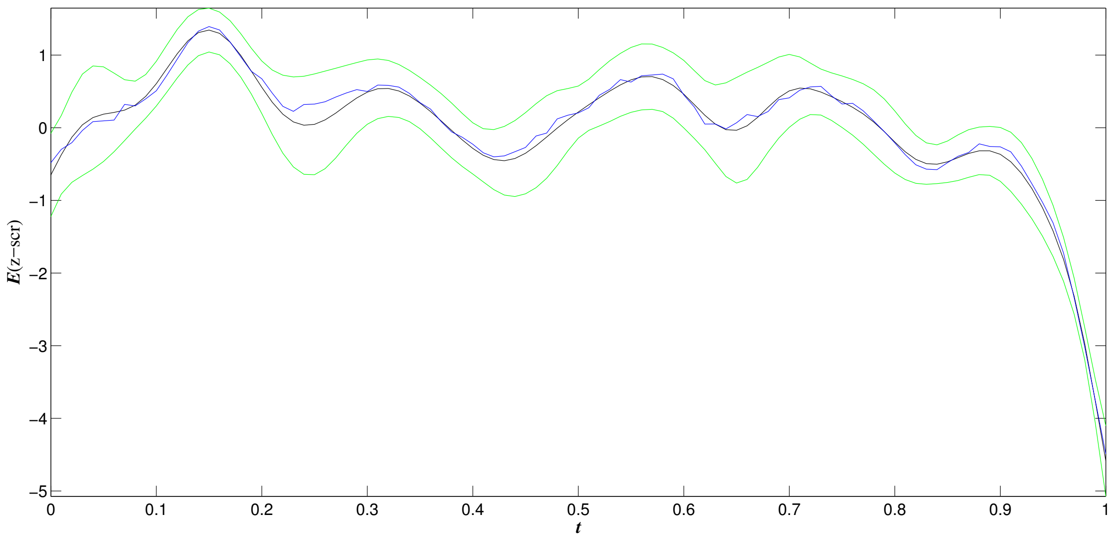

FIGURE 3.10: Averaged contours for calculating the spatiotemporal index. The mean (black line), median (blue line) and standard deviation (green lines) of the contours are displayed.

3.6.3.9 Calculating spatial variability

After the contours were nonlinearly stretched in time, spatial variability was measured by calculating the variation of the spatial differences between each SPL contour and the overall mean contour. Figure 3.12 shows the graphs displaying the steps towards calculating spatial variability. The upper panel shows all nonlinearly scaled sound pressure level contours. The middle panel represents the spatial differences of each contour against the mean contour (relative differences). The bottom panel shows the mean of all contours in the spatial dimension (black line), the median (blue line), and the standard deviation of the mean (green lines). Spatial variability is defined as the summed standard deviation over all intervals at every 2% along the contour (Ramsay & Silverman, 2006; Anderson et al., 2008).

3.7 Statistical analysis

This section details the methodology used for the statistical analyses of assessing the intra-rater reliability and inter-rater reliability of the different speaking tasks, and the methodology to compare the participant groups with respect to the results of the diadochokinetic tasks, the results of the intelligibility experiments, the results of the variability analyses in the sentence

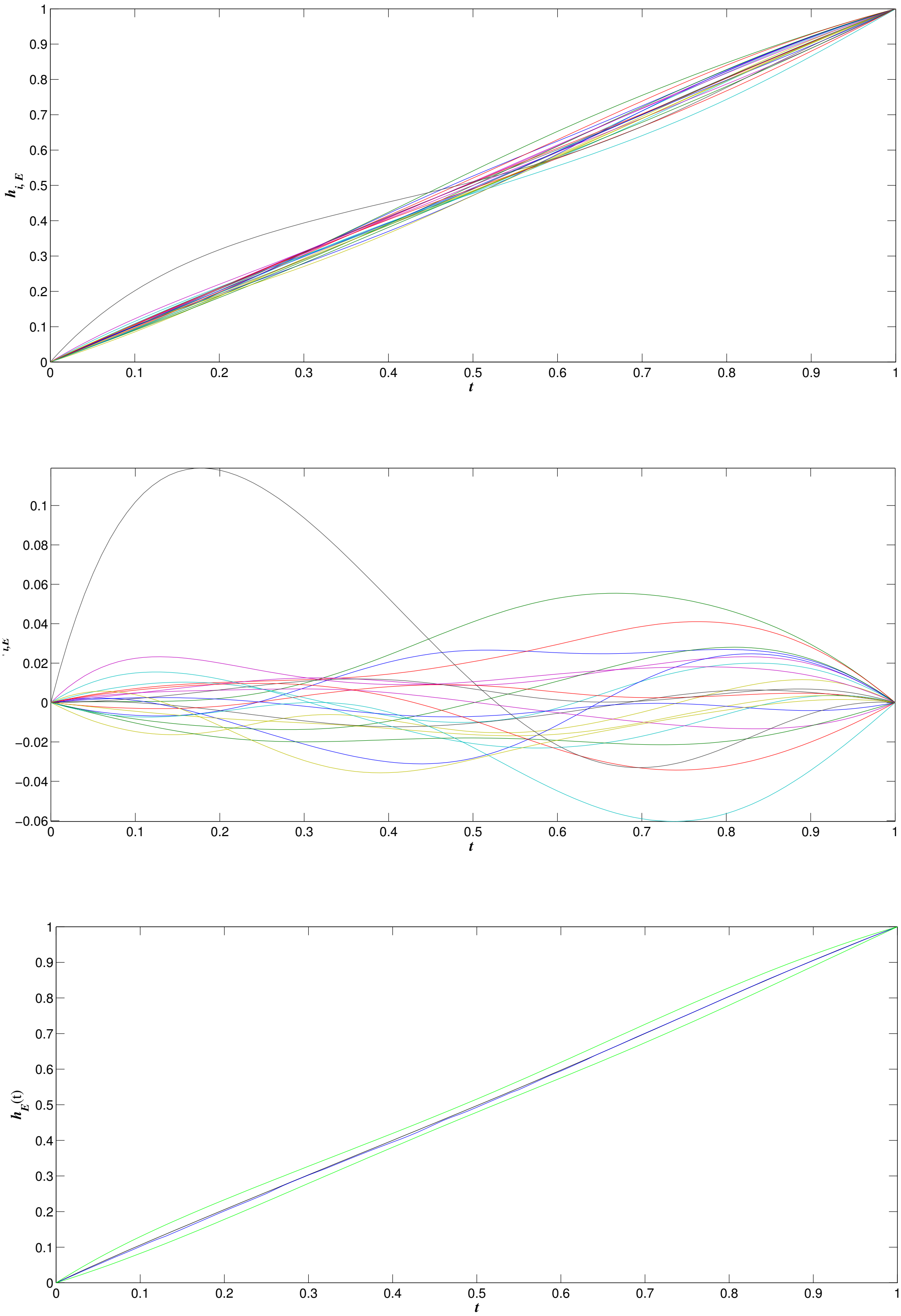

FIGURE 3.11: Calculating temporal variability by FDA. Upper panel: the extracted phase (temporal) time-scaled SPL contours. Middle pattern: differences in temporal dimension between each contour and the mean (error). Bottom panel: mean (black line), median (blue line) and standard deviation (green lines) of the contours in temporal dimension.

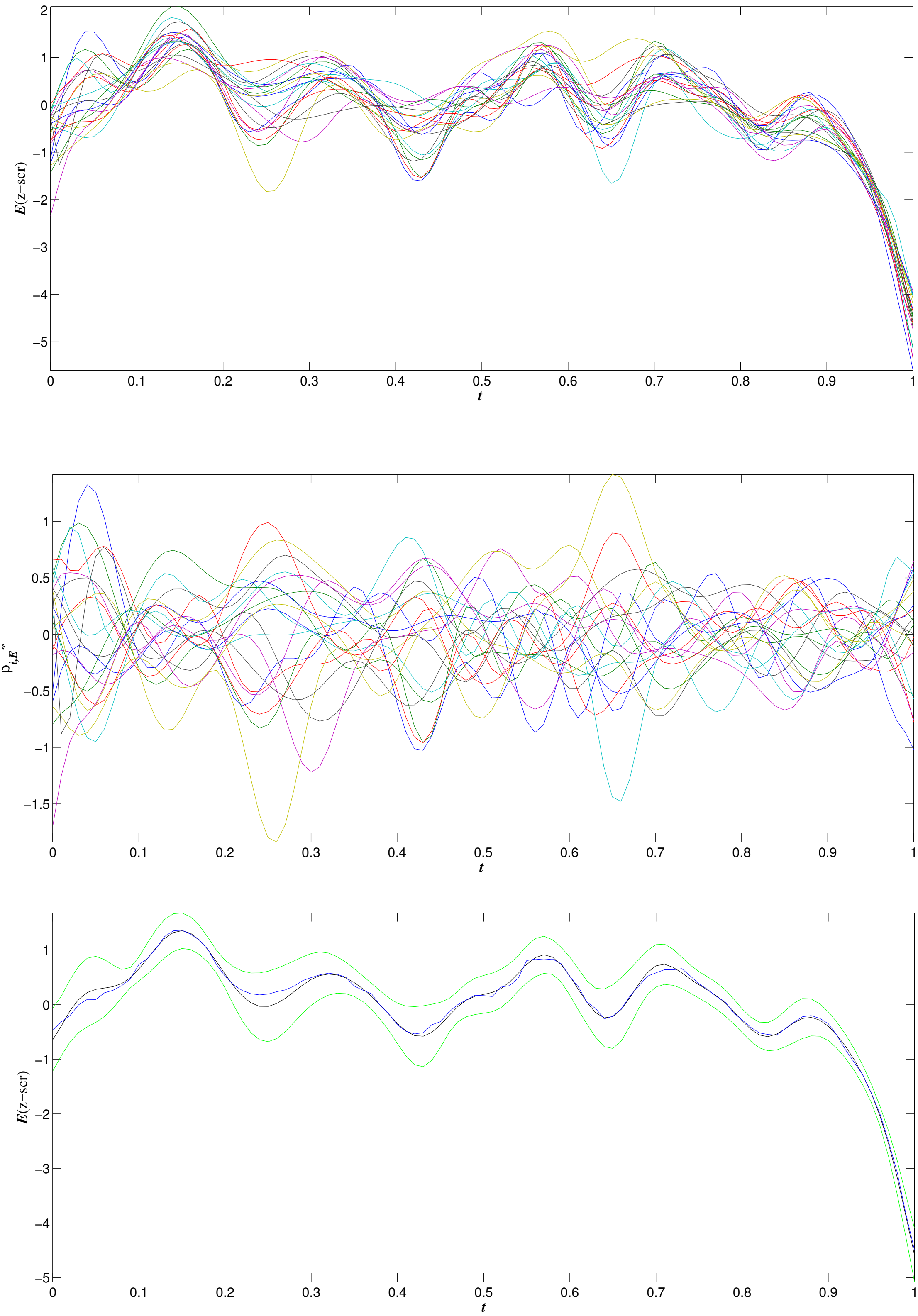

FIGURE 3.12: Calculating spatial variability by FDA. Upper panel: the extracted amplitude (spatial) time-aligned SPL contours. Middle panel: differences in spatial dimension between each contour and the mean (error). Bottom panel: mean (black line), median (blue line) and standard deviation (green lines) of the contours in spatial dimension.

repetition tasks, and the correlations between the tasks. Statistical analyses were performed with IBM SPSS version 20 (IBM, 2011).

3.7.1 Intra-rater and inter-rater reliability analyses

To assess the intra-rater and inter-rater reliability of the analysis of the diadochokinetic tasks, inter-rater reliability of the intelligibility scaling experiment, inter-rater reliability of the transcription experiment, and intra- and inter-rater reliability of sentence annotations, a series of Intraclass Correlation Coefficients (ICCs) was calculated. ICCs are used to assess the consistency and/or agreement of measurements made by multiple raters measuring the same quantity (McGraw & Wong, 1996; Neel, 2009). In the models used in this study, the absolute agreement model type was used, where both systematic differences and consistency between annotators are relevant in determining reliability. The ICCs were calculated for both single measures and average measures. The single measures ICC is an index for the reliability of the ratings for a typical single rater, and the average measures ICC is an index for the reliability of all different raters averaged together (Weir, 2005). Generally ICC values of < 0.4 indicate poor agreement; 0.4 - 0.6 moderate; 0.6 - 0.8 good; and > 0.8 very good agreement (Shrout & Fleiss, 1979). To assess inter-rater reliability, a randomly selected proportion of the data were annotated by a trained phonetician independent of the project, who was experienced in the segmentation of acoustic data.

3.7.1.1 Intra- and inter-rater reliability of the diadochokinetic tasks

To assess the intra-rater reliability and inter-rater reliability of placing start and end markers during annotation of syllables in the diadochokinetic tasks, a proportion of the data was selected for reanalysis. Around 10% of the DDK data were selected at random, yielding a data set of 24 diadochokinetic trials. Of those 24 trials, 9 trials were randomly selected from speakers of the hypokinetic dysarthria group and 15 were randomly selected from healthy speakers.

The syllable repetition rates of all annotations were extracted and submitted to a two-way mixed effects ICC model in order to obtain intra-rater and inter-rater reliability measures to determine the consistency of placing start and end markers, following procedures set out by Sheard, Adams, and Davis (1991) and Neel (2009). The factor annotator was treated as a random factor, and the factor syllable repetition rate was treated as a fixed factor.

The results of the annotation correlations for the intra-rater reliability assessment are displayed in table 3.12.

TABLE 3.12: Intraclass Correlation Coefficients of intra-rater reliability of syllable annotations in DDK tasks.

Speakers		ICC	95 % C.I.	Significance
Healthy speakers	Single Measure	.998	.997 to .998	$F(343, 343) = 827.8, p < .001$
	Average Measure	.999	.999 to .999	$F(343, 343) = 827.8, p < .001$
HD speakers	Single Measure	.999	.999 to .999	$F(155, 155) = 2018.9, p < .001$
	Average Measure	1.000	.999 to 1.000	$F(155, 155) = 2018.9, p < .001$

The results of the annotation correlations for the inter-rater reliability assessment of placing start and end markers can be found in table 3.13.

TABLE 3.13: Intraclass Correlation Coefficients of inter-rater reliability of syllable annotations in DDK tasks.

Speakers		ICC	95 % C.I.	Significance
Healthy speakers	Single Measure	.998	.997 to .998	$F(343, 343) = 811.0, p < .001$
	Average Measure	.999	.998 to .999	$F(343, 343) = 811.0, p < .001$
HD speakers	Single Measure	.998	.997 to .998	$F(155, 155) = 858.0, p < .001$
	Average Measure	.999	.998 to .999	$F(155, 155) = 858.0, p < .001$

The Intraclass Correlation Coefficients of intra-rater reliability and inter-rater reliability of syllable annotations in the DDK tasks were high for both healthy speakers and speakers with hypokinetic dysarthria. Coefficients varied between .997 and 1.000. Similar studies assessing DDK rates have found ICC values between 0.991 and 0.993 (Yang, Chung, Chi, Chen, & Wang, 2011), 0.66 to 0.85 (Waite, Theodoros, Russell, & Cahill, 2012), and 0.841 (Roy et al., 2009). The results showed that syllable boundary annotations were placed consistently, both within rater and between raters. Differences in ICC-scores between healthy speakers and hypokinetic dysarthric speakers were negligible. Overall, the ICC scores showed that the syllable annotations of the diadochokinetic tasks were annotated reliably for both speaker types.

3.7.1.2 Inter-rater reliability of the intelligibility scaling experiment

Intraclass Correlation Coefficients were calculated to assess inter-rater reliability of the intelligibility ratings of the reading passage and the monologue task obtained from the 15 listeners. The intelligibility ratings were obtained from all 23 speakers with hypokinetic dysarthria. For three speakers of the reading passage and two speakers of the monologue, intelligibility ratings were not available from all 15 listeners, e.g., because of early button presses. Missing data were replaced by best approximations based on means, variances, and covariances through an Expectation-Maximization Missing Value Analysis following e.g., Musil, Warner, Yobas, and Jones (2002) and Morgan, Mageandran, and Mei (2010).

The ratings produced by each of the 15 listeners were submitted to a 15 by 23 two-way mixed effects ICC model to determine consistency of ratings among listeners. In this model, the factor Rating was treated as a random factor, and the factor Listener was treated as a fixed factor.

The results of the scaling of the reading task and the monologue can be found in table 3.14.

TABLE 3.14: Intraclass Correlation Coefficients of reading and monologue tasks.

Speech dimension		ICC	95 % C.I.	Significance
Reading	Single Measure	.660	.524 to .800	$F(22, 308) = 30.07$, $p < .001$
	Average Measure	.967	.943 to .984	$F(22, 308) = 30.07$, $p < .001$
Monologue	Single Measure	.688	.556 to .820	$F(22, 308) = 34.02$, $p < .001$
	Average Measure	.971	.950 to .986	$F(22, 308) = 34.02$, $p < .001$

The ICC scores of the intelligibility ratings for a typical rater were .660 and .688 for the reading task and the monologue task respectively, and can be considered good. For the average of all raters, ICC scores were .967 and .971 for both speaking tasks, and can be considered to be very good (Shrout & Fleiss, 1979). Other studies investigating speech intelligibility reported ICC scores varying between 0.31 (Pennington, Miller, Robson, & Steen, 2010), 0.47 (Pennington et al., 2013), 0.69 (Kim & Kuo, 2011), and 0.80 (Wilkinson & Brinton, 2003). Overall, inter-rater reliability was slightly higher in the monologue task compared to the reading task, but both tasks were rated very reliably and consistently on intelligibility.

3.7.1.3 Inter-rater reliability of the transcription experiment

Intraclass Correlation Coefficients were calculated to assess inter-rater reliability of the transcription percentages for the 15 listeners. The intelligibility ratings were obtained from all 23 speakers with hypokinetic dysarthria. In six instances, a listener was unable to transcribe the sentence, e.g., because he / she erroneously pressed a button too early. The missing data points were replaced by best approximations based on means, variances, and covariances by means of a missing value analysis.

Each of the 23 speakers with hypokinetic dysarthria produced 10 sentences, yielding a total of 230 individual stimuli. Each of these stimuli was transcribed by three different listeners. The 230 stimuli with three transcription percentages were submitted to a 3 by 230 two-way mixed effects ICC model to determine the consistency of stimulus ratings amongst listeners. In this model, the factor Stimulus was treated as a random factor, and the factor Transcription was treated as a fixed factor.

The results of the transcription correlations for sentences and speakers are displayed in table 3.15.

TABLE 3.15: Intraclass Correlation Coefficients of transcription task.

Speech dimension		ICC	95 % C.I.	Significance
Transcription	Single Measure	.499	.423 to .572	$F(229, 458) = 3.99$, $p < .001$
	Average Measure	.749	.687 to .801	$F(229, 458) = 3.99$, $p < .001$

The ICC score of stimuli ratings for a typical, single rater was .499 and can be considered moderate, while the ICC score for all raters was .749 and can be considered good. Other studies using ICCs to determine inter-rater reliability of transcription tasks have reported values ranging from 0.70 to 0.85 (Singh, Epstein, Myers, Farmer, & Lynch, 2010), 0.75 to 0.94 (Beijer et al., 2012), 0.94 to 0.96 (dos Santos Barreto & Zazo Ortiz, 2015), and 0.977 (Chen et al., 2010). The results show that across listeners, the sentences were transcribed with moderate to good reliability, and fall within the same range of values reported in the literature, indicating that transcription of the unpredictable sentences was reliable.

3.7.1.4 Intra- and inter-rater reliability of the phrase annotations

To assess the reliability of placing start and end markers during annotation of phrase annotations in the sentence repetition task, a proportion of the variability data was selected for reanalysis. Around 10% of the variability data were selected at random, yielding a data set of 32 sound files. Of those 32 files, 14 were randomly selected from hypokinetic speakers, and 18 were randomly selected from healthy speakers. Each of the sound files contained around 20 phrase repetitions, yielding a total of around 720 phrase repetitions.

The annotation boundaries marking the start and end of the phrases were extracted from the reanalysed data and compared to the original start and end marker positions. Mean and standard deviation of the absolute time differences of start markers and end markers were calculated separately for the speech files of speakers in the clinical groups and for the speech files of speakers in the control groups.

In addition, the durations of all phrase repetitions were extracted and submitted to a two-way mixed effects Intraclass Correlation Coefficient (ICC) model to determine the consistency of phrase repetition durations. In this model the factor Annotator was treated as random factor, and the factor Phrase Duration was treated as a fixed factor.

Average absolute differences between the original annotations and intra-rater annotations are displayed in table 3.16, and the results of the annotation correlations for the intra-rater reliability assessment in table 3.17.

Average absolute differences between the original annotations and inter-rater annotations are displayed in table 3.18, and the results of the annotation correlations for the inter-rater reliability assessment in table 3.19.

TABLE 3.16: Absolute average durational differences between original and intra-rater annotations (in sec).

Speakers	Marker position	Mean difference (s)	SD difference (s)
Healthy speakers	Start marker	.0032	.0030
	End marker	.0105	.0133
HD speakers	Start marker	.0098	.0273
	End marker	.0278	.0688

TABLE 3.17: Intraclass Correlation Coefficients of intra-rater reliability of phrase annotations.

Speakers		ICC	95 % C.I.	Significance
Healthy speakers	Single Measure	.999	.999 to .999	$F(394, 394) = 2760.8, p < .001$
	Average Measure	1.000	1.000 to 1.000	$F(394, 394) = 2760.8, p < .001$
HD speakers	Single Measure	.998	.997 to .998	$F(287, 287) = 896.2, p < .001$
	Average Measure	.999	.999 to .999	$F(287, 287) = 896.2, p < .001$

TABLE 3.18: Absolute average durational differences between original and inter-rater annotations (in sec).

Speakers	Marker position	Mean difference (s)	SD difference (s)
Healthy speakers	Start marker	.0034	.0030
	End marker	.0067	.0063
HD speakers	Start marker	.0049	.0120
	End marker	.0084	.0123

TABLE 3.19: Intraclass Correlation Coefficients of inter-rater reliability of sentence annotations.

Speakers		ICC	95 % C.I.	Significance
Healthy speakers	Single Measure	.998	.998 to .999	$F(394, 394) = 1206.9, p < .001$
	Average Measure	.999	.999 to .999	$F(394, 394) = 1206.9, p < .001$
HD speakers	Single Measure	.955	.944 to .964	$F(287, 287) = 43.45, p < .001$
	Average Measure	.977	.971 to .982	$F(287, 287) = 43.45, p < .001$

The Intraclass Correlation Coefficients for intra-rater and inter-rater reliability of phrase durations were high for both speakers with hypokinetic dysarthria and healthy speakers, with inter-rater reliability for the HD speakers slightly higher compared to the other reliability analyses. Furthermore, absolute duration differences between the original annotations and reanalysed intra-rater annotations ranged between 3.2 ms for the start marker of the repetitions in the control groups and 27.8 ms for the end marker of the repetitions in the clinical groups. Absolute duration differences between original annotations and inter-rater annotations ranged between 3.4 ms for the start marker in the control group and 8.4 ms for the end marker in the clinical group. Both measures of reliability show that there are minimal differences between intra-rater reliability and inter-rater reliability. On average, reliability was higher for the control groups compared to the clinical groups, and higher for the start markers of the utterances, compared to the end markers. These results show that phrase starts and phrase ends based on acoustic information could be marked with a high reliability and consistency.

3.7.2 Analysis of the effect of gender

Since the speakers of the age-matched control group were not completely matched in gender with the group of speakers with hypokinetic dysarthria, the possible effect of gender was investigated in a selected representative proportion of the diadochokinetic data and the variability data.

3.7.2.1 Diadochokinetic data

From the set of diadochokinetic data, the effect of gender was investigated in the age-matched control group for mean syllable repetition rate and the coefficient of variation of syllable duration in the four DDK tasks by means of a series of one-way analyses of variance, and displayed in table 3.20.

Effects of gender in the age-matched group were present for DDK task /pʌtʌkʌ/, both in mean syllable repetition rates and in variation of syllable duration. The results showed that female

TABLE 3.20: Effect of gender in age-matched control group on syllable repetition rate in DDK tasks.

DDK task	Measurement	Result
/pa/	Mean	$F(1, 23) = .249, p = .623$
	CoV	$F(1, 23) = .171, p = .684$
/ta/	Mean	$F(1, 23) = .269, p = .609$
	CoV	$F(1, 23) = 1.74, p = .201$
/ka/	Mean	$F(1, 23) = .476, p = .498$
	CoV	$F(1, 23) = .021, p = .885$
/pataka/	Mean	$F(1, 23) = 5.32, p = .031$
	CoV	$F(1, 23) = 7.72, p = .011$

speakers showed lower mean syllable repetition rates, but higher variation in syllable duration, compared to the male speakers.

3.7.2.2 Variability data

The possible effect of gender on variability results was assessed by analysing the spatiotemporal index during the three rate conditions and all four speech parameters. A series of one-way analyses of variance was carried out to assess the effect of gender on variability[1]. The results are displayed in table 3.21.

The results show that gender effects were absent in speech parameters Intensity, Fundamental Frequency and Second Formant. In speech parameter First Formant, significant effects were present during the Habitual Rate speaking condition and the Fast Rate speaking condition. In both cases, females showed a higher variability compared to the males in the group.

[1]The increased risk of a type I error (the incorrect rejection of a true null hypothesis) associated with making multiple statistical tests can be corrected by adjusting the significance level, usually by means of a Bonferroni correction. Whilst the four different speech parameters in this study were independent observations, the six speaking conditions may be considered to be repetitive sampling and therefore subject to correction for multiple tests. However, a correction would signify lowering the chance of incorrectly rejecting the null hypothesis (genders are equal) and help the desired outcome in this study. Thus, uncorrected probability values were used in the analyses of the diadochokinesis and variability data (Cabin & Mitchell, 2000; Armstrong, 2014).

TABLE 3.21: Effect of gender on the spatiotemporal index.

Speech parameter	Speaking condition	Result
SPL	Habitual Rate	$F(1, 23) = .047, p = .831$
	Fast Rate	$F(1, 23) = .168, p = .686$
	Slow Rate	$F(1, 23) = 2.06, p = .165$
F0	Habitual Rate	$F(1 ,23) = .139, p = .713$
	Fast Rate	$F(1, 23) = .001, p = .986$
	Slow Rate	$F(1, 23) = 1.08, p = .310$
F1	Habitual Rate	$F(1, 21) = 9.33, p = .006$
	Fast Rate	$F(1, 23) = 4.34, p = .049$
	Slow Rate	$F(1, 12) = .722, p = .414$
F2	Habitual Rate	$F(1, 11) = .141, p = .715$
	Fast Rate	$F(1, 15) = 1.83, p = .197$
	Slow Rate	$F(1, 7) = .982, p = .360$

In conclusion, the results showed that with respect to syllable repetition rate measurements, the possibility that gender plays a role in the results for DDK task /pʌtʌkʌ/ cannot be ruled out. Gender may also play a role in First Formant variability, where female speakers showed higher variability values at Habitual and Fast Rate. The possible influence of these factors are evaluated during the discussion of the results.

3.7.3 Statistical analysis of main results

3.7.3.1 Analysis of diadochokinetic tasks

For the diadochokinetic tasks, the following three acoustic measures were statistically analysed: mean syllable repetition rate, variability of mean syllable duration expressed as Coefficient of Variation (CoV), and variability of peak intensity of syllables expressed as CoV.

Two separate linear mixed models (LMM) were used to analyse the DDK outcome measures across tasks and groups (Quené & Van den Bergh, 2004; Quené, 2008; Quené & Van den Bergh, 2008). With the first model, the group of speakers with hypokinetic dysarthria were compared with the group of age-matched control speakers. With the second model, the effect of age was analysed by comparing the results of the speakers of the young adult group with the speakers of the older adult group.

In the LMM analyses, Group and Syllable Repetition Task were assigned as fixed factors, and Subject was assigned as random factor. The Maximum Likelihood estimation method was used with Compound Symmetry with Correlation Parameterization as covariance structure, as this yielded the lowest values for Schwarz's Bayesian Information Criterion. When exploring post-hoc effects, the Bonferroni correction was applied to compensate for multiple comparisons.

3.7.3.2 Analysis of inter-correlations of intelligibility data

To assess to what degree the intelligibility ratings and transcription scores correlate across tasks, the strength of inter-correlations of the measures was calculated, c.f. Stipancic, Tjaden, and Wilding (2016). Pearson two-tailed correlations were calculated between the ratings of the reading task, the ratings of the monologue task, and the percentage correctly described words in the transcription task. Correlations with a significance of $p < .05$ were marked as statistically significant.

3.7.3.3 Analysis of sentence durations of sentence repetition tasks

To analyse whether sentence durations obtained in the sentence repetition task were different across groups and tasks, two separate LMM analyses were applied with Group (HD and AMC or YA and OA) and Speaking Condition (Habitual Rate, Fast Rate, Slow Rate, Increased Length, Increased Complexity, Dual task) as Fixed Factors. The factor Subject was assigned as Random Factor. The Maximum Likelihood estimation method was used with Compound Symmetry with Correlation Parameterization as covariance structure. When exploring post-hoc effects, the Bonferroni correction was applied to compensate for multiple comparisons. Subsequently, a series of two-tailed one-sample t-tests was applied to determine whether participants significantly increased or decreased speaking rate across the different speaking tasks from the Habitual Rate condition. To compare the increased and decreased rate between the two groups, two-tailed paired-sample t-tests were used.

3.7.3.4 Analysis of variability measures of sentence repetition tasks

Following the statistical methodology of the analysis of sentence durations, LMM analyses were carried out to compare variability measures across groups and speech tasks. The statistical models were applied separately to each of the three variability measures spatiotemporal index, spatial variability and temporal variability. In addition, the model was applied separately to each of the speech parameters sound pressure level (SPL), fundamental frequency (F0), first formant (F1) and second formant (F2). To eliminate possible confounding effects of sentence length on the variability measures, Sentence Duration was assigned as a Covariate in all models.

For the spatiotemporal index, the Heterogeneous First-order Autoregressive covariance type was selected. This structure assumes heterogeneous variances and correlations that decline exponentially with distance. For both spatial variability and temporal variability, the Diagonal covariance type was selected. This structure assumes heterogeneous variances and zero correlation between elements. The Maximum Likelihood estimation method was used. When exploring post-hoc effects, the Bonferroni correction was applied to compensate for multiple comparisons.

Variability measures: classification of groups

In order to evaluate the speaking conditions and acoustic parameters of the variability measures for their suitability to classify dysarthria and speaker age, a Binomial Logistic Regression analysis was carried out (Reed & Wu, 2013). Prior to this analysis, the number of obtained variables [72; 4 speech parameters x 6 speaking conditions x 3 variability measures] were clustered and reduced by means of a Principal Component Analysis (Whitehill & Ciocca, 2000; Mulaik, 2009). PCA was used to extract the principal components, i.e., the factors containing a combination of variables that explain the largest variance across speakers. Combining variables into clusters can reveal underlying commonalities that distinguish the groups under investigation. The extracted principal components were rotated by means of oblique rotation using the Oblimin procedure, which assumes that extracted factors can be correlated. Rotation was carried out to simplify the interpretation of the involvement of variables. Missing values were replaced with the mean values across cases.

The extracted principal components were entered as predictors into a Logistic Regression model to analyse the relationship between the predictors and the dichotomous outcome variables (dysarthria / healthy; young / older speakers). The choice of the method to enter predictors into the model was driven by accuracy of classification outcome. For the dysarthric and healthy speakers the Enter method was applied, in which all outcome variables in a block are entered simultaneously. For the young and older adult speakers the Forward Stepwise (Likelihood Ratio) method was applied, which is a stepwise selection method in which outcome measures are entered based on statistically significant improvements of the model fit.

3.7.3.5 Analysis of correlations between variability data, diadochokinetic performance, intelligibility ratings, and medical history details

The variability measures were correlated with standard assessments of speech motor performance and details of the clinical speakers' medical history in order to further characterize the clinical speaker group, and to be able to interpret the results in a wider clinical context.

Firstly, a series of bivariate correlation analyses was carried out for the speakers with hypokinetic dysarthria to analyse the degree of correlation amongst measures of the diadochokinetic tasks (CoV of mean syllable durations and CoV of maximum syllable intensity), the intelligibility results (ratings of the reading task, ratings of the monologue task, transcriptions of unpredictable sentences), disease duration (time between diagnosis and data collection in years), medication use (levodopa use in mg / day), and ACE-R score. The strength of the relationship between the measures was determined by the Pearson correlation coefficient with a 2-tailed test of significance. Correlations with a significance of $p < .05$ were marked as statistically significant.

Secondly, the outcome measures listed above were correlated with the variability results (72 conditions; 6 speaking conditions x 4 acoustic parameters x 3 variability measures). The strength of the relationship between the measures was determined by the Pearson correlation coefficient with a 2-tailed test of significance. Subsequently, Bonferroni corrections were applied to the correlation coefficient values of the six side-by-side tested speaking conditions, separately applied for each variability measure and speech parameter. Given the exploratory nature of the study, and the lack of empirical knowledge about the nature of possible relations amongst variability data and other outcome measures, correlations with a significance of $p <$ .05 were marked as statistically significant, and correlations with a significance of $p < .1$ were marked as a trend, to limit the possibility of actual relationships within the data to go undetected, c.f., Armstrong (2014) and Darlington and Hayes (2016).

The following chapter 4 will now report the results of the investigations described above.

Chapter 4

Results

4.1 Introduction

The results of the analyses of the variability, acoustic, and intelligibility results for the four participant groups are reported in this chapter. This chapter is divided into six parts. Section 4.2 reports the results of the cognitive status. In section 4.3, the results of the analyses of the diadochokinetic tasks are reported. In section 4.4, the results of the intelligibility analyses are presented. With respect to the variability analyses, comparisons of groups and conditions are reported in section 4.5, and group classification results are presented in section 4.6. The results of correlations between acoustic performance, intelligibility ratings, and variability measures are presented in section 4.7.

4.2 Evaluation of cognitive status

As the presence of dementia might influence speech production (Emre et al., 2007; Rosenthal et al., 2010), the ACE-R score was used as a measurement parameter to see whether speech performance was associated with cognitive status. An ACE-R score below the threshold was not an exclusion criterion beforehand, and all speakers who participated were judged to be able to carry out all assessment tasks used in the current study, irrespective of the possible presence of cognitive impairment. The authors of the ACE-R define a cut-off score of 82/100 indicating cognitive impairment, with an associated sensitivity of 0.84 and a specificity of 1.0 (Mioshi et al., 2006). Other studies have proposed to use a cut-off score of 75 with an associated sensitivity of 0.9 and specificity of 0.9 (Larner, 2006, 2007), or a cut-off score of 73 with an associated sensitivity of 0.87 and specificity of 0.91 (Larner, 2013). When maintaining a cut-off score of 73, the ACE-R scores show that within the group of speakers with hypokinetic dysarthria one person scores below the threshold (HD22: 60), while within the groups of unimpaired speakers none of the participants scored below the threshold. The results of the evaluation of cognitive status on speech production are reported in section 4.7, with a special focus on the overall performance of the speaker with significant cognitive decline, and how his results compare with the overall group findings in terms of the nature of relationships found between the different variables.

4.3 Diadochokinetic tasks

To assess regularity of articulatory movements, a series of diadochokinetic (DDK) tasks had been administered. Acoustic measures included mean syllable repetition rates, variability in syllable duration, and variability in syllable peak intensity. The results were compared across groups and tasks.

Group averages and standard deviations of the measures of syllable repetition rates, syllable length variability, and syllable intensity variability are displayed in table 4.1.

The results are explored further below, separately by outcome measure.

4.3.1 Syllable repetition rates

The syllable repetition rates of the tasks /pʌ/, /tʌ/, /kʌ/, and /pʌtʌkʌ/ were measured in syllables per second. For task /pʌtʌkʌ/, the rate of one complete repetition was used, and as such, syllable repetition rates of this task were not directly comparable with syllable repetition rates of the other tasks, and related statistical results were not reported.

Table 4.1: Group averages and standard deviations of DDK task measures.

Measure	Group	/pa/	/ta/	/ka/	/pataka/
Repetition Rate	HD	6.60 (1.14)	6.28 (1.00)	5.85 (1.00)	2.06 (0.38)
	AMC	6.85 (0.61)	6.61 (0.61)	5.97 (0.66)	2.37 (0.25)
	YA	5.37 (1.55)	5.06 (1.40)	4.76 (1.30)	2.27 (0.33)
	OA	6.78 (0.50)	6.52 (0.51)	5.93 (0.61)	2.41(0.25)
CoV Duration	HD	11.71 (3.97)	11.98 (6.96)	11.85 (7.39)	14.60 (11.59)
	AMC	6.93 (1.82)	8.30 (2.79)	8.24 (2.89)	7.21 (4.72)
	YA	9.47 (4.84)	9.00 (3.80)	10.59 (8.01)	8.38 (5.60)
	OA	7.07 (1.72)	7.69 (2.49)	8.14 (3.61)	7.07 (5.03)
CoV Intensity	HD	3.27 (1.37)	3.30 (2.22)	3.18 (2.17)	3.34 (1.57)
	AMC	2.60 (0.81)	3.02 (1.60)	2.86 (1.03)	3.04 (1.15)
	YA	3.59 (0.86)	3.41 (1.01)	2.85 (0.87)	3.45 (1.36)
	OA	2.75 (0.79)	3.54 (1.83)	3.10 (1.02)	3.00 (0.98)

The results are displayed in Figure 4.1 and raw data is listed in Appendix I.

When comparing the speakers with hypokinetic dysarthria with their age-matched controls, the following results were found. The between-subject factor Group was not significant: $F(1, 45.8) = 2.16$, $p = .153$. The effect of Task was significant: $F(3, 235.6) = 1456.9$, $p < .001$. Pooled over groups, syllable repetition rates of /pʌ/ were higher compared to /tʌ/ ($p = .002$), which in turn were higher than /kʌ/ ($p < .001$). The interaction effect of Group by Task was not significant: $F(3, 235.6) = .761$, $p = .517$.

When comparing the effect of age, the results showed that the factor Group was significant: $F(1, 20.3) = 12.3$, $p = .001$. Pooled over syllable repetition tasks, the group of Older Adults were significantly faster compared to the group of Young Adults. The factor Task was also significant: $F(3, 157.4) = 694.7$, $p < .001$. Pooled over groups, syllable repetition rates were higher for /pʌ/ than /tʌ/ ($p = .022$), which in turn were higher compared to /kʌ/ ($p < .001$).

4.3.2 Variability in mean syllable length

The variability in syllable length was expressed in percentages as the coefficient of variation (CoV), as this enabled the comparison of measurements with a wide spread of means across

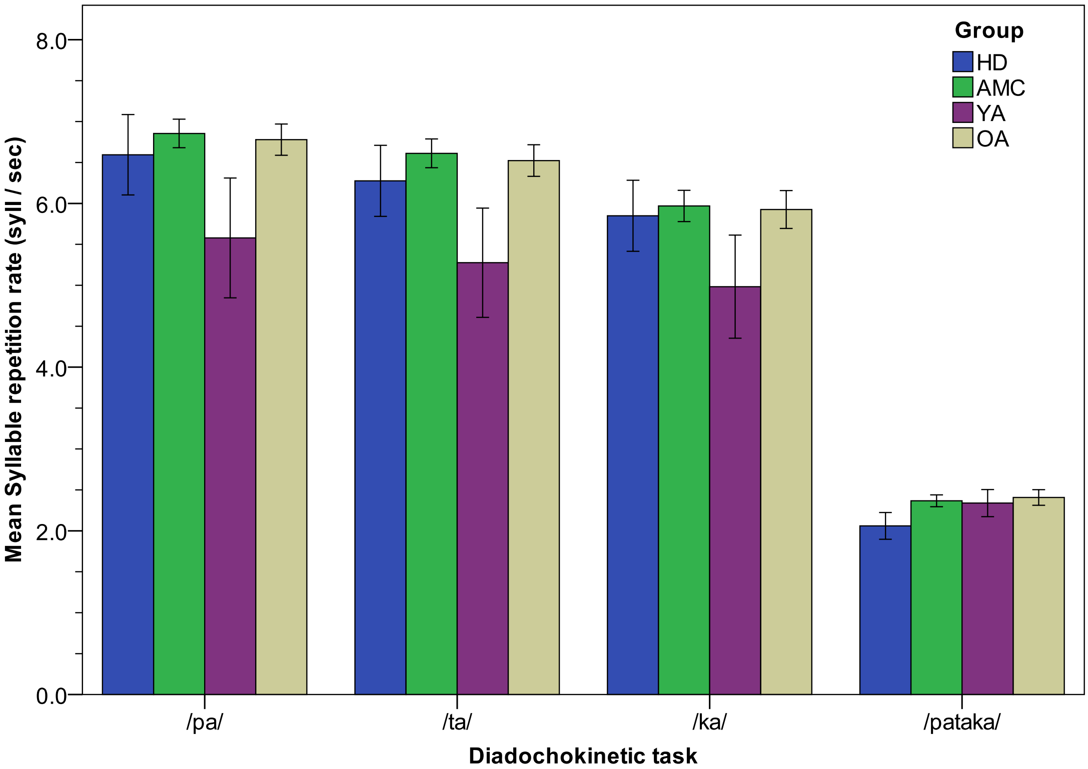

FIGURE 4.1: Syllable repetition rates in four diadochokinetic tasks. Error bars represent a 95% confidence interval.

groups and tasks. The summarized results are displayed in Figure 4.2, and the results for each speaker are displayed in Appendix J.

A significant Group effect was present [$F(1, 39.8) = 25.0$, $p < .001$] when comparing the group of hypokinetic dysarthric speakers with the age-matched control group: the HD group showed a significantly higher CoV of syllable length compared to the AMC group. No significant main effect of Task or interaction effect of Task by Group was present.

When comparing the groups of Young adults and Older adults, no significant main effects of Group or Task were present. The interaction effect of Group by Task was also non-significant.

4.3.3 Variability in peak vowel intensity

The variability in peak vowel intensity, expressed as the Coefficient of Variation (CoV), was compared across speaker groups and syllable repetition tasks. The results are displayed in

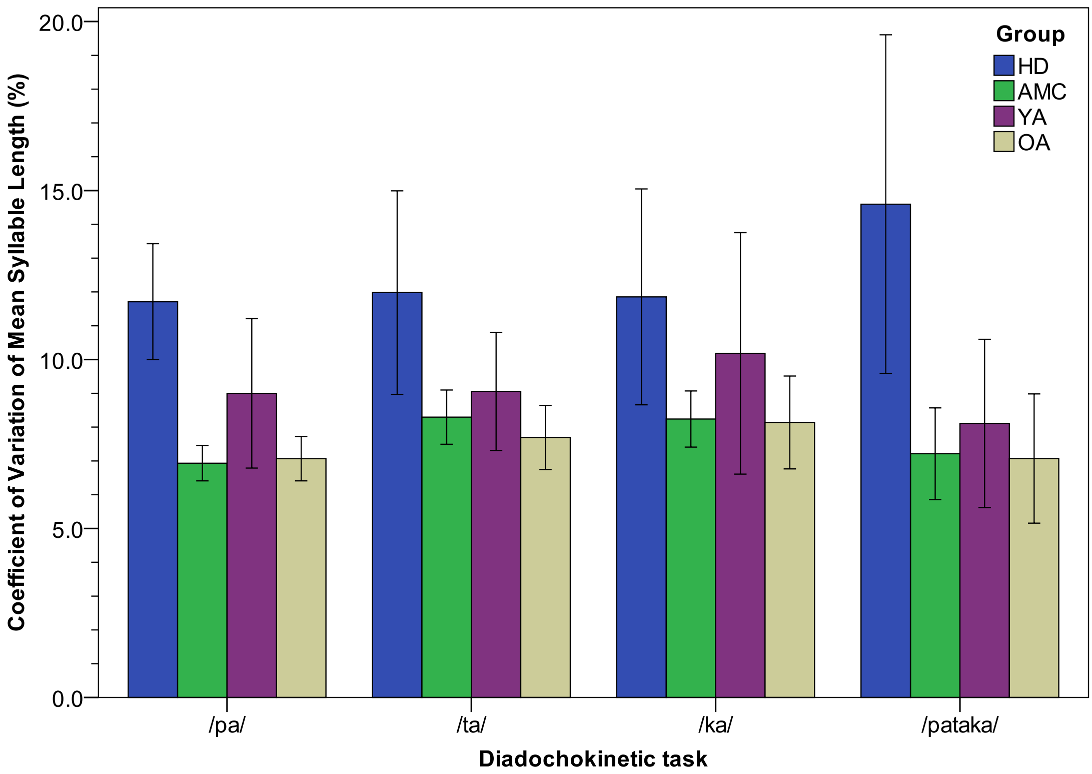

FIGURE 4.2: Coefficient of Variation of mean syllable length in four diadochokinetic tasks. Error bars represent a 95% confidence interval.

Figure 4.3, and raw data is displayed in Appendix K.

When comparing the group of dysarthric speakers with the age-matched control group for the four DDK tasks, no significant results were found: the CoV of peak sound pressure level did not differ across groups and tasks.

When comparing the two groups differing in age, there were no significant main effects of Group or Task. However, a significant Group by Task effect was present: [$F(3, 158.4) = 4.03$, $p = .009$]. A post-hoc comparison showed that for task /pʌ/, the group of younger adults had a significantly higher CoV compared to the group of older adults ($p = .016$), while in the other diadochokinetic tasks no group differences were found.

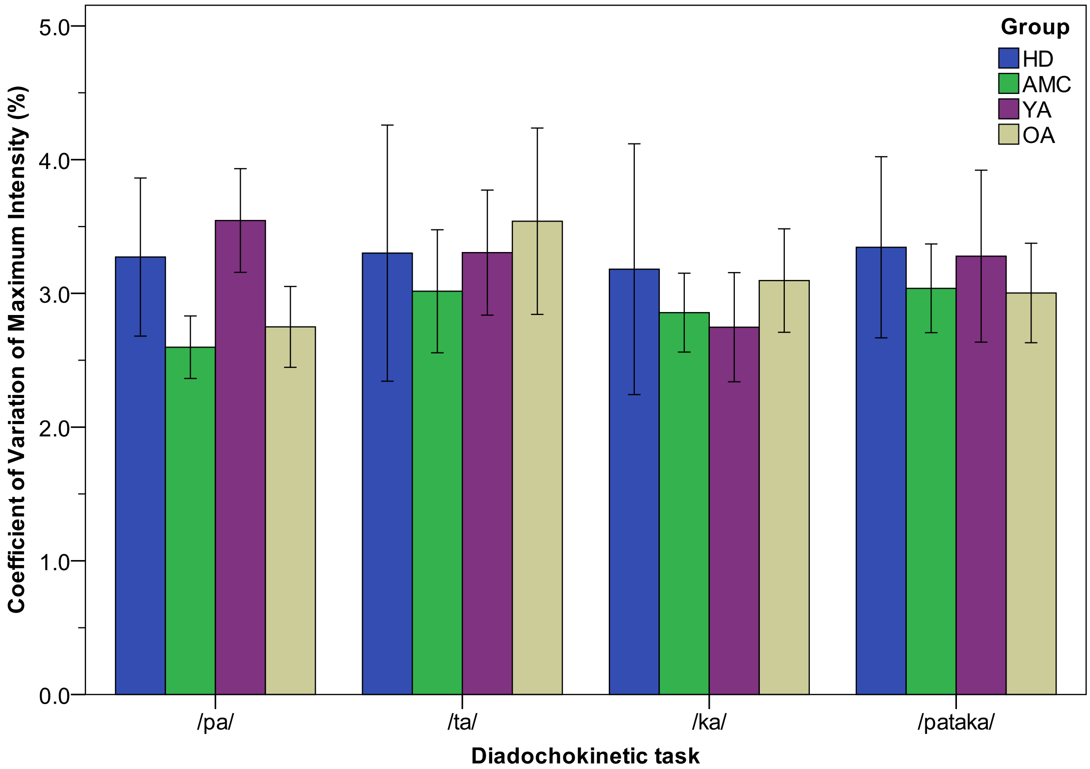

FIGURE 4.3: Coefficient of Variation of peak vowel intensity in four diadochokinetic tasks. Error bars represent a 95% confidence interval.

4.4 Intelligibility analysis

In order to correlate measures of variability with an assessment of intelligibility, three speaking tasks had been devised and administered to the speakers with hypokinetic dysarthria. A Likert scaling task had been designed to measure intelligibility in the reading passage and in a monologue fragment. The scaling task incorporated ratings of intelligibility ranging from 1 (able to understand nothing at all) to 9 (able to understand everything, without any listener effort). Intelligibility scores were obtained by averaging the scaling ratings for each speaker, separately for the reading task and the monologue. A transcription task had been devised to obtain a percentage correctly transcribed words in a series of unpredictable sentences. In the Transcription task, intelligibility scores were obtained by calculating the mean percentage of words transcribed correctly for each speaker. The methodology to obtain the three intelligibility measures is further described in section 3.6.2.

The descriptive statistics of the intelligibility analyses are displayed in table 4.2.

Table 4.2: Overview of intelligibility results: mean intelligibility ratings (on a 9-point scale) for reading and monologue tasks, and percentage correctly transcribed words.

		Reading		Monologue		Transcription (%)	
Group	Speaker	Mean	SD	Mean	SD	Mean	SD
HD	HD01	8.93	0.26	8.73	0.59	96.2	9.1
HD	HD02	8.87	0.35	8.87	0.35	89.5	16.3
HD	HD03	8.67	0.49	8.27	1.10	83.3	24.6
HD	HD04	8.67	0.82	8.13	0.99	88.6	16.5
HD	HD05	7.80	1.21	6.93	1.28	86.7	18.0
HD	HD06	8.53	0.63	7.93	1.16	84.2	16.7
HD	HD07	5.27	1.29	6.60	1.60	67.6	24.0
HD	HD08	8.40	1.49	7.64	0.93	80.8	21.4
HD	HD09	8.07	0.96	7.60	1.06	93.3	13.4
HD	HD10	8.07	0.96	7.80	1.01	84.8	17.6
HD	HD11	6.93	0.70	6.33	1.50	71.9	24.2
HD	HD12	8.00	1.00	6.80	1.37	80.9	22.2
HD	HD13	6.47	1.51	7.67	0.82	78.6	25.7
HD	HD14	8.21	0.58	8.00	1.07	87.6	15.8
HD	HD15	8.64	0.50	8.73	0.46	91.4	16.2
HD	HD16	6.93	1.79	8.53	0.83	78.1	21.8
HD	HD17	8.87	0.35	8.80	0.41	96.2	7.4
HD	HD18	4.87	1.25	5.20	1.47	35.2	31.1
HD	HD19	8.73	0.46	8.27	0.80	91.0	15.7
HD	HD20	7.79	0.98	7.60	0.99	73.3	23.9
HD	HD21	6.93	0.96	6.67	1.26	91.4	11.6
HD	HD22	5.27	1.34	2.87	0.99	41.4	30.1
HD	HD23	7.40	0.91	4.93	1.90	84.2	20.3
Group mean		7.67	0.90	7.34	1.04	81.1	19.3

The strength of the relationship between the three intelligibility measures was measured by calculating two-tailed Pearson correlations. The results of the inter-correlations of the three perceptual measures are further described in section 4.7.

4.5 Variability analysis: comparing groups and conditions

For the variability analysis, the acoustic dimensions of sound pressure level, fundamental frequency, first formant frequencies, and second formant frequencies had been extracted from the acoustic signal of the repetitions of the sentence “Tony knew you were lying in bed”. The target sentence had been produced under the following speaking conditions: habitual speaking rate, slow speaking rate, fast speaking rate, with increased sentence length (“one two three Tony knew you were lying in bed five six seven”), with increased sentence length and complexity (“I heard that Tony knew you were lying in bed this Sunday morning”), and during a dual task involving spiral drawing. The different speaking conditions were compared between the speakers of the group with hypokinetic dysarthria and the age-matched control group, and between young and older adults. A series of linear mixed model (LMM) analyses was applied to explore differences between the participant groups and speaking conditions.

4.5.1 Sentence durations

The durations of the sentence repetitions in the variability task were measured and compared across speech conditions and speaker groups. The sentence durations were taken from the spoken sentence fragments used in the variability analyses, that is, starting from the voicing onset of /o/ in ‘Tony’, and ending at the onset of the /b/ in ‘bed’.

Group averages and standard deviations of sentence durations (in seconds) are displayed in table 4.3.

TABLE 4.3: Group averages and standard deviations of sentence durations (in seconds) of variability tasks.

Group	Slow	Hab	Fast	IL	IC	Dual
HD	1.77 (0.69)	1.34 (0.31)	1.10 (0.28)	1.11 (0.31)	1.21 (0.32)	1.20 (0.32)
AMC	2.51 (1.23)	1.36 (0.26)	1.04 (0.19)	1.22 (0.28)	1.23 (0.25)	1.29 (0.33)
YA	2.50 (0.86)	1.32 (0.19)	0.99 (0.11)	1.24 (0.18)	1.17 (0.15)	1.26 (0.16)
OA	2.57 (1.37)	1.47 (0.23)	1.10 (0.18)	1.27 (0.24)	1.33 (0.25)	1.38 (0.31)

The average sentence durations are also displayed in figure 4.4 separated by group and speaking condition. An overview of sentence durations is listed in Appendix L.

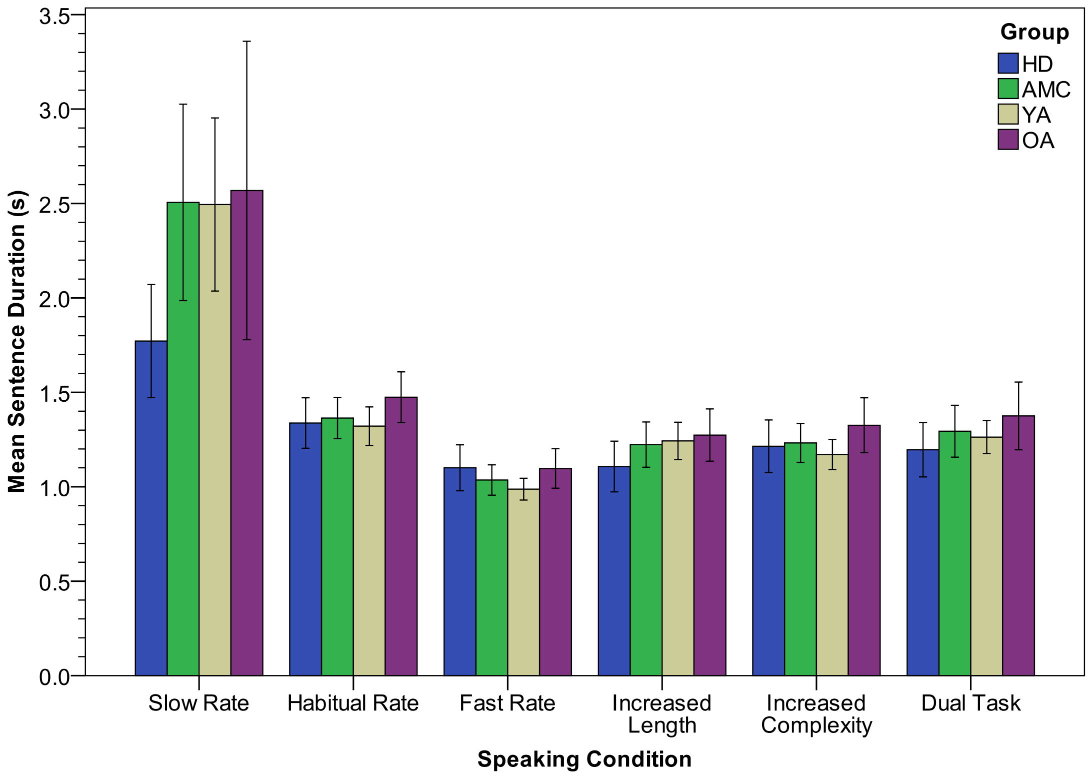

FIGURE 4.4: Mean sentence durations in the six speaking conditions of the variability task. Error bars represent a 95% confidence interval.

When comparing sentence durations of the hypokinetic dysarthric speakers with the age-matched control group for the six speaking conditions, the following results were found. The main effect of Group was not significant: $F(1, 47.6) = 2.61$, $p = .113$, sentence durations across the six speaking conditions were comparable across groups. A significant Group by Speaking Condition interaction effect was present: $F(5, 318.6) = 7.26$, $p < .001$. Pairwise comparisons showed that in the Slow Rate condition, the HD group was significantly faster compared to the age-matched control group ($p < .001$). No between-group differences were found for the other speaking conditions.

The analysis of the percentages change in duration from the Habitual Rate condition to the other speaking conditions showed that the HD group significantly decreased rate in the Slow Rate condition: $t(22) = -3.91$, $p = .001$, and increased rate in the Fast Rate condition: $t(22) =$

8.51, $p < .001$. Furthermore, a significant increase in rate was observed in the IL condition: $t(22) = 9.18$, $p < .001$, the IC condition: $t(22) = 2.84$, $p = .010$, and the Dual Task: $t(21) = 4.41$, $p < .001$. The speaker of the AMC group significantly decreased rate in the Slow Rate condition: $t(23) = -5.20$, $p < .001$, and increased rate in the Fast Rate condition: $t(23) = 11.04$, $p < .001$. The AMC group also increased rate in the IL condition: $t(23) = 2.47$, $p = .021$ and the IC condition: $t(23) = 5.01$, $p < .001$. No significant rate change was observed in the Dual Task condition: $t(23) = 1.29$, $p = .211$.

When comparing the HD and AMC groups in the magnitudes of rate increase and decrease, it was found that the AMC group decreased rate to a significantly greater extent than the HD group: $t(22) = 2.63$, $p = .015$. No group differences were observed in the percentage rate increase in the Fast rate condition: $t(22) = -1.61$, $p = .122$.

In general, AMC and HD speakers were able to change speaking rate from habitual rate to fast rate, and to slow down rate from habitual to slow rate. In addition, for both groups relative rate increases were observed in other speaking conditions, when compared to the Habitual Rate condition.

When comparing the two groups differing in age, the following results were found. A main effect of Group was absent: $F(1, 34.1) = 1.08$, $p = .307$, indicating that across tasks the YA and OA speakers had on average comparable sentence durations. The effect of the Group by Speaking Condition was not significant: $F(5, 237.8) = .113$, $p = .989$; the different speaking conditions generally yielded equal durations between groups.

The average percentage rate change for the YA speakers across the different speaking conditions indicated a significant decrease in the Slow Rate condition: $t(15) = -5.78$, $p < .001$, and a significant increase in the Fast Rate condition: $t(15) = 9.81$, $p < .001$. No significant change was observed in the IL condition: $t(15) = 2.00$, $p = .063$. Furthermore, significant increases were found in the IC condition: $t(15) = 5.59$, $p < .001$, and in the Dual Task condition $t(15) = 2.25$, $p = .040$. For the OA speakers, a significant decrease in rate was observed in the Slow Rate condition: $t(13) = -3.19$, $p = .007$, as well as an increase in the Fast Rate condition: $t(15)$

= 9.83, $p < .001$. Furthermore, significant faster rates were observed in the IL condition: $t(13) = 3.16$, $p = .008$, and the IC condition $t(13) = 3.42$, $p = .005$. No significant rate change was found in the Dual Task: $t(13) = 1.30$, $p = .251$.

When comparing the YA and OA groups in the magnitudes of rate increase and decrease, it was found that both groups decreased rate to a similar extent: $t(13) = -.788$, $p = .451$. They also increased rate to a similar degree: $t(22) = .020$, $p = .985$.

Overall, both age groups showed largely comparable behaviour when increasing or decreasing rate in the Fast Rate and Slow Rate conditions.

4.5.2 Variability measures

The following sections report the statistical results of the variability measures. The results are reported separately by variability estimator, and further divided into HD and AMC speaker group comparisons and YA and OA speaker group comparisons. A summarized overview of the significant results of the variability comparisons between groups is listed in table 4.7, and an overview of significant differences between speech tasks for each of the four participant groups is displayed in table 4.8.

4.5.3 The spatiotemporal index

Group averages and standard deviations of the spatiotemporal index of the six speaking conditions are displayed in table 4.4, separated by speech parameter.

The results are explored further below, separately by outcome measure.

4.5.3.1 Sound pressure level

The mean STI of SPL is displayed in Figure 4.5 and Appendix M, separated by group and speaking condition.

TABLE 4.4: Group averages and standard deviations of the spatiotemporal index.

Parameter	Group	Slow	Hab	Fast	IL	IC	Dual
SPL	HD	24.85 (6.11)	22.32 (5.93)	22.98 (7.84)	25.51 (6.36)	25.35 (7.17)	26.16 (6.23)
	AMC	23.95 (5.16)	19.00 (4.37)	21.56 (6.19)	22.33 (5.03)	20.96 (3.89)	23.90 (6.46)
	YA	21.13 (3.59)	19.00 (4.17)	19.06 (3.54)	24.77 (6.14)	24.69 (4.26)	21.01 (3.04)
	OA	24.14 (5.32)	17.92 (4.52)	21.20 (6.91)	20.80 (5.54)	20.58 (3.36)	24.35 (6.72)
F0	HD	17.03 (8.89)	14.94 (9.53)	14.54 (10.74)	16.58 (8.62)	18.85 (7.64)	15.16 (7.57)
	AMC	17.87 (7.89)	12.37 (4.45)	11.89 (7.99)	14.67 (5.69)	17.59 (7.00)	15.72 (7.57)
	YA	11.84 (4.23)	10.25 (5.07)	9.97 (6.34)	16.07 (7.30)	17.04 (6.39)	11.08 (2.92)
	OA	18.90 (7.80)	12.88 (4.63)	13.84 (9.76)	15.89 (5.74)	19.06 (6.61)	18.14 (6.99)
F1	HD	25.87 (6.70)	24.80 (6.19)	25.60 (8.03)	26.20 (6.64)	23.59 (7.74)	27.62 (6.70)
	AMC	22.06 (4.97)	21.26 (5.12)	23.27 (7.88)	18.59 (5.66)	19.94 (5.59)	24.69 (6.49)
	YA	25.60 (6.45)	23.05 (4.39)	26.07 (7.03)	21.42 (5.65)	23.71 (4.93)	22.83 (6.00)
	OA	22.05 (5.18)	19.65 (4.92)	21.55 (8.63)	17.37 (4.97)	18.28 (5.51)	23.26 (6.37)
F2	HD	23.84 (6.04)	25.49 (9.29)	21.77 (7.22)	22.26 (7.43)	22.56 (8.07)	22.40 (6.23)
	AMC	22.07 (4.92)	18.79 (5.44)	17.76 (5.11)	18.59 (6.20)	22.43 (7.18)	19.79 (5.69)
	YA	28.49 (3.73)	20.03 (5.37)	20.21 (7.27)	21.63 (6.49)	21.64 (6.19)	21.72 (7.50)
	OA	20.51 (6.87)	17.49 (5.19)	18.81 (6.08)	18.36 (8.35)	23.54 (7.08)	21.12 (6.83)

The results of comparing the STI of SPL of the hypokinetic dysarthric speakers with the age-matched control group were as follows. The main effect of Group was significant: $F(1, 45.7) = 4.77$, $p = .034$; the speakers of the HD displayed higher STI values across speaking conditions, compared to the AMC group. The main effect of Task was significant: $F(5, 314.0) = 7.75$, $p < .001$. STI values in the Habitual Rate condition were significantly lower compared to those in the Slow Rate ($p = .002$), IL ($p = .002$), the IC ($p = .010$), and the Dual task ($p < .001$) conditions. The interaction effect of Group and Speech Task was not significant: $F(5, 314.0) = 1.13$, $p = .343$. However, some post-hoc comparisons were significant. When comparing groups separately per task, it was found that in the IC condition STI values were higher in the HD group compared to the AMC group ($p = .013$). When comparing tasks separately per group, it was found that the HD group had significantly higher STI values in the Dual task compared to the Habitual Rate task ($p = .026$). The AMC group showed higher STI values in the Slow Rate ($p < .001$), Fast Rate ($p = .028$), IL ($p = .012$), and the Dual task ($p < .001$) conditions, compared to the Habitual Rate condition. STI values in the Dual task were higher compared to the IC condition ($p = .006$).

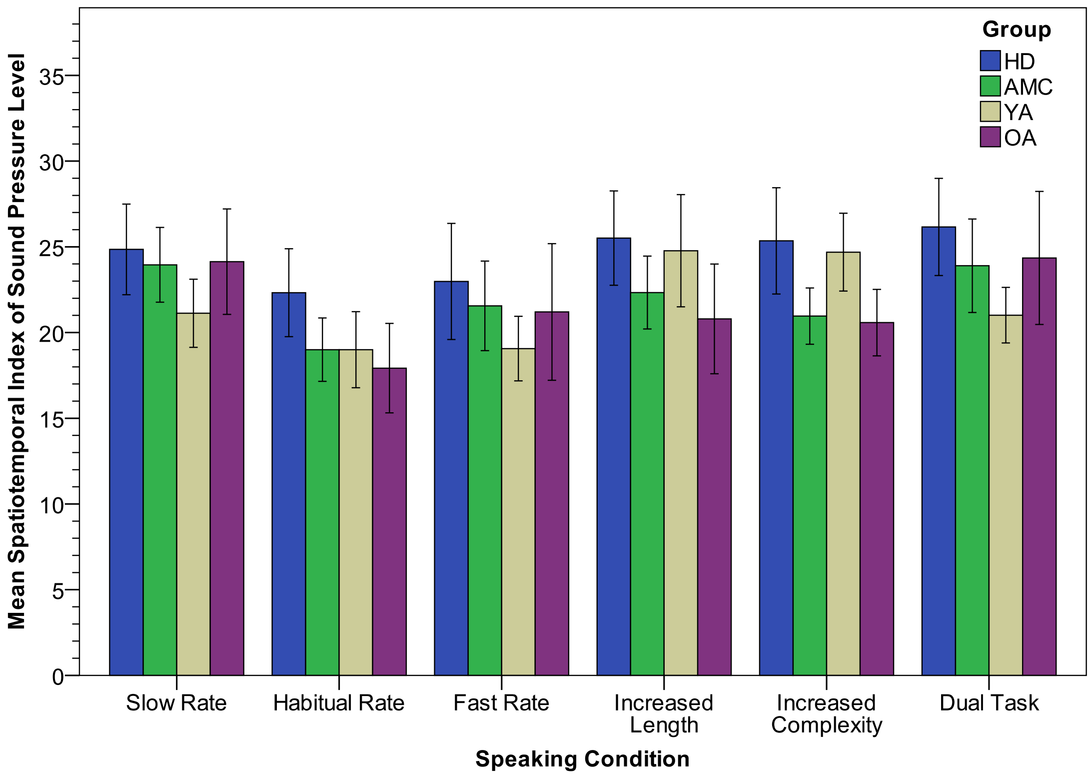

FIGURE 4.5: The spatiotemporal index of SPL in the six speaking conditions. Error bars represent a 95% confidence interval.

When comparing the two groups differing in age, the following results were found. The main effect of Group was non-significant: $F(1, 30.2) = .010$, $p = .920$. The main effect of Task was significant: $F(5, 233.6) = 7.30$, $p < .001$. Across groups, STIs in the Habitual Rate condition were lower compared to the Slow Rate, IL, IC and the Dual task conditions (all $p < .001$). The interaction effect of Group by Task was significant: $F(5, 233.6) = 6.41$, $p < .001$. Post-hoc comparisons per speech condition showed that in the IL and IC conditions, the YA group had higher STI values, compared to the OA group ($p = .015$ and $p = .012$, respectively). In the Dual condition, the effect was reversed; the OA group had a higher STI compared to the YA group ($p = .040$). When comparing speech conditions separately by group, it was shown that the YA had lower STIs in the Habitual Rate condition compared to the IL and IC conditions (both $p = .003$). The OA had lower STIs in the Habitual Rate condition compared to the Slow Rate and Dual task (both $p < .001$), and STIs in the IC condition were lower compared to the Slow

Rate (p = .034) and Dual task (p =.018). Furthermore, STIs in the IL condition were lower compared to the Dual task (p = .034).

4.5.3.2 Fundamental frequency

The mean STI of F0 is displayed in Figure 4.6, separated by group and task. Raw data are summarized in Appendix N.

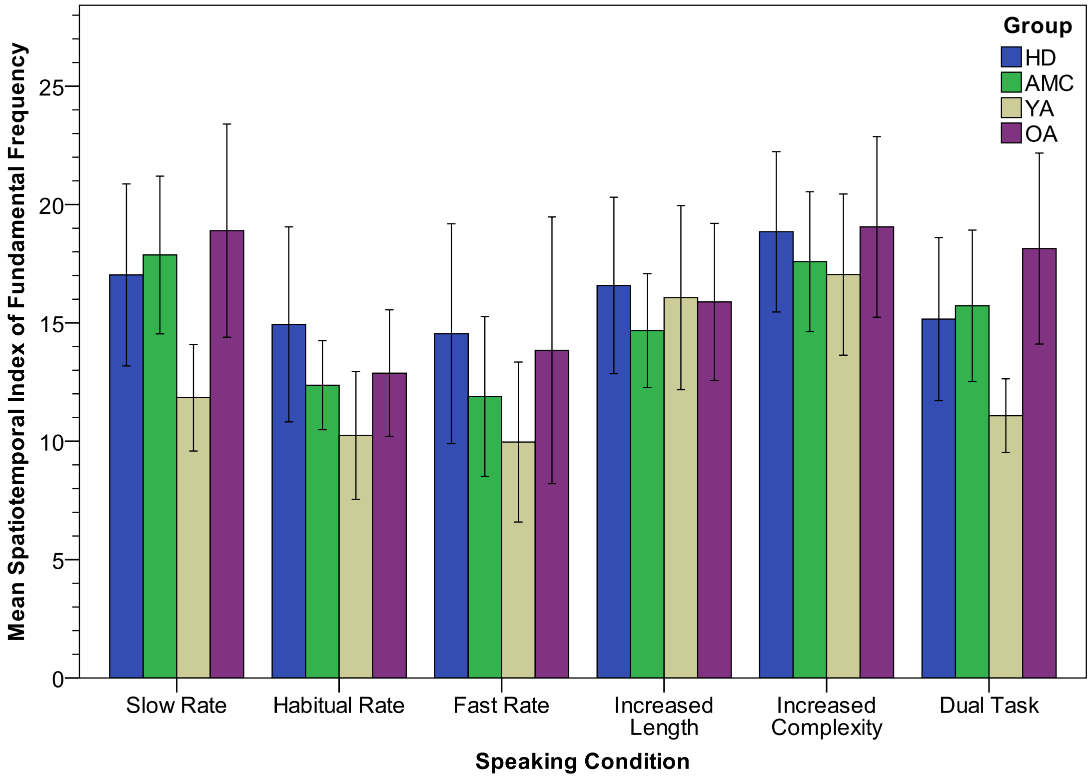

FIGURE 4.6: The spatiotemporal index of F0 in the six speaking conditions. Error bars represent a 95% confidence interval.

When comparing the STI of F0 between the HD and AMC groups, the following results were found. The main effect of Group was not significant: $F(1, 45.5) = .468$, $p = .497$, while the effect of Task was significant: $F(5, 314.7) = 7.37$, $p < .001$. The Habitual Rate condition showed lower STI values compared to the Slow Rate (p = .003) and IC conditions ($p < .001$), and the Fast Rate condition also showed lower STI values compared to the Slow Rate (p = .001) and IC conditions ($p < .001$). The Group by Task interaction effect was non-significant: $F(5, 314.7)$ = 1.00, p = .417. Post-hoc comparisons of groups per task did not indicate differences. When comparing tasks for each group it was found that the HD group did not show differences across tasks, while the AMC group displayed lower STIs in the Habitual Rate condition compared to the Slow Rate ($p < .001$), IC ($p < .001$) and Dual task ($p = .021$) conditions. Similarly, they showed lower STIs in the Fast Rate condition compared to the Slow Rate ($p < .001$), IC ($p < .001$) and Dual task ($p = .024$) conditions.

Comparison of the YA and OA groups showed the following. The main effect of Group was significant: $F(1, 31.1) = 7.92$, $p = .008$. The OA group showed higher STIs of F0 compared to the YA group. The effect of Task was also significant: $F(5, 235.3) = 8.24$, $p < .001$. The Habitual Rate conditions showed lower STIs compared to the Slow Rate condition ($p = .031$), the IL condition ($p = .006$), and the IC condition ($p < .001$). STIs in the Fast Rate condition were lower compared to the IL condition ($p = .015$) and the IC condition ($p < .001$). The Group by Task interaction effect was significant: $F(5, 235.3) = 2.78$, $p = .018$. Comparing the groups separately for each task, it was found that the OA group displayed higher STIs in the Slow Rate and Dual task (both $p = .001$) compared to the YA group. When comparing speech conditions separately by group, it was shown that the YA had lower STIs in the Habitual Rate task compared to the IL ($p = .030$) and IC ($p = .009$) conditions, as well as in the Fast Rate task compared to the IL ($p = .030$) and IC ($p = .005$) conditions. Furthermore, the YA showed higher STIs in the IC condition compared to the Dual Task condition ($p = .038$). The OA had lower STIs in the Habitual Rate condition compared to the Slow Rate ($p = .001$), IC ($p = .001$), and Dual task ($p = .007$) conditions. Furthermore lower STIs were found in the Fast Rate condition compared to the Slow Rate ($p = .011$) and IC ($p = .007$) conditions.

4.5.3.3 First formant

The mean STI of First Formant frequencies (F1) is displayed in Figure 4.7, separated by group and speech task, and raw data are listed in Appendix O.

When comparing the STI of F1 of the HD and AMC groups, the following results were found. The main effect of Group was significant: $F(1, 47.1) = 4.99$, $p = .030$; the HD group had a

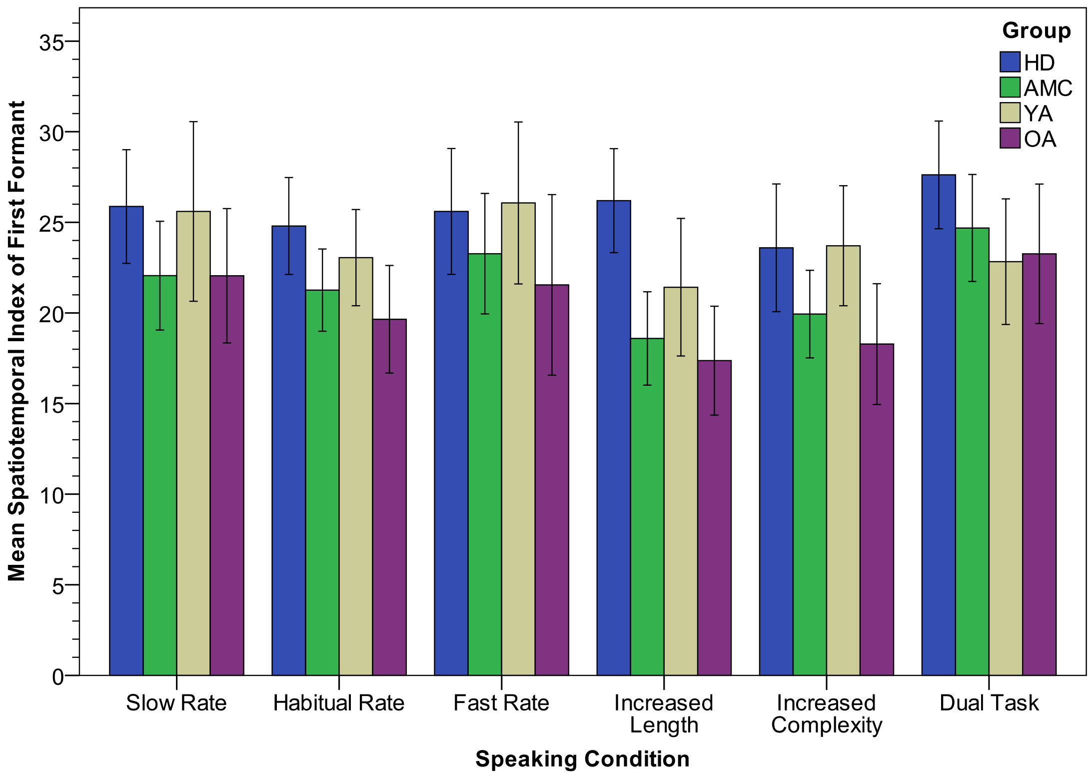

FIGURE 4.7: The spatiotemporal index of F1 in the six speaking conditions. Error bars represent a 95% confidence interval.

significantly higher STI value compared to the AMC group. The main effect of Task was significant: $F(5, 284.2) = 8.08$, $p < .001$. Compared to the Habitual Rate condition, the STI was higher in the Dual task ($p = .003$). The STI in the Fast Rate condition was higher compared to the IC condition ($p = .020$). The STI in the Dual task was higher in the IL ($p < .001$) and IC ($p < .001$) conditions. The Group by Task interaction effect was significant: $F(5, 284.2) = 2.35$, $p = .041$. The following significant post-hoc effects were found. When comparing Groups separately per Task, it was found that in the IL condition STI values were higher in the HD group compared to the AMC group ($p < .001$). When comparing Tasks per Group, it was found that the HD group had significantly higher STI values in the Dual task compared to the IC task ($p = .019$). The AMC group showed higher STI values in the Dual task compared to the Habitual rate ($p = .039$), the IL ($p < .001$), and the IC ($p < .001$) conditions. STIs in the Fast Rate conditions were higher compared to the IL ($p = .005$) and IC ($p = .018$) conditions, and in similar vain, STIs in the Slow Rate condition were higher compared to the IL ($p < .001$) and IC ($p = .002$) conditions.

When comparing the two groups differing in age, the following results were found. The main effect of Group was marginally significant: $F(1, 29.2) = 4.24$, $p = .049$. The YA group showed higher STI values compared to the OA group. The main effect of Task was significant: $F(5, 196.4) = 4.65$, $p < .001$. Mean STIs in the IL condition were lower compared to the Fast Rate ($p = .005$) and Slow Rate ($p = .004$) conditions. The Group by Task interaction effect was significant: $F(5, 196.4) = 2.57$, $p = .028$. When comparing the two groups for each task, it was found that the YA showed higher STIs in the Fast Rate ($p = .019$) and IC ($p = .009$) conditions, compared to the OA speakers. When comparing tasks for each group, it was found that the YA speakers did not show differences across speech tasks. The OA speakers had higher STIs in the Fast Rate condition compared to the IL condition ($p = .044$), higher STIs in the Slow Rate compared to the IL ($p = .001$) and IC ($p = .001$) conditions, and higher STIs in the Dual task compared to the IL and IC conditions (both $p < .001$).

4.5.3.4 Second formant

The mean STI of Second Formant frequencies (F2) is displayed in Figure 4.8, separated by group and speech task, and in raw data are listed in Appendix P.

When comparing the STI of F2 of the HD group with the AMC group, no significant main effect of Group was found: $F(1, 41.2) = 4.10$, $p = .050$. The effect of Task was significant: $F(5, 156.1) = 2.66$, $p = .025$. The STI of F2 in the Slow Rate task was higher compared to the Fast Rate task ($p = .038$). The interaction effect of Group by Task was not significant: $F(5, 156.1) = 1.97$, $p = .086$, but some post-hoc comparisons were significant. When comparing the groups for individual tasks, it was found that the HD group had higher STI values in the Habitual Rate condition compared to the AMC group ($p = .004$). When comparing Tasks for each Group, the results showed that the HD group showed a marginally higher STI in the Habitual Rate condition compared to the Fast Rate condition ($p = .045$). The AMC group did not show differences across tasks.

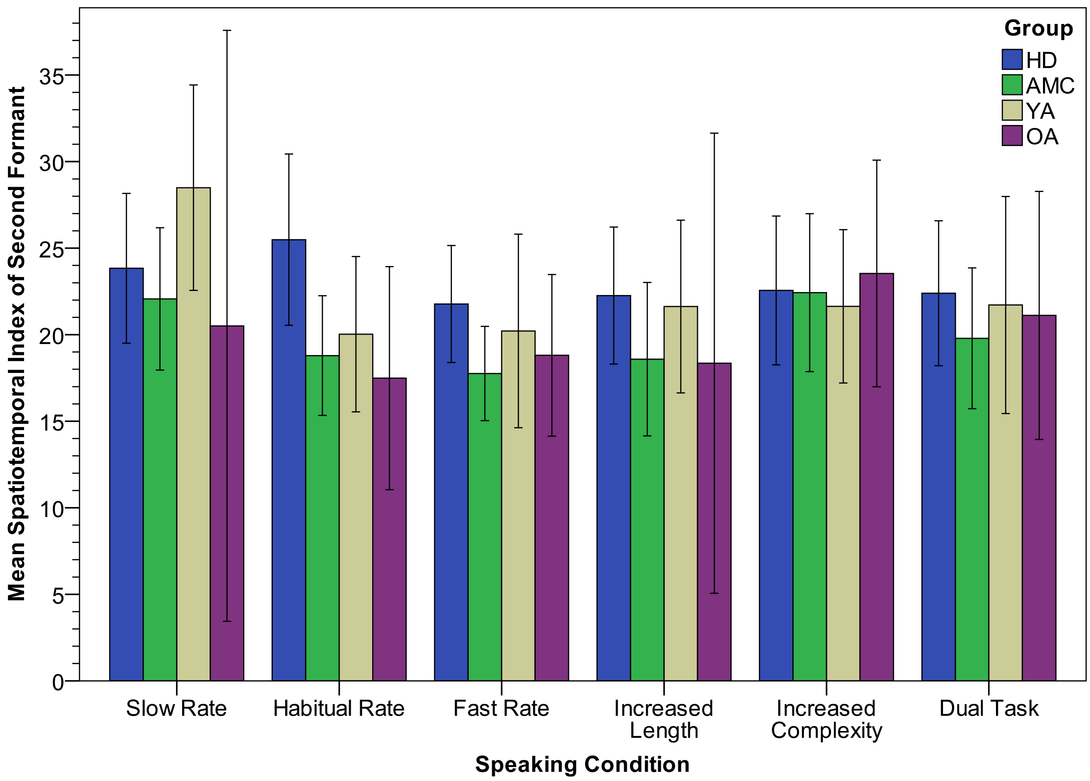

FIGURE 4.8: The spatiotemporal index of F2 in the six speaking conditions. Error bars represent a 95% confidence interval.

The analysis of the groups differing in age did not yield significant results. The effect of Group was: $F(1, 27.1) = .797$, $p = .380$; Task: $F(5, 97.2) = 2.30$, $p = .051$ and Group by Task: $F(5, 97.2) = 1.39$, $p = .236$. Further post-hoc comparisons were also not significant.

4.5.3.5 Summary of results: the spatiotemporal index

The statistical results of the spatiotemporal index and the average group values showed the following noteworthy trends. Variability was generally higher in the HD speakers compared to the AMC speakers across all four speech parameters. However, significant group differences across all speaking conditions were only found for SPL and F1. Absolute differences in group means were the smallest in F0 compared to other speech parameters. With respect to F2, absolute differences in group means were comparable to those found for F1. However, as a sizable portion of F2 data had to be discarded, differences between groups did not become significant, as suggested by the finding that at least some comparisons between YA and OA speakers were nearly significant, e.g., the main effect of Group and the interaction effect of Group x Task in the comparison between HD and AMC speakers, as well as the effect of Task in the comparison between YA and OA speakers.

Notable findings of the YA and OA groups were that, across speech tasks, the OA group showed higher variability in F0, compared to the YA group. In contrast, the YA group showed higher F1 variability compared to the OA group.

Generally, the Habitual and Fast Rate conditions resulted in the lowest STI values, and this pattern was mostly present for all groups, and across all speech parameters.

4.5.4 Spatial variability

Group averages and standard deviations of spatial variability of the six speaking conditions are displayed in table 4.5, separated by speech parameter.

TABLE 4.5: Group averages and standard deviations of spatial variability.

Parameter	Group	Slow	Hab	Fast	IL	IC	Dual
SPL	HD	0.368 (0.107)	0.333 (0.107)	0.357 (0.133)	0.385 (0.113)	0.386 (0.117)	0.407 (0.108)
	AMC	0.351 (0.082)	0.282 (0.072)	0.334 (0.108)	0.345 (0.080)	0.322 (0.066)	0.379 (0.119)
	YA	0.340 (0.070)	0.308 (0.075)	0.309 (0.06)	0.402 (0.125)	0.393 (0.076)	0.345 (0.054)
	OA	0.357 (0.089)	0.266 (0.081)	0.331 (0.126)	0.323 (0.088)	0.313 (0.065)	0.390 (0.130)
F0	HD	0.264 (0.140)	0.236 (0.159)	0.241 (0.195)	0.255 (0.143)	0.284 (0.127)	0.236 (0.122)
	AMC	0.275 (0.128)	0.186 (0.070)	0.184 (0.152)	0.215 (0.080)	0.269 (0.118)	0.247 (0.134)
	YA	0.189 (0.062)	0.161 (0.078)	0.148 (0.079)	0.252 (0.115)	0.248 (0.096)	0.168 (0.040)
	OA	0.281 (0.116)	0.192 (0.071)	0.219 (0.191)	0.231 (0.081)	0.292 (0.12)	0.285 (0.127)
F1	HD	0.388 (0.134)	0.371 (0.134)	0.403 (0.164)	0.376 (0.130)	0.368 (0.153)	0.427 (0.133)
	AMC	0.311 (0.102)	0.313 (0.099)	0.352 (0.159)	0.259 (0.095)	0.286 (0.117)	0.368 (0.138)
	YA	0.415 (0.105)	0.361 (0.100)	0.410 (0.150)	0.313 (0.086)	0.376 (0.136)	0.357 (0.099)
	OA	0.316 (0.112)	0.274 (0.087)	0.317 (0.183)	0.243 (0.090)	0.241 (0.095)	0.338 (0.127)
F2	HD	0.338 (0.114)	0.368 (0.163)	0.304 (0.133)	0.299 (0.119)	0.329 (0.138)	0.319 (0.120)
	AMC	0.321 (0.095)	0.273 (0.089)	0.226 (0.059)	0.240 (0.070)	0.322 (0.153)	0.287 (0.087)
	YA	0.457 (0.070)	0.309 (0.106)	0.290 (0.127)	0.280 (0.091)	0.332 (0.109)	0.307 (0.118)
	OA	0.247 (0.087)	0.266 (0.096)	0.235 (0.068)	0.241 (0.089)	0.343 (0.180)	0.305 (0.105)

4.5.4.1 Sound pressure level

The mean spatial variability values of sound pressure level are displayed in Figure 4.9, separated by group and speech task, and in Appendix Q.

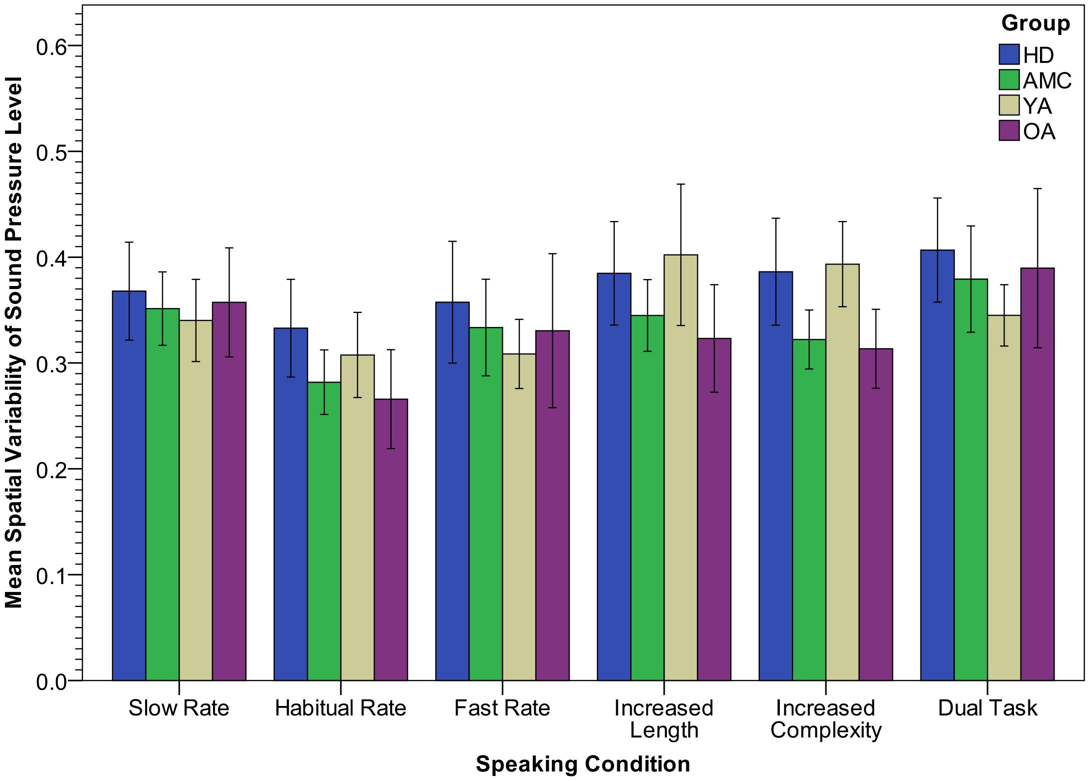

FIGURE 4.9: Spatial variability of SPL in the six speaking conditions. Error bars represent a 95% confidence interval.

When comparing SpatVar of SPL between the HD and AMC group, the following results were found. The main effect of Group was not significant: $F(1, 46.0) = 3.54$, $p = .066$. The effect of Task was significant: $F(5, 314.4) = 7.90$, $p < .001$. Across groups, SpatVar in the Habitual Rate condition was significantly lower compared to the Slow Rate ($p = .002$), IL ($p = .002$), IC ($p = .010$) and Dual task ($p < .001$). Furthermore, SpatVar in the Fast Rate condition was lower compared to the Dual task ($p = .011$). The Group by Task interaction effect was not significant: $F(5, 314.4) = 1.13$, $p = .343$, however, some post-hoc comparisons were significant: SpatVar in the IC task was significantly higher in the HD group compared to the AMC group. Individual group differences between tasks were as follows. The HD group displayed lower SpatVar values in the Habitual Rate condition compared to the Dual Task ($p = .026$).

The AMC group showed lower SpatVar in the Habitual Rate condition compared to the Slow Rate ($p < .001$), the Fast Rate ($p = .028$), IL ($p = .012$), and Dual task ($p < .001$) conditions. In addition, SpatVar in the IC condition was lower compared to the Dual task condition ($p = .006$).

When comparing the two groups differing in age, the following results were found. The Group effect was not significant: $F(1, 30.0) = .959$, $p = .335$. The effect of Task was significant: $F(5, 233.4) = 6.56$, $p < .001$. Across groups, lower SpatVar values were found in the Habitual Rate condition compared to the Slow Rate ($p = .007$), IL ($p < .001$), IC ($p = .002$), and Dual task ($p < .001$) conditions. The Group by Task interaction effect was significant: $F(5, 233.4) = 5.15$, $p < .001$. When comparing groups across tasks, it was found that in the IL and IC conditions, SpatVar was higher in the Young Adult group compared to the Older Adult group (both $p = .008$). When comparing speech tasks separately for the two groups, the following comparisons were significant. For the YA, SpatVar was significantly lower in the Habitual Rate condition, compared to the IL ($p = .009$) and IC ($p = .027$) conditions. SpatVar in the Fast Rate condition was also lower compared to the IL ($p = .010$) and the IC ($p = .030$) conditions. For the OA, SpatVar was significantly lower in the Habitual Rate condition compared to the Slow Rate ($p < .001$), Fast Rate ($p = .028$), and Dual task ($p < .001$) conditions. In addition, SpatVar in the IL ($p = .021$) and IC ($p = .004$) were significantly lower compared to the Dual task condition.

4.5.4.2 Fundamental frequency

The mean SpatVar of fundamental frequency (F0) contours is displayed in Figure 4.10, separated by group and speech task, and in Appendix R.

The HD group and AMC group did not differ across spatial variability of fundamental frequency contours: $F(1, 45.0) = 699$, $p = .408$. The effect of Task was significant: $F(5, 314.2) = 4.35$, $p = .001$. Across groups, SpatVar was lower in the Habitual Rate condition, compared to the Slow Rate ($p = .026$) and IC ($p = .005$) conditions. SpatVar was lower in the Fast Rate condition compared to the IC condition ($p = .019$). The Group by Task interaction effect was not significant: $F(5, 314.2) = 1.138$, $p = .340$. Some individual post-hoc comparisons were

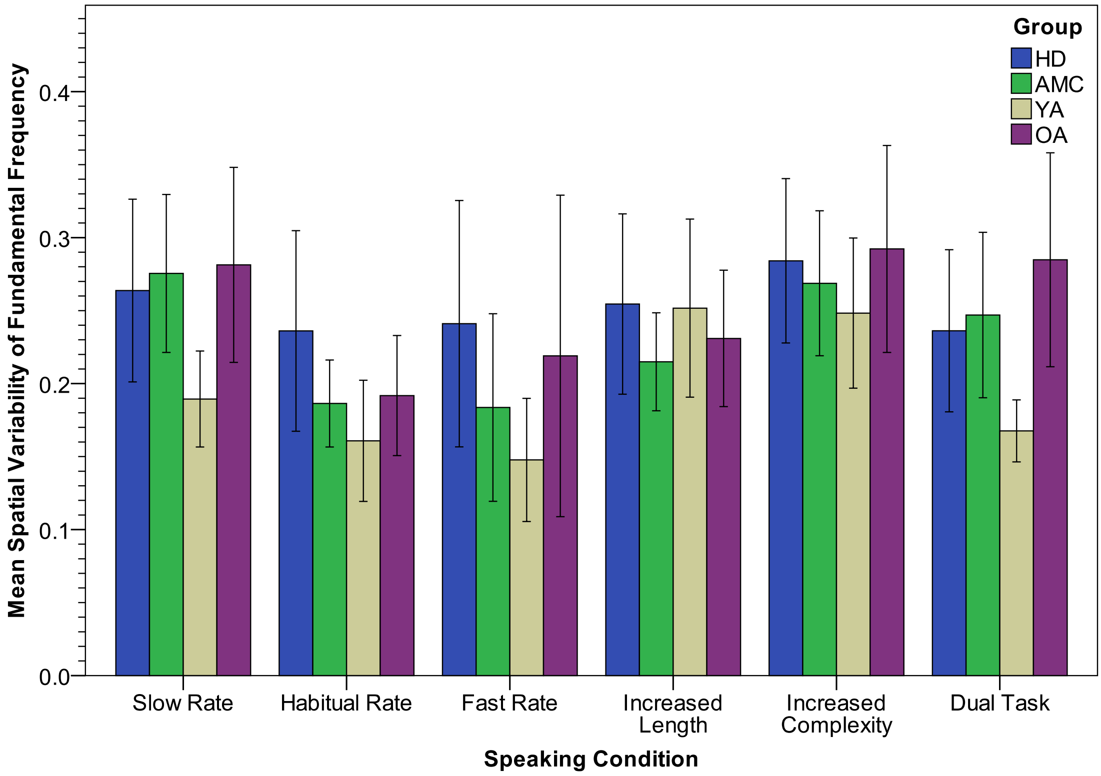

FIGURE 4.10: Spatial variability of F0 in the six speaking conditions. Error bars represent a 95% confidence interval.

significant when comparing tasks separately per speaker group. The AMC group displayed lower SpatVar values in the Habitual Rate condition compared to the Slow Rate (p = .002), IC (p = .002), and Dual task (p =.023) conditions. SpatVar was lower in the Fast Rate condition compared to the Slow Rate and IC conditions (both p = .006). The HD group did not show differences across tasks.

The YA and OA groups significantly differed in SpatVar: $F(1, 33.0) = 7.85$, p = .008; the OA groups showed higher variability across tasks compared to the YA group. The effect of Task was also significant: $F(5, 236.7) = 5.57$, $p < .001$. SpatVar in the Habitual Rate task was significantly lower compared to the IL (p = .043) and IC ($p < .001$) conditions. SpatVar in the Fast Rate condition was lower compared to the IC condition (p = .001). The Group by Task interaction effect was significant: $F(5, 236.7) = 2.56$, p = .028. The OA group showed higher SpatVar in the Slow Rate (p = .008), Fast Rate (p = .039), and Dual task (p = .001) conditions, compared to the YA group. When comparing tasks per group, it was found that the YA group showed a marginally higher SpatVar in the IL condition compared to the Fast Rate condition (p = .042). The OA group showed higher SpatVar in the Slow Rate (p = .010), IL (p = .002), and Dual task (p = .006) conditions, compared to the Habitual Rate condition.

4.5.4.3 First formant

Spatial variability was calculated for the contours of speech parameter first formant (F1). The mean SpatVar of F1 is displayed in Figure 4.11, separated by group and speech task, and in Appendix S.

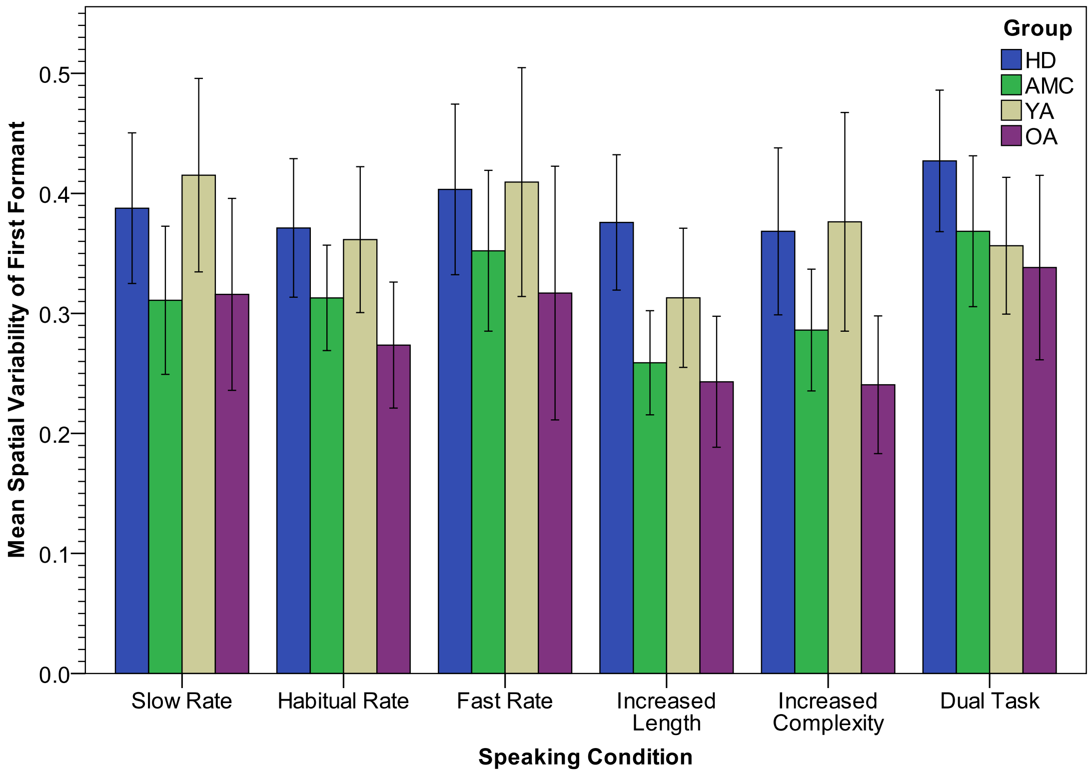

FIGURE 4.11: Spatial variability of F1 in the six speaking conditions. Error bars represent a 95% confidence interval.

When comparing SpatVar of F1 between the HD and AMC groups, the following results were found. The main effect of Group was not significant: $F(1, 47.0) = 3.97$, $p = .052$. The effect of Task was significant: $F(5, 284.2) = 6.43$, $p < .001$. SpatVar was lower during Habitual Rate compared to the Dual task (p = .020), and lower in the IC condition compared to the Fast Rate condition (p = .034). Furthermore, SpatVar values in the IL and IC conditions (both p < .001) were lower compared to the Dual task condition. The Group by Task interaction effect was not significant: F(5, 284.2) = 1.09, p = .368. Post-hoc comparisons were significant when comparing the groups per task: the HD group showed higher SpatVar in the IL (p = .012) and the IC (p = .022) conditions compared to the AMC group. When comparing tasks per group it was found that the AMC group showed lower variability in the IL condition compared to the Slow Rate (p = .010) , Fast Rate (p = .017), and Dual task (p < .001) conditions, as well as lower variability in the IC condition compared to the Slow Rate (p = .009), Fast Rate (p = .013), and Dual task (p < .001) conditions.

When comparing the two groups differing in age, the following results were found. The main effect of Group was significant: F(1, 30.2) = 5.06, p = .032. SpatVar was significantly higher in the Young Adult group, compared to the Older Adult group. The effect of Task was significant: F(5, 197.0) = 5.11, p < .001. Across groups was SpatVar significantly lower in the IL condition compared to the Slow Rate (p = .002) and Fast Rate (p = .004) conditions, as well as lower in the IC condition compared to the Slow Rate (p = .021) and the Fast Rate condition (p = .038). No significant interaction effect of Task by Group was present: F(5, 197.0) = 2.09, p = .069. However, some post-hoc comparisons were significant. When comparing groups separately for task, it was found that the YA group had higher SpatVar compared to the OA in the Fast Rate (p = .016) and IC (p = .004) conditions. When comparing tasks separately for group, it was found that the OA group had lower SpatVar in the IL condition compared to the Slow Rate (p = .014) and Dual task (p = .004) conditions, and lower SpatVar in the IC condition compared to the Slow Rate (p = .001), Fast Rate (p = .011), and Dual task (p < .001) conditions. No task differences were found for the YA group.

4.5.4.4 Second formant

The mean spatial variability values of speech parameter second formant (F2) are displayed in Figure 4.12, separated by group and speech task, and raw data are displayed in Appendix T.

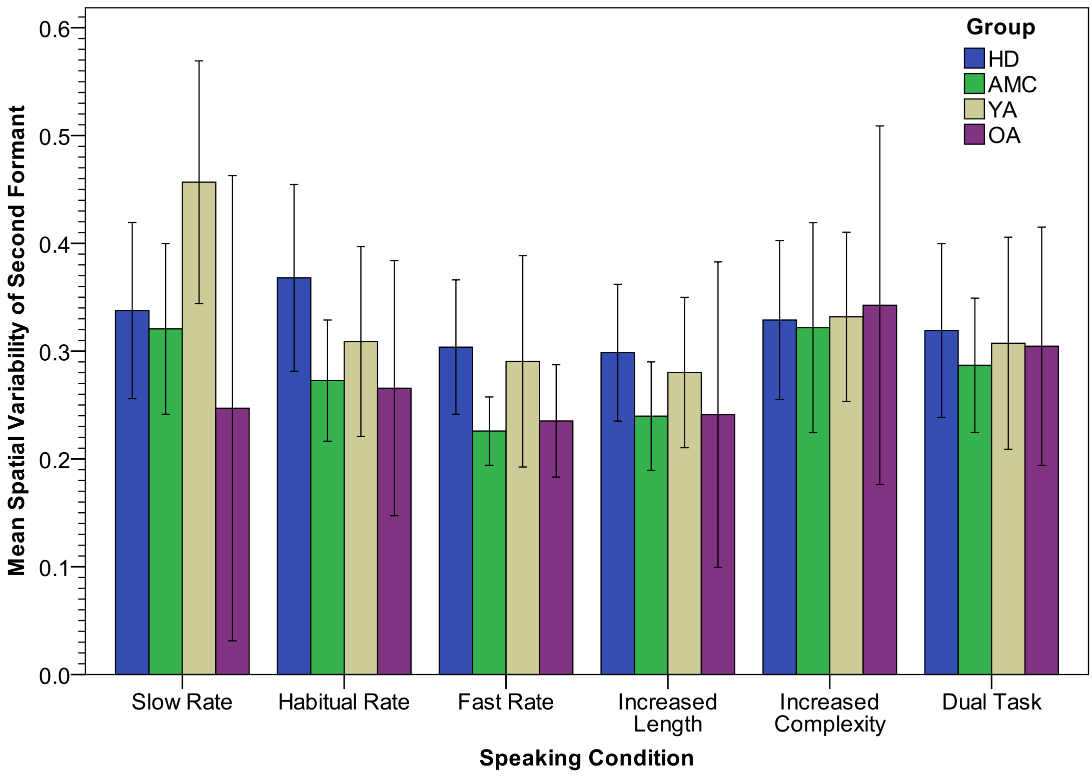

FIGURE 4.12: Spatial variability of F2 in the six speaking conditions. Error bars represent a 95% confidence interval.

When comparing SpatVar of F2 in the HD group and AMC group, no significant results were found for the main effect of Group: $F(1, 42.2)$ 2.98, p = .092. The effect of Task was significant: $F(5, 157.2) = 3.20$, p = .009. SpatVar in the Fast Rate condition was lower compared to the Slow Rate (p = .043) and Habitual Rate (p = .026) conditions. The interaction effect of Group by Task was not significant: $F(5, 157.2)$ = .850, p = .516. Further post-hoc comparisons revealed a marginally higher SpatVar for the HD group in the Habitual Rate condition compared to the AMC group (p = .043). No task differences were found separated by group.

The following was found when comparing the two groups differing in age. The effect of Group was non-significant: $F(1, 27.5) = 1.41$, p = .245. There was a marginally significant effect of Task: $F(5, 97.7) = 2.50$, p = .036, but no significant differences were found amongst the speaking conditions. The Group by Task interaction effect was not significant: $F(5, 97.7)$ = 1.83, p = .114. However, post-hoc comparisons revealed that in the Slow Rate condition, the

YA group showed higher SpatVar compared to the OA group (p = .012). When comparing tasks per group, it was found that the YA group had higher SpatVar in the Slow Rate compared to the IL condition (p = .012). No task differences were found for the OA group.

4.5.4.5 Summary of results: spatial variability

The statistical results of spatial variability showed that, whilst average values were always higher in the HD group, no significant group differences were found when pooled over speaking conditions. As evidenced by the large standard deviations, both groups showed a large within-group variation, possibly contributing to the non-significant results. However, group differences were found across all four speech parameters for at least one individual task: usually the IC speaking condition.

The spatial variability results of the YA and OA speakers largely reflected those found for the STI: in comparing groups, the OA group showed higher F0 variability, whilst the YA group showed higher F1 variability.

The habitual rate task displayed generally the lowest spatial variability across speaker groups and speaking conditions.

4.5.5 Temporal variability

Group averages and standard deviations of temporal variability of the six speaking conditions are displayed in table 4.6, separated by speech parameter.

4.5.5.1 Sound pressure level

The mean temporal variability of SPL is displayed in Figure 4.13, separated by group and speech task, and in Appendix U.

TABLE 4.6: Group averages and standard deviations of temporal variability.

Parameter	Group	Slow	Hab	Fast	IL	IC	Dual
SPL	HD	0.0209 (0.0088)	0.0161 (0.0057)	0.0198 (0.0110)	0.0213 (0.0096)	0.0199 (0.0082)	0.0248 (0.0131)
	AMC	0.0171 (0.0062)	0.0152 (0.0081)	0.0172 (0.0085)	0.0145 (0.0050)	0.0135 (0.0037)	0.0179 (0.0095)
	YA	0.0164 (0.0041)	0.0166 (0.0045)	0.0211 (0.0090)	0.0188 (0.0105)	0.0215 (0.0102)	0.0185 (0.0064)
	OA	0.0189 (0.0070)	0.0132 (0.0072)	0.0169 (0.0107)	0.0130 (0.0036)	0.0135 (0.0041)	0.0178 (0.0111)
F0	HD	0.0369 (0.0220)	0.0345 (0.0224)	0.0336 (0.0187)	0.0420 (0.0206)	0.0394 (0.0166)	0.0387 (0.0162)
	AMC	0.0261 (0.0120)	0.0286 (0.0141)	0.0292 (0.0196)	0.0358 (0.0230)	0.0316 (0.0166)	0.0354 (0.0223)
	YA	0.0225 (0.0126)	0.0269 (0.0128)	0.0284 (0.0124)	0.0394 (0.0250)	0.0382 (0.0150)	0.0327(0.0117)
	OA	0.0285 (0.0147)	0.0293 (0.0169)	0.0326 (0.0243)	0.0397 (0.0281)	0.0296 (0.0140)	0.0379 (0.0232)
F1	HD	0.0262 (0.0155)	0.0212 (0.0069)	0.0274 (0.0152)	0.0287 (0.0147)	0.0216 (0.0112)	0.0332 (0.0202)
	AMC	0.0160 (0.0039)	0.0156 (0.0059)	0.0221 (0.0093)	0.0158 (0.0059)	0.0160 (0.0045)	0.0247 (0.0130)
	YA	0.0229 (0.0064)	0.0236 (0.0107)	0.0416 (0.0264)	0.0217 (0.0080)	0.0246 (0.0097)	0.0264 (0.0106)
	OA	0.0164 (0.0041)	0.0152 (0.0052)	0.0206 (0.0081)	0.0141 (0.0043)	0.0143 (0.0039)	0.0221 (0.0124)
F2	HD	0.0272 (0.0084)	0.0307 (0.0161)	0.0268 (0.0098)	0.0297 (0.0173)	0.0240 (0.0092)	0.0274 (0.0117)
	AMC	0.0215 (0.0076)	0.0202 (0.0106)	0.0200 (0.0079)	0.0242 (0.0142)	0.0256 (0.0140)	0.0206 (0.0080)
	YA	0.0244 (0.0100)	0.0199 (0.0147)	0.0211 (0.0108)	0.0244 (0.0133)	0.0178 (0.0058)	0.0221 (0.0145)
	OA	0.0211 (0.0068)	0.0153 (0.0087)	0.0200 (0.0091)	0.0221 (0.0159)	0.0243 (0.0124)	0.0203 (0.0088)

When comparing TempVar of SPL of the HD and AMC group, the following results were found. The effect of Group was significant: $F(1, 46.4) = 6.80$, $p = .012$; TempVar of sound pressure level was significantly higher in the HD group compared to the AMC group. The effect of Task was significant: $F(5, 314.8) = 6.84$, $p < .001$. TempVar in the Habitual Rate task was lower compared to the Slow Rate ($p = .006$) and Dual task ($p < .001$) conditions. TempVar was also lower in the IL ($p = .016$) and IC ($p = .001$) conditions compared to the Dual task condition. The Group by Task interaction effect was significant: $F(5, 314.8) = 2.38$, $p = .038$. When comparing groups for each task, it was found that the HD group had higher TempVar in the IL ($p = .002$), IC ($p = .009$), and Dual task ($p = .003$) conditions compared to the AMC group. When comparing tasks per group, it was found that the HD had higher TempVar in the Dual task compared to the Habitual Rate condition ($p < .001$). The AMC group had higher TempVar in the Slow Rate ($p = .036$) and Dual task ($p = .028$) conditions compared to the IC condition.

When comparing the two groups differing in age, it was found that the effect of Group was not significant: $F(1, 30.0) = 3.46$, $p = .073$. The effect of Task was marginally significant: $F(5, 233.4) = 2.34$, $p = .043$, but no task differences were found across groups. The interaction

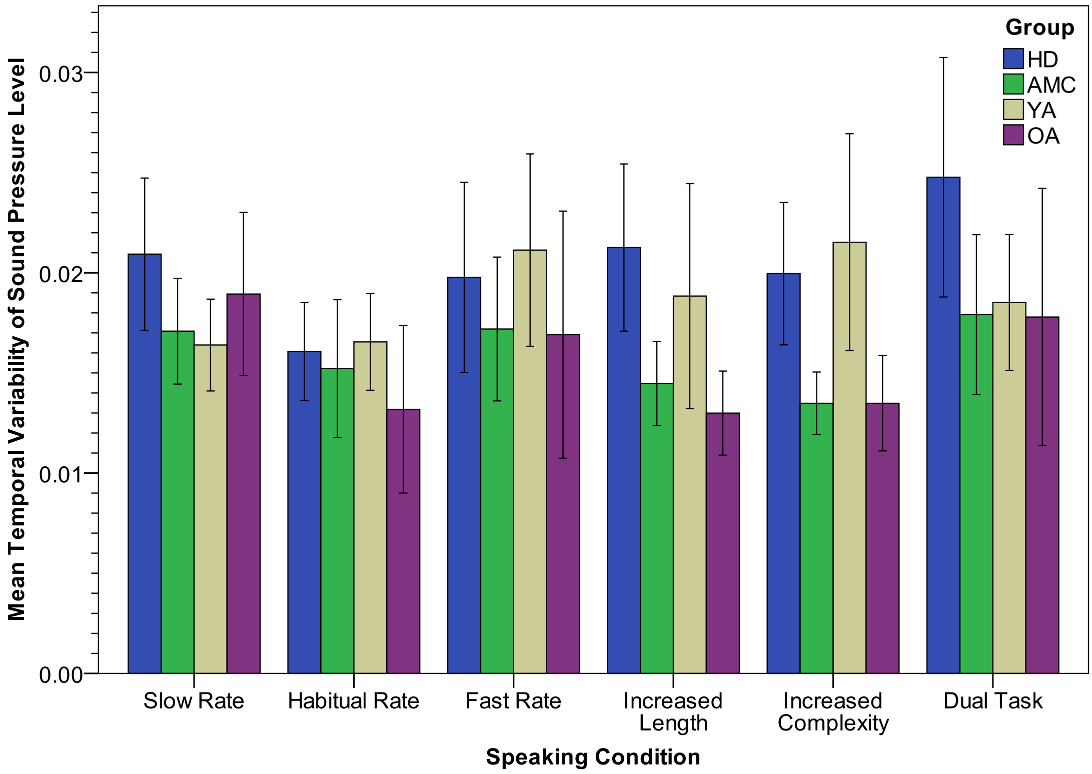

FIGURE 4.13: Temporal variability of SPL in the six speaking conditions. Error bars represent a 95% confidence interval.

effect of Group by Task was significant: $F(5, 233.4) = 3.64$, $p = .003$. The YA group had higher TempVar in the IL ($p = .022$) and the IC ($p = .002$), compared to the OA group. When comparing tasks for each group, it was found that the YA group did not show differences across the tasks. The OA group showed higher TempVar in the Slow Rate condition compared to the Habitual Rate ($p = .012$), the IL ($p = .008$) and IC ($p = .022$) conditions.

4.5.5.2 Fundamental frequency

The mean TempVar of fundamental frequency contours (F0) is displayed in Figure 4.14, separated by group and speech task, and in Appendix V.

When comparing TempVar of F0 between the HD group and AMC group, the following results were found. The effect of Group was non-significant: $F(1, 46.8) = 2.74$, $p = .105$. The effect of Task was significant: $F(5, 316.1) = 2.88$, $p = .015$, but no task differences were found across groups. The Group by Task interaction effect was not significant: $F(5, 316.1) = .491$, $p =$

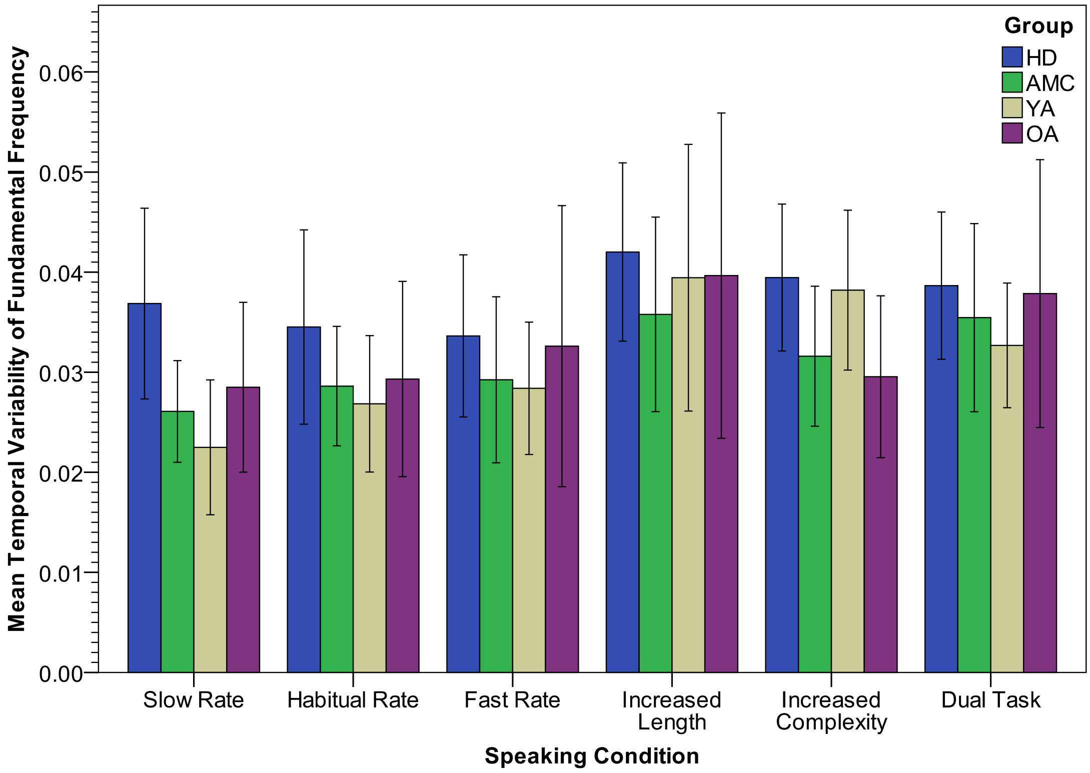

FIGURE 4.14: Temporal variability of F0 in the six speaking conditions. Error bars represent a 95% confidence interval.

.783. Some post-hoc comparisons were significant. When comparing groups per task, it was found that TempVar was marginally higher during the Slow Rate condition for the HD group compared to the AMC group (p = .049). When comparing tasks per groups, the results showed no task differences for the HD group. For the AMC group, TempVar in the Slow Rate condition was marginally lower compared to the IL condition (p = .049).

When comparing the groups differing in age, no significant main effect of Group was found: $F(1, 33.7)$ = .190, p = .666. The effect of Task was significant: $F(5, 237.5) = 3.96$, p = .002. TempVar in the Habitual Rate (p = .027) and Slow Rate (p = .002) conditions were lower compared to the IL condition. The interaction effect of Group by Task was significant: $F(5, 237.5) = 1.10$, p = .356. No differences were found between groups when evaluating tasks separately. No significant effects were found when comparing tasks separated by group.

4.5.5.3 First formant

The mean TempVar of first formant frequency contours (F1) is displayed in Figure 4.15, separated by group and speech task, and raw data can be found in Appendix W.

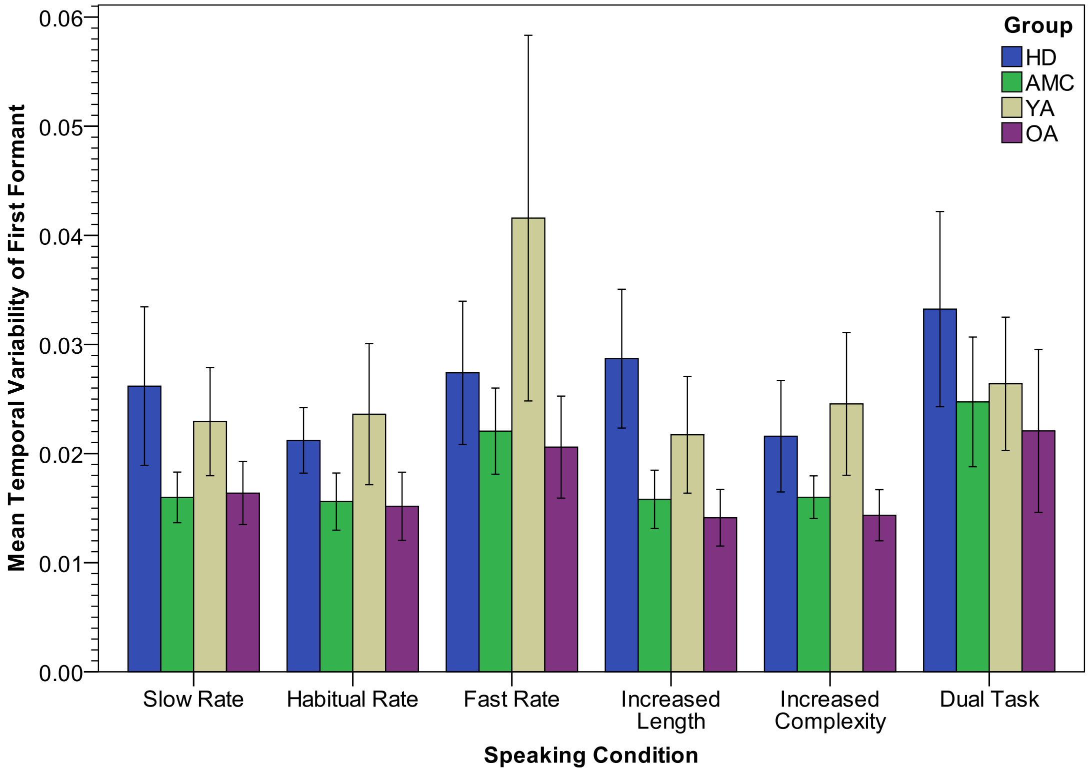

FIGURE 4.15: Temporal variability of F1 in the six speaking conditions. Error bars represent a 95% confidence interval.

When comparing TempVar of F1 between the HD and AMC groups, the following results were found. The effect of Group was significant: $F(1, 45.9) = 12.9$, $p = .001$; TempVar was higher in the HD group compared to the AMC group. The effect of Task was also significant: $F(5, 283.8) = 11.9$, $p < .001$. Across groups it was found that TempVar was higher in the Dual task compared to the Slow Rate, Habitual Rate, IL, and IC conditions (all $p < .001$). In addition TempVar in the Fast Rate condition was significantly higher compared to the Habitual Rate condition ($p = .002$). The interaction effect of Group by Task was not significant: $F(5, 283.8) = 1.92$, $p = .090$. When comparing groups per task, it was found that the HD group showed higher TempVar in the Slow Rate ($p = .005$), IL ($p < .001$), and Dual task ($p = .002$) conditions. When comparing task for each speaker group, it was found that the HD group had higher

TempVar in the Dual task condition compared to the Slow Rate (p = .039), Habitual Rate (p < .001), and IC (p < .001) conditions, and TempVar was higher in the IL condition compared to the Habitual Rate condition (p = .037). The AMC group displayed higher TempVar in the Dual task condition compared to the Slow Rate (p = .015), Habitual Rate (p = .001), IL (p < .001), and IC (p = .001) conditions. Furthermore, TempVar in the Fast Rate condition was higher compared to the Habitual Rate (p = .030), IL (p = .023), and IC (p = .032) conditions.

When comparing the Young and Older adults, the following results were found. The Group effect was significant: $F(1, 23.6) = 13.5$, $p = .001$. Across speech tasks, the group of Young adults had significantly higher TempVar compared to the group of Older adults. The effect of Task was significant: $F(5, 190.5) = 14.4$, $p < .001$. TempVar in the Fast Rate condition was higher compared to the Slow Rate, Habitual Rate, IL, IC conditions (all p < .001), and the Dual task condition (p = .002). Furthermore, TempVar in the Dual task condition was higher compared to the IL condition (p = .036). The interaction effect of Group by Task was significant: $F(5, 190.5) = 5.05$, $p < .001$. When comparing groups per task, it was found that TempVar was higher in the YA group during Slow Rate (p = .042), Habitual Rate (p = .015), Fast Rate (p < .001), IL (p = .011), and IC (p = .006) conditions, compared to the OA group. When comparing tasks per group, it was found that the OA had higher TempVar in the Dual task compared to the Habitual Rate (p = .011), IL (p = .002), and IC (p = .004) conditions. In addition, TempVar was higher in the Fast Rate condition, when compared to the IL (p = .016) and IC (p = .036) conditions. The YA group showed higher TempVar in the Fast Rate condition compared to all other conditions (p < .001).

4.5.5.4 Second formant

The mean TempVar of second formant frequency contours (F2) is displayed in Figure 4.16, and raw data are displayed in Appendix X.

When comparing the HD and AMC groups it was found that TempVar of F2 was significantly higher in the HD group: $F(1, 42.6) = 7.45$, $p = .009$. The effect of Task was not significant:

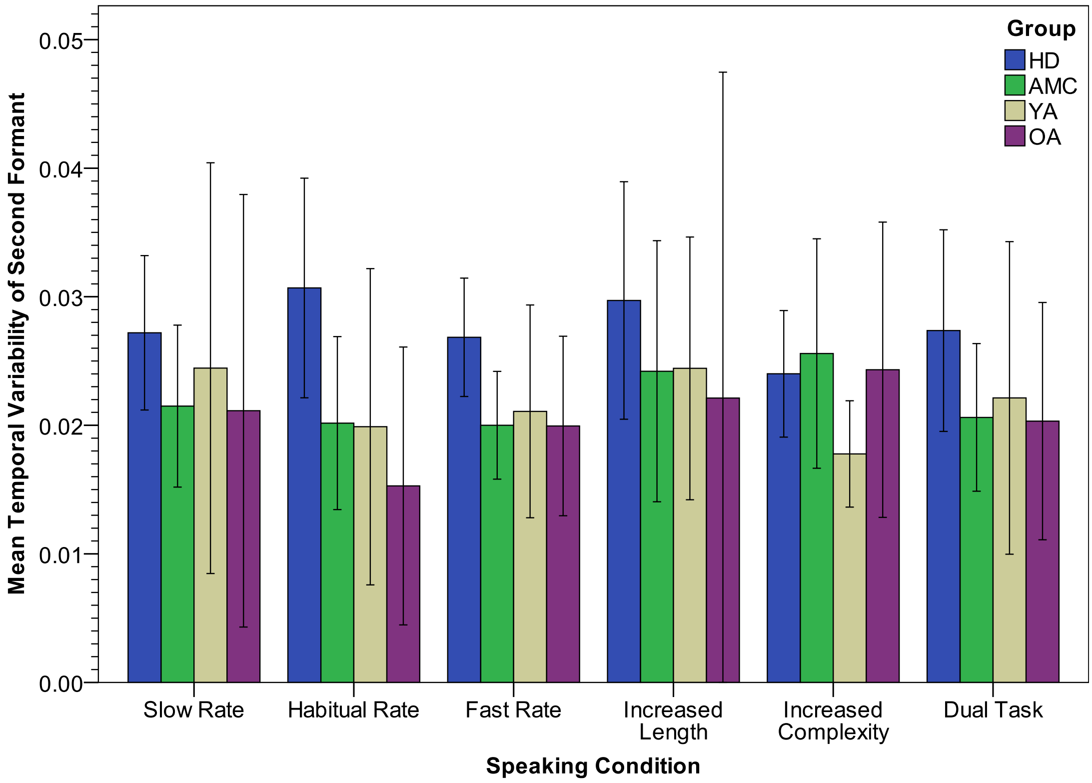

FIGURE 4.16: Temporal variability of F2 in the six speaking conditions. Error bars represent a 95% confidence interval.

$F(5, 163.1) = .728$, $p = .603$. The Group by Task effect was also non-significant: $F(5, 163.1) = 1.96$, $p = .087$. When comparing groups for individual tasks it was found that the HD group displayed higher TempVar in the Habitual Rate ($p = .001$) and Dual task ($p = .018$) conditions, compared to the AMC group. No further post-hoc comparisons were significant.

When comparing the group of Young adults with the group of Older adults, no significant results were found; Group: $F(1, 23.7) = .708$, $p = .490$; Task: $F(5, 96.8) = 1.18$, $p = .327$; Group by Task $F(5, 96.8) = 1.59$, $p = .170$. None of the post-hoc pairwise comparisons yielded significance.

4.5.5.5 Summary of results: temporal variability

The results of the analysis of the temporal variability estimator showed that, across speaking conditions, the speakers of the HD group demonstrated higher variability values for SPL, F1, and F2, compared to the AMC group, with the largest group differences found in the dual task condition.

Group differences between young and older speakers were limited, with the most notable finding of higher F1 temporal variability in the group of YA speakers, reflecting the results of the STI and spatial variability.

4.5.6 Summary of variability results

Comparisons between groups

A systematic overview of all significant results of the LMM analyses of variability comparisons between groups is listed in table 4.7. This table compares the four speaker groups side by side, i.e., the HD group versus the AMC group and the YA group versus the OA group, separately for each variability estimator and speech parameter. The table indicates significant outcomes for overall group effects as well as for individual task effects. The overall group effects represent the main effects of Group pooled over all six speaking conditions, and are reported in the unshaded table rows. Individual task effects were derived from the post-hoc analyses for each group comparison, and are reported in the shaded rows. In each comparison that showed significant differences, the table indicates which speaking conditions were affected as well as the general direction of the differences, i.e., which group showed a higher degree of variability. The direction of group differences in individual tasks as established by the post-hoc analyses followed the direction of the main effect of Group, unless stated otherwise.

When comparing variability across groups, the analyses showed that in general speakers with hypokinetic dysarthria displayed higher variability compared to age-matched control speakers, and these differences were found across the three variability measures and the four speech parameters. Group differences were mostly present in the Increased Complexity speaking condition across the different measures and speech parameters, indicating that variability values obtained during this condition are most prominent in discriminating speakers with hypokinetic dysarthria from control speakers. Speech parameters SPL and F1 were the most prominent in distinguishing between the two groups.

With respect to differences in variability between the young adult and older adult groups, two independent trends were found. The young adult group showed higher variability in the Increased Length and Increased Complexity speaking conditions for SPL and F1 contours. In turn, the older adults showed higher variability in the F0 contours in the Slow Rate and Dual speaking conditions, compared to the young adults, indicating that a clear pattern dividing the two groups was absent. With respect to F2 variability, main effects of group or effects of individual tasks differentiating groups were mostly absent, possibly due to the small group sizes left for comparison.

Comparisons between tasks

Table 4.8 summarizes the significant differences between speech tasks for each of the four participant groups separately. In general, speaker groups were affected differently during the six speaking conditions, with the following overall trends. Differentiations between speech tasks usually involved the Slow and Dual tasks, in which variability values were generally higher compared to the Habitual task. These trends were most noticeable for SPL, and mostly absent for F2.

The speakers with hypokinetic dysarthria generally showed higher variability values during the Dual tasks compared to the Habitual task across some of the variability estimators and speech parameters, most notably SPL.

Task-related differences for the age-matched control speakers were observed for Slow and Dual tasks, showing higher variability compared to the Habitual task.

The young adult group displayed higher variability in the Increased Length and Increased Complexity tasks.

TABLE 4.7: Summary of the results of variability analyses: significant group differences across combined speaking conditions and individual speaking conditions. Significant overall group comparisons (main effect of group) are unshaded. Significant individual task differences (post-hoc analyses) are shaded. IL: Increased Length, IC: Increased Complexity.

		HD vs AMC	YA vs OA
STI	SPL	Higher in HD	
		IC	IL, IC: YA > OA; Dual: OA > YA
	F0		Higher in OA
			Slow, Dual: OA > YA
	F1	Higher in HD	Higher in YA
		IL	Fast, IC
	F2		
		Hab: HD > AMC	
SV	SPL		
		IC: HD > AMC	IL, IC: YA > OA
	F0		Higher in OA
		IC: HD > AMC	Slow, Fast, Dual
	F1		Higher in YA
		IL, IC: HD > AMC	Fast, IC: YA > OA
	F2		
		Hab: HD > AMC	Slow: YA > OA
TV	SPL	Higher in HD	
		IL, IC, Dual: HD > AMC	IL, IC: YA > OA
	F0		
		Slow: HD > AMC	
	F1	Higher in HD	Higher in YA
		Slow, IL, Dual	Slow, Hab, Fast, IL, IC
	F2	Higher in HD	
		Hab, Dual	

The older adult group generally had higher variability values in the Slow and Dual tasks, compared to the Habitual, Increased Length, and Increased Complexity tasks.

Table 4.8: Summary of the results of variability analyses: differences between tasks for each group. IL: Increased Length, IC: Increased Complexity.

		HD	AMC	YA	OA
STI	SPL	Dual > Hab	Slow, Fast, Dual > Hab; Dual > IC	IL, IC > Hab	Slow, Dual > Hab, IC; Dual > IL
	F0		Slow, Dual > Hab, Fast	IL, IC > Hab, Fast; IC > Dual	Slow, IC, Dual > Hab; Slow, IC > Fast
	F1	Dual > IC	Dual > Hab, IL, IC; Slow, Fast > IL, IC		Fast > IL; Slow, Dual > IL, IC
	F2	Hab > Fast			
SV	SPL	Dual > Hab	Slow, Fast, Dual > Hab; Dual > IC	IL, IC > Hab, Fast	Slow, Fast, Dual > Hab; Dual > IL, IC
	F0		Slow, IC, Dual > Hab; Slow, IC > Fast	IL > Fast	Slow, Dual > Hab
	F1		Slow, Fast. Dual > IL, IC		Slow, Dual > IL; Slow, Fast, Dual > IC
	F2			IL > Slow	
TV	SPL	Dual > Hab	Slow, Dual > IC		Slow > Hab, IL, IC
	F0		IL > Slow		
	F1	Dual > Slow, Hab, IC; IL > Hab	Dual > Slow, Hab, IC; Fast > Hab, IL, IC	Fast > All others	Dual > Hab, IL, IC; Fast > IL, IC
	F2				

4.6 Variability analysis: group differentiation

In order to evaluate the suitability of the variability measures to diagnose dysarthria and classify speaker age, i.e., to investigate which the variability outcome measures were most suitable to differentiate between speakers with hypokinetic dysarthria and healthy speakers and between young and older adults, Principal Component Analyses (PCA) and subsequent Binomial Logistic Regression Analyses were carried out. The PCA was carried out to reduce and bundle related outcome measures into factors. To assess to what extent these factors were able to differentiate groups, they were subsequently used as input to build a Binomial Logistic Regression Model to analyse the relationship between the outcome measures and the dichotomous outcome variables (dysarthria / healthy speakers; young / older speakers).

The 72 variables were included in two Principal Component Analyses, with the first analysis containing all the cases of the HD and AMC groups, and the second analysis all the cases of the YA and OA groups. The reported results of the Logistic Regression Analysis include the initial model fit (Block 0), the final iteration step of the fitted model (Block 1) including predictors, the classification table, and variables associated with predictors that significantly contributed to the model.

4.6.1 Classification of HD and AMC speakers

From the Principal Component Analysis involving the HD and AMC groups 16 components were selected, based on the Kaiser criterion (eigenvalues greater than 1.0). These extracted components together accounted for about 87.6% of the total variance.

Next, the 16 extracted components were used as predictors in the Logistic Regression Analysis to model classification of dysarthria. The results for the HD and AMC speakers are displayed in table 4.9.

The results of the Enter Method regression analysis showed that one predictor (Factor 12) significantly contributed to the model (p = .032). This predictor was able to increase the goodness of fit of the logistic regression model, albeit as a trend: Omnibus test of model coefficients: χ^2 (1) = 24.48, p = .080. The model explained 54.1% (Nagelkerke R^2) of the variance in classifying dysarthria. The predictor added to the model resulted in 80.9% of the speakers being correctly classified. The *sensitivity* of detecting dysarthria, or the true positive rate, expressed as $\frac{true\ positives}{true\ positives\ +\ false\ negatives}$ x 100, was 73.9%. The *specificity* of detecting speakers without dysarthria, or the true negative rate, expressed as $\frac{true\ negatives}{true\ negative\ +\ false\ positives}$ x 100 was 87.5%.

To pinpoint which variability measures were most effective in signalling dysarthric speech, predictor Factor 12 was further investigated. Factor 12 had a positive coefficient (B = 1.267), and the predictor contained six positively loading variability measures. Higher values of the measures in this predictor were associated with an increased likelihood of exhibiting hypokinetic dysarthria. These included all three variability measures of sound pressure level in the IC task, temporal variability of fundamental frequency in the IC task, and temporal variability of first formant frequency in the Slow Rate and IC tasks. The results of the LMM analyses confirmed the contribution of this factor to signalling dysarthria. Four measures showed significant group differences: the three variability measures of sound pressure level in the IC task, and temporal variability of first formant frequency in the Slow Rate task. All four measures were found to be higher in the speakers with hypokinetic dysarthria. Mean variability values of the two other measures were also higher in the group of hypokinetic speakers, but these effects were not significant.

Taking all findings together, the results of the logistic regression analysis were in accordance with the results of the LMM analyses. Both analyses indicated that a prominent role in differentiating speakers with hypokinetic dysarthria from unaffected control speakers was found in variability measures of the sound pressure level contour of the speaking condition with increased complexity, in which the speakers with hypokinetic dysarthria consistently showed higher speech motor variability.

4.6.2 Classification of YA and OA speakers

From the PCA involving the YA and OA groups 17 components were extracted with a total variance explained of 94.1%. The 17 extracted components were used as predictors in the Logistic Regression Analysis, and the results are displayed in table 4.10.

The results of the Forward Stepwise (Likelihood Ratio) Method regression analysis showed that four predictors (Factors 1, 4, 6, and 12) were able to increase the goodness of fit of the logistic regression model: Omnibus test of model coefficients: χ^2 (4) = 29.44, $p < .001$. The model explained 83.5% (Nagelkerke R^2) of the variance in classifying age groups. The combination of the four predictors added to the model resulted in 90.0% of the speakers being correctly classified, with a sensitivity, or the true positive rate, of detecting ageing speakers of 92.9%, and a specificity, or the true negative rate, of 87.5%.

The predictors that significantly contributed to the logistic regression model were further investigated. Factor 1 had a negative coefficient (B = -10.150), and the predictor contained six

TABLE 4.9: Results of Binomial Logistic Regression Analysis of HD and AMC speakers.

Block 0: beginning block								
Step 0	B	S.E.	Wald	df	Sig	Exp (B)		
Constant	-.43	.292	.021	1	.884	.958		
Block 1: method = enter								
Omnibus test of model coefficients				Chi-square	df	Sig.		
			Step	24.478	16	.080		
			Block	24.478	16	.080		
			Model	24.478	16	.080		
Model fit	-2 Log Likelihood				Cox & Snell R^2	Nagelkerke R^2		
	40.657 (from 65.135)				.406	.541		
Step 1	B	S.E.	Wald	df	Sig	Exp (B)	lower	upper
FAC1	.901	.520	3.001	1	.083	2.462	.888	6.825
FAC2	.441	.430	1.052	1	.305	1.555	.669	3.613
FAC3	-.685	.556	1.519	1	.218	.504	.170	1.498
FAC4	-.098	.573	.029	1	.865	.907	.295	2.789
FAC5	.275	.514	.286	1	.593	1.316	.480	3.608
FAC6	-.115	.487	.056	1	.813	.891	.343	2.317
FAC7	-.477	.504	.898	1	.343	.621	.231	1.665
FAC8	-.950	.599	2.513	1	.113	.387	.120	1.252
FAC9	.309	.507	.373	1	.542	1.363	.505	3.680
FAC10	-.591	.483	1.497	1	.221	.554	.215	1.427
FAC11	-.883	.537	2.700	1	.100	.414	.144	1.185
FAC12	1.267	.592	4.586	1	.032	3.552	1.113	11.330
FAC13	-.256	.511	.250	1	.617	.774	.284	2.109
FAC14	.589	.538	1.199	1	.274	1.803	.628	5.179
FAC15	-.314	.499	.395	1	.530	.731	.275	1.942
FAC16	-.400	.525	.581	1	.446	.670	.239	1.875
Constant	.312	.449	.484	1	.487	1.366		
Classification Table								
	Predicted							
Observed	AMC	HD	Percentage Correct					
AMC	21	3	87.5 %					
HD	6	17	73.9 %					
Overall Percentage			80.9 %					
Variables associated with significantly contributing predictors								
FAC12								
Variable	*r*							
TV_SPL_IC	.855							
STI_SPL_IC	.805							
SV_SPL_IC	.788							
TV_F1_Slow	.643							
TV_F1_IC	.559							
TV_F0_IC	.502							

positively loading variability measures: STI and spatial variability of sound pressure level during the IL and IC tasks, and temporal variability of first formant frequency during the IL and IC tasks. Higher values of the measures in Factor 1 were associated with a decreased likelihood of having older age. The LMM analyses confirm the contribution of this predictor: all measures showed significantly higher values in the group of young adults.

The second predictor (Factor 4) also had a negative coefficient (B = -3.625), and combined eight positively loading variability measures, all related to second formant frequency: all three variability measures of the Fast Rate and IL tasks, and the STI and spatial variability of the Dual task. Again, higher values of measures in this factor were associated with a decreased likelihood of being member of the older age group. When drawing in the results of the LMM analyses, it was found that, whilst none of these measures indicated significant group differences, all showed higher values for the group of young adult speakers, confirming the contribution of the predictor to the model.

The third predictor (Factor 6) had a positive coefficient (B = 3.408), and contained three negatively loading variability measures: spatial variability of sound pressure level in the Slow Rate and IC conditions, and temporal variability of fundamental frequency in the Slow Rate condition. Higher values of the measures in this factor were associated with a decreased likelihood of being member of the older age group. The results of the LMM analyses indicated that the measure of spatial variability of sound pressure level during the IC task showed significantly higher variability in the group of younger adults, whilst the other two measures showed higher values for the older speakers, albeit not significantly different from the young speakers.

The fourth predictor (Factor 12) had a positive coefficient (B = 11.724), and contained four negatively loading variability measures: all variability measures of first formant frequency during the Fast Rate task, and temporal variability of first formant frequency during the Habitual task. Similar to Factor 6, higher variability values in this factor were associated with a decreased likelihood of having older age. The results of the LMM analyses showed that all these measures were found to be significantly higher in the group of young adults.

Overall, the four predictors contributing to the logistic regression model were generally in accordance with the results of the LMM analyses. The contributions of predictor one and predictor four were consistent with the direction of the significant group differences found in the LMM analyses. Predictor two showed a similar consistently in direction, although group differences were not found to be significant, and the third predictor had one out of three related variability measures that showed a direction similar to the group difference found in the LMM analyses.

4.7 Correlations between outcome measures

In order to answer research question three and establish how the variability results related to standard clinical assessments of speakers with dysarthria, the results obtained for the variability measures reported above were correlated with DDK performance, intelligibility ratings, and quantifiable information from the medical history of the participants. In addition, the various clinical assessments were correlated with each other to identify potential patterns in the data that might contribute to the interpretation of all results found in this study. Pearson Correlations were determined with a 2-tailed test of significance. Correlations with a value of $p < .05$ were marked as statistically significant.

4.7.1 Correlations between intelligibility ratings, diadochokinesis results, and medical history details

A series of bivariate correlation analyses was carried out for the speaker group with hypokinetic dysarthria to analyse the degree of correlation amongst measures of the intelligibility results (ratings of the reading task, ratings of the monologue task, transcriptions of unpredictable sentences), disease duration (years between diagnosis and data collection), medication use (levodopa dose in mg / day), ACE-R score, and the results of the diadochokinetic analysis.

The results of the correlations between intelligibility ratings and medical history details are displayed in table 4.11.

Table 4.10: Results of Binomial Logistic Regression Analysis of YA and OA speakers.

Block 0: beginning block								
Step 0	B	S.E.	Wald	df	Sig	Exp (B)		
Constant	-.134	.366	.133	1	.715	.875		
Block 1: method = forward stepwise (likelihood ratio)								
Omnibus test of model coefficients				Chi-square	df	Sig.		
			Step	5.936	1	.015		
			Block	29.442	4	.000		
			Model	29.442	4	.000		
Model fit	-2 Log Likelihood				Cox & Snell R^2	Nagelkerke R^2		
	12.013 (from 41.455)				.625	.835		
Step 1	B	S.E.	Wald	df	Sig	Exp (B)	lower	upper
FAC1	-1.635	.650	6.329	1	.012	.195	.055	.697
Constant	-.293	.445	.432	1	.511	.746		
Step 2								
FAC1	-2.320	.910	6.503	1	.011	.098	.017	.585
FAC12	2.392	1.198	3.991	1	.046	10.940	1.046	114.4
Constant	-.516	.556	.860	1	.354	.597		
Step 3								
FAC1	-3.679	1.696	4.703	1	.030	0.025	.001	.702
FAC4	-1.390	.846	2.702	1	.100	.249	.047	1.307
FAC12	4.539	2.613	3.018	1	.082	93.602	.559	15677.7
Constant	-.542	.627	.748	1	.387	.582		
Step 4								
FAC1	-10.150	5.308	3.656	1	.056	.000	.000	1.289
FAC4	-3.625	1.943	3.481	1	.062	.027	.001	1.201
FAC6	3.408	1.941	3.082	1	.079	30.202	.673	1356.0
FAC12	11.724	6.226	3.547	1	.060	123524.0	.620	2.460E10
Constant	-1.369	1.054	1.685	1	.194	.254		
Classification Table								
	Predicted							
Observed	YA	OA	Percentage Correct					
YA	14	2	87.5 %					
OA	1	13	92.9%					
Overall Percentage			90.0 %					
Variables associated with significantly contributing predictors								
FAC1		FAC4			FAC6		FAC12	
Variable	*r*	Variable	*r*		Variable	*r*	Variable	*r*
STI_SPL_IC	.893	TV_F2_Fast	.894		TV_F0_Slow	-.929	TV_F1_Fast	-.913
TV_SPL_IC	.889	STI_F2_Fast	.891		SV_SPL_Slow	-.572	TV_F1_Hab	-.906
TV_SPL_IL	.641	TV_F2_IL	.839		SV_SPL_IC	-.531	STI_F1_Fast	-.591
STI_SPL_IL	.592	SV_F2_Fast	.832				SV_F1_Fast	-.572
TV_F1_IC	.575	STI_F2_IL	.825					
TV_F1_IL	.574	SV_F2_Dual	.761					
		STI_F2_Dual	.733					
		SV_F2_IL	.666					

TABLE 4.11: Results of correlations between intelligibility ratings and medical history details.

		Reading	Monologue	Transcription	Disease Dur	L-Dopa
ACE-R	Correlation	.547	.638	.622	-.275	-.024
	Sig (2-tailed)	.007	.001	.002	.203	.913
Reading	Correlation		.759	.847	-.304	-.058
	Sig (2-tailed)		< .001	< .001	.158	.791
Monologue	Correlation			.761	-.456	-.141
	Sig (2-tailed)			< .001	.029	.522
Transcription	Correlation				-.130	.021
	Sig (2-tailed)				.556	.923
Disease Dur	Correlation					.435
	Sig (2-tailed)					.038

The results of the correlations amongst intelligibility ratings, and in relation with medical history details, showed the following notable patterns. Strong significant correlations were found amongst the three intelligibility measure, indicating a coherent assessment of intelligibility in the dysarthric speakers. Furthermore, strong positive significant correlations were found between the ACE-R score and all three intelligibility measures: higher ACE-R scores were associated with higher intelligibility scores. This relationship was particularly exemplified by the fact that the two HD speakers with the lowest ACE-R scores (HD22 and HD18) also had the lowest intelligibility scores across all three measures.

A significant negative correlation was found between intelligibility ratings of the monologue task and disease duration: a longer disease duration was associated with a decreased intelligibility during the monologue, indicating that this task was most sensitive in capturing disease progression. This pattern could also be found in the correlations between the intelligibility ratings and the ACE-R score, in which the monologue task showed the strongest correlation, compared to the two other tasks used for intelligibility assessment. Medication use and disease duration were significantly correlated: a longer disease duration was associated with increased levodopa use. These results indicate that with disease progression, intelligibility of monologue speech decreased, and speakers were prescribed higher doses of levodopa to manage the progressing disease symptoms. Interestingly, no significant negative correlations were found between ACE-R score and disease duration or levodopa intake.

The results of the correlations between the diadochokinetic results and intelligibility and medical history details are the following. Significant correlations between DDK measurement results (rate, CoV of syllable durations, CoV of intensity) and the three intelligibility ratings were absent. Furthermore, no significant correlations were found between the DDK results and disease duration. A single significant positive correlation was found between ACE-R score and DDK rate of /pʌtʌkʌ/: r = .445, p = .033. A higher ACE-R score was associated with a higher repetition rate for this task. Two significant positive correlations were found when correlated with levodopa intake: DDK intensity CoV of /pʌ/: r = .482, p = .020, and /kʌ/: r = .500, p = .015. Here, higher levodopa intake was associated with higher variability in syllable intensity. Overall, the results of the diadochokinetic analyses were barely relatable to the quantifiable aspects of the medical history of the clinical participants in this study, particularly considering the relatively large p-values in light of the relative large number of correlations performed in investigating interrelationships between the different measures.

4.7.2 Correlations between variability data and other outcome measures

A series of two-tailed Bonferroni-corrected Pearson correlation analyses was carried out to explore the relationship amongst the variability data and the other outcome measures, to be able to interpret the variability results in a wider context. An overview of significant correlations ($\alpha : p < .05$) and trends ($\alpha : p < .1$) for each of the comparisons is listed below.

4.7.2.1 Variability results and ACE-R score

Four negative correlations were found between the variability results and ACE-R scores (i.e., in these cases, a lower ACE-R score was associated with increased variability): SpatVar of SPL in the Slow condition: r = -.535, p = .048, and the STI (r = -.492, p = .099), SpatVar (r = -.570, p = .025), and TempVar (r = -.587, p = .018) of F0 in the Fast condition.

Speakers with low ACE-R scores showed higher variability, and these effects were predominantly present for F0 in the Fast Rate condition.

4.7.2.2 Variability results and medication use

Two trends of positive correlations were found between the variability results and levodopa intake (i.e., in these cases, a larger daily levodopa dosage was associated with increased variability): the STI of SPL in the Dual task condition: $r = .536$, $p = .074$, and TempVar of SPL in the Dual task condition: $r = .549$, $p = .062$.

These results indicated that speakers with higher levodopa dosage displayed higher STI and temporal variability values of Sound Pressure Level in the Dual task. Whilst correlations were few and rather weak, the overall pattern suggests that higher medication use was associated with a reduced speech motor stability during the Dual task condition.

4.7.2.3 Variability results and disease duration

The correlational analyses revealed two trends and two significant correlations between variability and disease duration, all of which were positive (i.e., a longer disease duration was associated with an increase in variability): the STI of SPL in the Slow ($r = .501$, $p = .090$) and Dual ($r = .515$, $p = .098$) conditions, as well as the STI ($r = .559$, $p = .042$) and SpatVar ($r = .566$, $p = .036$) of F1 in the Dual condition.

A longer disease duration was associated with the presence of higher variability values of both Sound Pressure Level and First Formant frequency. Similar to the results of the correlations involving medication use, the strongest correlations involved mainly the Dual task.

4.7.2.4 Variability results and intelligibility

The variability results were correlated with the intelligibility results (intelligibility ratings of the reading passage and the monologue, and the percentage correctly transcribed words in unpredictable sentences). Correlations between variability results and intelligibility were largely absent. No notable correlations for the reading passage ratings were found. One trend and one significant correlation were found for the intelligibility ratings of the monologue task, and one trend was found for the sentence transcription task. The correlations were negative, i.e., a decrease in intelligibility was associate with a increase in variability.

Two notable correlations were found between the variability results and the intelligibility ratings of the monologue fragment: TempVar of F0 in the Fast rate condition: r = -.602, p = .012, and TempVar of F2 in the Increased Length Condition: r = -.617, p = .066.

One trend was found between the variability results and the percentage correctly transcribed words: TempVar of F2 in the Increased Length condition: r = -.612, p = .072.

Generally, the overall number and strength of correlations was found to be low, and only variability in the temporal dimension was found to be related to measures of intelligibility.

4.7.2.5 Variability results and CoV of syllable durations and intensity in four DDK tasks

The spatiotemporal index, spatial variability and temporal variability were correlated with the CoV of syllable durations and CoV maximum syllable intensity in the four diadochokinetic tasks /pʌ/, /tʌ/, /kʌ/, and /pʌtʌkʌ/.

Variability results and CoV of syllable durations

An overview of trends and significant correlations between variability results and CoV of syllable durations is given in Table 4.12, separated by DDK task.

TABLE 4.12: Correlations between variability results and CoV of syllable durations.

/pʌ/			/tʌ/			/kʌ/			/pʌtʌkʌ/		
Variable	*r*	*p*	Variable	*r*	*p*	Variable	*r*	*p*	Variable	*r*	*p*
STI_F0_Slow	-.518	.066				TV_SPL_Dual	.557	.090	SV_SPL_IC	.505	.084
						TV_F1_Dual	.555	.042	SV_F1_IL	.514	.072
									TV_SPL_IC	.530	.054
									TV_F1_Fast	.496	.080
									TV_F1_Dual	.636	.006
									TV_F2_Dual	.824	.012

Some trends could be discerned in the correlations between variability and DDK syllable duration regularity, and these were largely dependent on DDK task. A negative trending relationship was found between /pʌ/ and variability of fundamental frequency, i.e., an increase in DDK duration variability was associated with a decrease in fundamental frequency variability. Correlations involving /tʌ/ were absent, whilst DDK duration variability of /kʌ/ and /pʌtʌkʌ/ tended to positively correlate with temporal variability of first formant frequency, and the most prominent correlations were usually present in the IC and Dual tasks.

Variability results and CoV of syllable intensity

The trends and significant correlations between variability results and CoV of syllable intensity is given in Table 4.13, separated by DDK task.

TABLE 4.13: Correlations between variability results and CoV of syllable intensity.

/pʌ/			/tʌ/			/kʌ/			/pʌtʌkʌ/		
Variable	*r*	*p*	Variable	*r*	*p*	Variable	*r*	*p*	Variable	*r*	*p*
STI_SPL_Dual	.570	.042	STI_SPL_Hab	.519	.066	STI_SPL_Hab	.526	.050	STI_SPL_Hab	.564	.030
TV_SPL_Hab	.591	.015	TV_SPL_Hab	.636	.006	STI_SPL_IC	.474	.088	SV_SPL_Hab	.642	.006
TV_SPL_Dual	.636	.012	TV_SPL_Fast	.447	.084	STI_SPL_Dual	.635	.012	SV_SPL_Fast	.649	.006
			TV_SPL_IL	.500	.075	SV_SPL_IC	.594	.015	SV_SPL_Dual	.615	.015
			TV_F0_Hab	.553	.036	SV_SPL_Dual	.662	.006	TV_SPL_Hab	.656	.006
						TV_SPL_Hab	.707	.005			
						TV_SPL_IC	.598	.012			
						TV_SPL_Dual	.683	.005			
						TV_F1_Slow	.689	.006			
						TV_F1_Dual	.562	.036			

The most notable findings of correlating variability measures with syllable intensity regularity across DDK tasks were that correlations almost always involved variability outcome measures of speech parameter SPL: an increase in SPL contour variability was associated with an increase in irregularities of peak SPL of the vowels in the DDK tasks. Significant correlations were found for all three acoustic variability measures. Correlations involving temporal variability and the Habitual Rate and Dual Task conditions were most frequently present.

Overall, few parallels could be identified when comparing the variability measures that stood out in the correlational analyses on the one hand and the variability measures that indicated group differences between hypokinetic and unaffected speakers in the logistic regression analysis on the other hand. Notable group differences as signalled by the logistic regression analysis predominantly involved variability in the Increased Complexity condition, whilst the correlational analyses of variability measures with the wider measures of speech performance usually involved the Habitual Rate, Fast Rate, and Dual Task conditions.

The following chapter will discuss how these findings relate to the existing literature and what answers they provide to the research questions outlined in chapter 2.

Chapter 5

Discussion

5.1 Introduction

This study sought to test the suitability of linear and nonlinear estimators of variability applied to acoustic properties extracted from audio recordings to distinguish speakers with hypokinetic dysarthria from healthy control participants, as well as healthy young adult speakers from older adult speakers. In addition, the results of the variability measures of the hypokinetic speakers were related to established clinical outcome measures of diadochokinetic performance, intelligibility ratings, and quantifiable details of medical history in order to be able to interpret the results of the variability assessment in a wider clinical context, and to evaluate the variability estimators on assessing speech motor control in the domains of clinical research and clinical practice.

In order to pursue this aim, three research questions were posed to investigate the various aspects of this project. However, before answering these specifically, some of the results will be compared to the existing literature in order to establish to what degree the current participants are representative of the wider speaker population (section 5.2). Section 5.3 will then discuss the results of the individual analyses in order to address the research questions. The limitations of the study and suggestions for future research are discussed in sections 5.4 and 5.5, respectively. The chapter will conclude with a discussion of the clinical implications of this study (section 5.6).

5.2 Results of the diadochokinetic tasks and sentence durations

In this section, the results of the acoustic analyses of the diadochokinetic tasks and the sentence durations of the sentence repetition tasks are discussed for each of the speaker groups, in order to establish whether the current speaker groups were comparable to the wider population.

5.2.1 Syllable repetition rates

When comparing syllable repetition rates of diadochokinetic tasks, it was found that for all speaker groups rates were highest in /pʌ/, followed by /tʌ/, and slowest in /kʌ/. This result has been reported often, both in normal and disordered speaker populations (Neel & Palmer, 2012; Duffy, 2013).

No differences in repetition rates were found between the hypokinetic dysarthric speakers and the healthy speakers. An early study by Canter (1965) showed that speakers with HD were systematically slower compared to control speakers during diadochokinetic tasks of /bʌ/, /dʌ/, and /gʌ/. Ackermann et al. (1995) also found that in similar alternating motion rate tasks, speakers with HD were significantly slower compared to healthy control speakers. In a comparable task, Gurd et al. (1998) found that speakers with HD were significantly slower compared to their respective controls during the fast repetition of repetition tasks including /du/ and /lu/.

However, similar to the results in the current study, there are a number of studies including Connor et al. (1989), Ludlow et al. (1987), and Tjaden and Watling (2003) that reported comparable syllable repetition rates between speakers with HD and healthy control speakers. In the face of reduced muscle strength, it has been suggested that speakers with HD compensate for orofacial bradykinesia by displaying reduced articulator displacements up to the point of articulatory undershoot, where they are failing to reach the intended target, but overall speed remains largely unaffected (Connor et al., 1989; McAuliffe et al., 2006b). These results also reflect the results of research on articulation rate in speakers with HD, which has reported similar rates compared to unimpaired speakers (Nishio & Niimi, 2001; Skodda & Schlegel, 2008).

When comparing the two age groups on articulatory movement speed, it was found that the group of older adults was faster across all tasks except /pʌtʌkʌ/, compared to the group of young adults. In contrast, Neel (2009) and Parnell and Amerman (1996) amongst others, found that young adults are usually faster compared to older speakers, although others, for example Flanagan and Dembowski (2002), failed to find systematic differences in diadochokinetic performance across age groups. Inspection of individual speaker data (see Appendix I) showed that a substantial number of young adults (Y02, Y03, Y04, Y06, Y07) failed to reach a modest rate of three syllables per second in at least one of the four diadochokinetic tasks. Unimpaired adult speakers should be able reach maximum syllable repetition rates between 6 and 7 syllables per second (Kent et al., 1987; Kent, 2015; Knuijt, Kalf, Engelen, Geurts, & de Swart, 2017). This indicates that in this task, a subset of young adults was considerably slower compared to what is previously reported.

The results of the syllable repetition rate analyses therefore indicate that speakers with hypokinetic dysarthria, the age-matched control speakers, and the older adult speakers showed comparable maximum syllable repetition rates compared to the literature. Although a subset of young adults underperformed across the diadochokinetic tasks by not reaching normally expected syllable repetition rates, most young adults performed within the normal range. Overall, the YA group can therefore also be regarded as performing as expected.

5.2.2 Variability in mean syllable length

The results of the group comparisons of variability in mean syllable length of the diadochokinetic tasks indicated that the speakers with hypokinetic dysarthria showed a higher variability in syllable length (mean CoV averaged between 11.71% - 14.60%) compared to the age-matched control speakers (mean CoV averaged between 6.93% - 8.30%). Ackermann et al. (1995) reported an average CoV of 13.7% in speakers with HD, which was also significantly higher compared to healthy speakers. Tjaden and Watling (2003) also found a significantly higher CoV in speakers with HD using identical diadochokinetic tasks, compared to unimpaired control speakers.

The groups of young adults and older adults showed comparable CoVs of syllable length across the four DDK tasks. in comparison, Padovani, Gielow, and Behlau (2009) analysed the CoVs of syllable length in two groups of younger and older healthy Portuguese speakers in identical DDK tasks, and also found no significant differences when comparing CoVs across groups. In the current study, the group of older adults displayed CoVs ranging from 6.9% for /pʌ/ to 8.3% for /kʌ/. In comparison, Pierce, Cotton, and Perry (2013) found CoVs ranging from 11.3% for /pʌ/ to 20.8% for /pʌtʌkʌ/ in a group of healthy speakers with an average age of 69 years, and Padovani et al. (2009) found CoVs ranging from 11.76% for /tʌ/ to 23.57% for /pʌtʌkʌ/ in a group of healthy speakers with an average age of 71 years. Although the methodology to obtain variability in syllable length might be different from study to study, it can be concluded that CoVs of syllable length of elderly speakers in this study were relatively low compared to existing literature. One of the possible underlying reasons of this particular outcome might be that the participants from the group of older adults were active community members, eager to participate and to perform well. Furthermore, it was ensured beforehand that cognitive problems influencing speech problems were excluded as much as possible, something that might not be controlled for in the aforementioned studies.

The analysis of variability of syllable length therefore also indicated that the group of speakers with hypokinetic dysarthria performed similarly as compared to the literature. Furthermore, the behaviour of the young and older adult speaker groups was generally comparable to results reported in current literature with respect to DDK syllable duration variability.

5.2.3 Variability in peak vowel intensity

The variability in peak vowel intensity failed to display significant differences across groups, when comparing the HD speakers with their controls. Whilst the clinical group showed a trend of higher CoVs of peak vowel intensity across all tasks compared to the age-matched control group, no statistically significant differences were found. This could be attributed to the very large standard deviations within the HD group. It is difficult to relate the current findings to existing studies, as research reporting variability in intensity parameters of diadochokinetic tasks performed by speakers with hypokinetic dysarthria is sparse. Kent and Kim (2003) and Rosen et al. (2005) found that vocal intensity of speakers with PD declined more rapidly than that of controls in DDK tasks, resulting in higher vowel intensity variability.

When comparing the two groups of healthy speakers differing in age, the results showed that the group of young adults had a higher overall CoV of peak vowel intensity in /pʌ/ compared to the older adults: 3.63% versus 2.75% respectively. Inspection of individual results shows that in this task the young adult speakers with highest CoVs were also the speakers with lowest syllable repetition rates, pointing at a general reduced effort in executing the diadochokinetic tasks. No further group differences were found in the other tasks. Padovani et al. (2009) report CoV values of peak vowel intensity ranging between 0.82% to 1.81% for young adult Portuguese speakers, compared to 1.86% to 3.23% for older adults. In their study, CoVs of all four DDK tasks were significantly higher for the older adults, compared to the younger adults.

Unlike the results of the few studies mentioned above, variability in peak vowel intensity in the clinical group in the current study was not significantly higher than in the unimpaired group. The two age groups were generally comparable, while an earlier study reported higher variability values for older adults. Due to the lack of literature and diversity in measurement procedures and severities amongst existing studies with respect to variability in peak vowel intensity, it is difficult to assess to what extent the speaker groups in this study were comparable to a wider population for this parameter.

5.2.4 Sentence durations in the sentence repetition task

In order to compare articulation rate characteristics across the speaker groups and to contrast these with the current literature, and to evaluate whether the speakers were able to increase articulation rate in the fast rate condition and decrease rate in the slow rate condition, mean sentence durations were extracted from the repetition tasks.

The results of the analysis of the overall sentence durations in the sentence repetition task (Appendix L) showed that across speaking conditions the hypokinetic speakers had comparable sentence durations compared to the age-matched control group, except for the Slow Rate condition, where the HD group showed shorter sentence conditions compared to the control speakers. With respect to articulation rate in hypokinetic dysarthria, studies have found that articulation rates in speakers with HD are usually found to be in the normal range (Nishio & Niimi, 2001; Weismer et al., 2001; Kleinow et al., 2001; Skodda & Schlegel, 2008). During the slow rate condition in the current study, however, the HD speakers were able to slow down their articulation rate, but not to the same degree as the healthy speakers. Similar results have been found by Lowit et al. (2006), who reported faster articulation rates in the slow rate condition of a sentence reading task for speakers with Parkinson's disease, compared to healthy control speakers. The results of the current study may also be due to the nature of the speaking task, as it has been found that HD speakers tend to rely more strongly on increasing pause time to reduce speaking rate (Nishio & Niimi, 2001; Tjaden & Wilding, 2011c; Tjaden, Sussman, & Wilding, 2014), a strategy they were explicitly instructed to avoid. The speakers of the HD group were able to significantly increase articulation rate during the fast rate condition, and this finding has been reported before (McHenry, 2003). Speakers of the AMC group were effective in slowing down and speeding up, a result that has been reported elsewhere (Wohlert & Smith, 1998; Lowit et al., 2006).

The overall sentence durations did not differ between the two speaker groups differing in age. The percentages increase and decrease in duration from the Habitual Rate condition to the Slow Rate and Fast Rate condition showed that both the young and older adults were able to slow down and speed up when instructed to do so, similar to reports in e.g., Wohlert and Smith

(1998), Smith and Kleinow (2000), Lowit et al. (2006). Furthermore, the proportional increase and decrease was not significantly different between the two groups in the rate change conditions, indicating that both groups performed similarly across the different speaking conditions.

A further observation was that, based on percentage change across speaking conditions, sentence durations often tended to be relatively shorter in the Increased Length task and the Increased Complexity task, compared to the Habitual Rate task. These findings were generally present across all four speaker groups. Recall that whilst the Increased Length and Increased Complexity sentences as a whole had more syllables compared to the sentence used in the Habitual Rate task, the sentence durations were measured from identical start and end points for each of the sentences (from the offset of /t/ in Tony to the onset of /b/ in bed respectively). The shorter sentence durations can be attributed to anticipatory shortening in longer phrases, in which a speaker uses anticipatory forward scanning to estimate the length of an utterance to determine the amount of time necessary for articulation (Quené, 2008; Jacewicz, Fox, & Wei, 2010). In addition, the HD and YA groups had shorter sentence durations in the Dual Task compared to the Habitual Rate condition, indicating a slightly rushed speech rate. Findings of higher speech rates during a concurrent visuomotor task have been reported elsewhere (Dromey & Bates, 2005). Overall, the behaviour of the speaker groups with respect to rate changes across the different speaking conditions of the sentence repetition task were generally as could be expected from what is known from the literature.

5.2.5 Summary

The analyses of maximum syllable repetition rates, syllable length variability and intensity variability of the diadochokinetic tasks, and the sentence durations of the repetition task showed that the results found for the speakers with hypokinetic dysarthria were generally within the norms cited in the existing literature on dysarthria. With respect to contrasting young speakers and older speakers, it could be observed that some of the speakers of the group of young adults displayed lower maximum syllable repetition rates, suggesting an under-performance in executing the diadochokinetic tasks. However, the performance across the speaking conditions of the sentence repetition tasks was comparable between the two age groups: average speaking rates, relative increases from habitual to fast rate, and decreases from habitual to slow rate were significant, and similar across the two groups. Therefore, it can be concluded that, whilst diadochokinetic performances in some young speakers were below average, the results of the durations in the sentence repetition tasks indicate that the speaker groups participating in the current study showed similar behaviour compared to existing literature, and thus were generalizable towards larger speaker populations beyond this study.

5.3 Discussion of the research questions

The previous sections established that the current speaker groups largely performed in line with the previous literature and can thus be regarded as being representative of the wider population. On this basis, the following sections will now focus on answering the individual research questions posed in the current study (section 2.9).

5.3.1 Differentiating hypokinetic dysarthric speech from unimpaired speech

The first research question was concerned with whether the variability estimators used in this study could differentiate between hypokinetic speech and the unimpaired speech of age-matched control speakers. Firstly, the results of the linear mixed model (LMM) analyses are discussed with respect to the significant differences in acoustic variability found between tasks within the two groups under investigation, as well as the significant differences found between the two groups. Secondly, the results of the Logistic Regression Analysis are discussed with respect to the suitability of acoustic variability outcome measures to identify dysarthria.

5.3.1.1 Differences between tasks

When evaluating the influence of the six speaking conditions on variability for the speakers with hypokinetic dysarthria as indicated by the LMM analyses, three notable trends could be distilled.

Firstly, the HD group showed higher STI, spatial variability, and temporal variability values for sound pressure level in the Dual task compared to the baseline task. These results are in line with results found by Bunton and Keintz (2008). In their study, a group of speakers with hypokinetic dysarthria displayed detrimental changes in intelligibility, speech rate, and fundamental frequency variation during a dual task execution. Ho et al. (2002) reported a reduction in speech intensity and an increase in speech intensity decay during a dual task paradigm in speakers with hypokinetic dysarthria, and Dromey et al. (2010) found that during a dual task, speakers with Parkinson's disease showed a reduced diphthong range and slope. The general consensus is that the concurrent execution of speech tasks and other motor tasks is associated with a decrease in speech performance in speakers with hypokinetic dysarthria due to the division in allocating attention.

Secondly, effects of speaking rate were largely absent; only the STI of second formant frequency was higher in the baseline task compared to the Fast Rate task. In contrast, McHenry (2003) found higher STI values in a fast rate condition when assessing a group of speakers with hypokinetic dysarthria. Anderson et al. (2008) reported significantly higher spatial variability in sound pressure at fast rate, compared to habitual rate for speakers with hypokinetic dysarthria, contrasting the absence of rate-related differentiation found in the current study. Although STI and FDA variability means of the HD group across the rate conditions suggest that for SPL, F0, and F1, average variability was always higher in the Slow Rate task and almost always higher in the Fast Rate task, compared to the baseline task, the statistical analysis did not confirm this assumption. This was most likely due to the high within-group variation which underline the heterogeneous behaviour of the speakers in this group.

Thirdly, effects of Increased Length and Increased Complexity were mostly absent as well. Only temporal variability values were found to be higher for first formant frequency in the Increased Length condition. In contrast, Walsh and Smith (2011) found higher STI values in both increased length and increased syntactic complexity tasks in speakers with hypokinetic dysarthria. Whilst the group means of the HD group suggest higher variability levels compared to the AMC group in the IL and IC tasks for speech parameters SPL, F0, and F1, again relatively high within-group variation prevented these differences to become significant.

The age-matched control speakers showed two general trends when comparing variability between speaking conditions.

Higher variability values were observed in the Fast Rate and Slow Rate conditions, when compared to the Habitual rate, Increased Length and Increased Complexity conditions. In comparison, Wohlert and Smith (1998) assessed the STI of lower lip movement in older healthy speakers, and also found higher STI values during slow and fast rate, compared to habitual rate.

The second trend showed, comparable to the findings of the HD speakers, higher variability values in the Dual task compared to the Habitual task. These results have been reported elsewhere, e.g., in Dromey and Benson (2003), Dromey and Bates (2005), Dromey and Shim (2008), Bailey and Dromey (2015), indicating the control speakers in this study performed similarly compared to previous studies with respect to speech motor control behaviour across the different speaking conditions.

5.3.1.2 Differences between groups

When comparing average STI values of speakers with hypokinetic dysarthria and age-matched control speakers, it was found that variability was generally higher in the HD group, notably for speech parameters sound pressure level (Increased Complexity task), first formant frequency (Increased Length task), and second formant frequency (Habitual task). These results are in accordance with several studies that report higher spatiotemporal index values for lower lip movements in speakers with HD compared to the AMC speakers (Wohlert & Smith, 1998; Harel, Cannizzaro, & Snyder, 2004; McHenry, 2004).

Spatial variability values were found to be higher in HD speakers as well. Specifically, group differences were present in individual speech tasks across all four speaking parameters: sound pressure level (Increased Complexity task), fundamental frequency (Increased Complexity task), first formant frequency (Increased Length and Increased Complexity tasks), and second formant frequency (Habitual task). In comparison, Anderson et al. (2008) reported higher spatial variability values of sound pressure level in speakers with Parkinson's disease compared to healthy speakers in a fast rate speaking condition, although not at habitual rate.

In line with the results of spatial variability, higher temporal variability values were found for one or more speech tasks in all speech parameters: sound pressure level (Increased Length, Increased Complexity, and Dual tasks), fundamental frequency (Slow task), first formant frequency (Slow, Increased Length, and Dual tasks), and second formant frequency (Habitual and Dual tasks). In contrast, Anderson et al. (2008) did not find significant differences in temporal variability of sound pressure level at either habitual or fast rate when comparing speakers with hypokinetic dysarthria and control speakers, although one of the HD speakers in their relatively small sampling group showed the highest temporal variability amongst all speakers.

Overall, the finding of higher variability is consistent with reports of earlier studies, in which individuals with HD usually have more variable sequencing of lip and jaw motions, when compared with healthy control participants.

5.3.1.3 Identification of dysarthria

Model performance

To investigate to what extent estimations of variability were able to distinguish between dysarthric and healthy speech, the 72 variability measures (3 variability estimators x 4 speech parameters x 6 speaking conditions) were factored and subjected as predictors to a Logistic Regression Analysis to explore the relationship between the predictors and the presence of dysarthria.

The results showed that the predictor was able to increase the goodness of fit of the logistic regression mode as a trend (p = .080). The measured specificity (87.5%) was found to be higher than the sensitivity (73.9%). When considering the relationship of sensitivity and specificity from a clinical perspective, it would be more desirable to have a high sensitivity to be able to diagnose as many patients as possible. At the same time, clinicians might allow for a lower specificity, so that a speaker at risk of dysarthria would receive further assessment or treatment, even though a lower specificity means that more speakers without speaking problems would receive unnecessary further assessment.

As of yet, no studies exist that employ logistic regression analyses to test the presence of dysarthria based on speech characteristics, which make comparisons of model performances difficult. To put the current model performance in terms of specificity and sensitivity values into context, the results are compared with studies that used discriminant analyses of different clinical and speech features to distinguish speakers with speech disorders and healthy speakers. Lansford and Liss (2014) used a stepwise discriminant function analysis to determine the extent to which vowel metrics of 10 different vowels were capable of distinguishing healthy from dysarthric speech of four dysarthria subtypes. Vowel metrics included vowel space measures, mean dispersions, and second formant slope. The overall model accuracy ranged between 66.7% and 84.2%. Howell and Davis (2011) constructed a logistic regression model to classify 132 children as persistent or recovered at the teenage years, by using stuttering history and symptom information obtained at around the age of 8 years. The score of the Stuttering Severity Instrument at first assessment was the only significant predictor in fitting the model, resulting in an overall correct classification score of 81.1% with a model sensitivity for persistent children of 84.1% and a specificity for recovered children of 78.3%, indicating an overall classification score comparable with the results of the current study. In the field of neurology, Hughes, Ben-Shlomo, Daniel, and Lees (1992) reported in their seminal study on the suitability of using clinical features in identifying Parkinson's disease. Data of a group of 100 patients of which 76% were confirmed to have Parkinson's disease according to post-mortem data were retroactively used to build a logistic regression model with PD or other parkinsonian disorder as outcome measure. Out of the set of clinical outcome measures, three predictors significantly adding to the model: no atypical features for PD, an asymmetrical onset, and no suggestion of a cause for another parkinsonian syndrome, resulting in a model sensitivity of around 80% and a specificity of around 65%. Wenning et al. (2000) investigated in 138 patients what clinical features are most useful to distinguish multiple system atrophy from Parkinson's disease by means of a logistic regression model with the post-mortem diagnosis as the outcome variable. Relevant clinical features were scored including poor initial response to levodopa, autonomic features present, early fluctuations, and initial rigidity. The optimal cut-off score associated with their model resulted in a sensitivity of 87.1% and specificity of 70.5%. Whilst compared to the findings of these studies the model classification power of the current study can be considered comparable or better, a sizeable number of HD speakers were misclassified, warranting further inspection. In the current study, six of the 23 hypokinetic speakers were classified as control speakers: HD02, HD04, HD05, HD16, HD17 and HD20. The misclassification of these speakers may partly be explained by mild levels of speech severity, particularly exemplified by speakers HD02, HD04, and HD17, who were amongst the most intelligible in relation to the other speakers in the HD group. For these speakers, their lower speech severity was possibly mirrored in the variability results, which were more reflective of healthy speakers, contributing to the logistic model misclassifying these speakers. However, the intelligibility ratings of the other misclassified speakers were generally not amongst the highest within the group, and in addition, some of the correctly classified speakers (HD01, HD15, HD19) possessed higher intelligibility scores.

Drawing in the results of the direct correlations between intelligibility and variability, it can be observed that the most prominent correlations were found for variability of F0 in the Fast Rate condition and variability of F2 in the Increased Length condition, and therefore different from the variability measure that was indicated by the model to differentiate between speaker groups: SPL in the Increased Complexity condition. This indicates that the intelligibility results cannot completely account for the misclassified speakers. It may be concluded that, whilst the model was characterized by a relative low sensitivity rate compared to the specificity rate, possibly related to the large proportion of speakers with mild severity, the overall model performance of the current study compares favourably with current studies using similar statistical methodology related to speech pathology or clinical diagnosis of Parkinson's disease.

Predictors adding to the model

To pinpoint which variability estimators were most effective in signalling dysarthric speech, only predictors that significantly contributed to the logistic regression model were further investigated. One predictor significantly contributed to the model: Factor 12. An increase of this predictor was associated with an increase in likelihood of having hypokinetic dysarthria. The factor contained six variability measures, of which four showed significant group differences, based on the LMM analyses. These included all three variability measures of sound pressure level in the Increased Complexity task, and temporal variability of first formant frequency in the Slow Rate task. All these estimators were found to be higher in the speakers with hypokinetic dysarthria. Further inspection of the six misclassified dysarthric speakers showed that average values for the six variability measures were lower compared to the other members of the group, i.e., they were approaching average values of the control group.

Overall, these results indicated that the most prominent measure contributing to predicting dysarthria was the presence of higher variability of sound pressure level contours in the Increased Complexity task. Walsh and Smith (2011) also investigated the effects of increased syntactic complexity on variability of lip aperture in speakers with Parkinson's disease with mild to moderate speech and voice impairments, largely comparable to the participants in the current study. Whilst in their study overall variability values across different sentence stimuli were higher for the PD speakers compared to control speakers and more complex sentence conditions resulted in higher variability indices in both groups of participants, an interaction effect between group and sentence complexity was absent, indicating that the individuals with PD were not disproportionately affected by the increased linguistic demands for the more complex sentences. The authors speculated that formulation and preparation demands were greatly reduced by using a reading paradigm to elicit the sentence repetitions, which would effectively have nullified the possible detrimental effects of disrupted speech production in PD speakers on the mild-to-moderate end of the disease (Walsh & Smith, 2011). The current study used a comparable reading paradigm to elicit sentences, but with the task of increased linguistic complexity resulting in disproportionally higher variability for speakers with hypokinetic dysarthria, suggesting the current acoustic based methodological approach is more sensitive to detecting differences arising from changes in speaking conditions.

The role of the basal ganglia

The higher spatial and temporal variability values found in speakers with hypokinetic dysarthria indicate a greater variability in generating a movement trajectory during the production of the target stimulus. As the basal ganglia play a role in the learning, planning, and execution of motor commands (Graybiel, Aosaki, Flaherty, Kimura, et al., 1994; Doyon et al., 2009), striatal dopamine loss resulting from damage to the basal ganglia control circuit could contribute to the production of more variable neural command signals in speakers with PD (Walsh & Smith, 2011; Kwak et al., 2010; Kucinski & Sarter, 2016). In their exploratory study, Anderson et al. (2008) reported higher spatial variability values of sound pressure level in speakers with hypokinetic dysarthria compared to healthy speakers, but found no evidence of group differences in temporal variability. In contrast, the results of the current study seem to indicate that, in addition to spatial deviations, the speakers also showed timing problems during articulation. Speakers with PD are found to have difficulties with initiating speech motor movements (Utter & Basso, 2008; Cantiniaux et al., 2010) and with switching between speech motor programs (Skodda, 2011), likely resulting in problems with maintaining temporal aspects of the speech motor program (Spencer & Rogers, 2005). Indeed, there is some evidence that the basal ganglia play an important role in temporal processing, see e.g., (Jones, Malone, Dirnberger, Edwards, & Jahanshahi, 2008; Parker et al., 2013; Jones & Jahanshahi, 2014), possibly contributing to the elevated temporal variability values found in the speakers with hypokinetic dysarthria.

The overall pattern of results in which the hypokinetic speakers, compared to healthy speakers, displayed higher variability values across all four speech parameters indicate that pathology of the basal ganglia and its resulting dysfunction of the dopaminergic circuitry have multi-dimensional consequences for speech production in speakers with PD. Specifically, the reduction in the mobility and control of speech movements underlying hypokinetic dysarthria might alter the movement range and variation in the range of intensity and fundamental frequency contours during the sentence repetition tasks, noted also in other studies (Harel, Cannizzaro, & Snyder, 2004; Skodda, Grönheit, & Schlegel, 2011). The current findings of increased first formant variability (found in the Increased Length task) and second formant variability (found in the Habitual task) point therefore towards a reduced temporal vocal tract stability (Zwirner & Barnes, 1992; Beverly et al., 2008; Rusz et al., 2011).

The current results also provide evidence for further involvement of the basal ganglia beyond motor planning and control. Whilst the primary function of the basal ganglia is linked to motor behaviour, several studies have implicated the basal ganglia with cognitive and language-specific functions, specifically linked to processes of working memory during the computation of syntactically complex sentences (Pickett, Kuniholm, Protopapas, Friedman, & Lieberman, 1998; Booth, Wood, Lu, Houk, & Bitan, 2007; Kotz, Schwartze, & Schmidt-Kassow, 2009). The finding that the Increased Complexity task was the most prominent speaking condition differentiating hypokinetic speech from healthy speech gives further support to the hypothesis that the basal ganglia, apart from their involvement in motor processes, might play a significant role in the integration of linguistic and motor processes. Supporting evidence can be found from the LMM analyses when looking at the significant differences between speech tasks. The speakers with hypokinetic dysarthria showed significantly higher variability values in the Increased Length speaking task compared to the habitual task, whilst the control speakers did not show such trend. Taken together, these deteriorating effects of longer and linguistically more complex sentences on speech motor stability provide further evidence for the involvement of the basal ganglia at the language / speech motor interface. This assumption is clearly supported by the performance pattern of HD22 who was the most impaired in the HD group. His ACE-R score indicated cognitive decline, his intelligibility ratings were amongst the lowest, and his results on the variability measures indicated elevated variability values in specifically the Increased Length and Increased Complexity condition. These results are fitting in the context of recent research bringing forward evidence that the basal ganglia are not only involved in the control of movement, but also cognition (Middleton & Strick, 2000; Aron et al., 2007). The current results of an interaction between cognitive decline and reduced motor stability in complex speaking conditions therefore fit in the context of a shared impact of lesions in the basal ganglia on motor control and cognition.

5.3.2 Differences between young and older healthy speakers

As previous research has found age-related differences in speech motor control, the second research question evaluated the effect of ageing on variability, by investigating whether the estimators could be used to capture differences between the speech of healthy young speakers and healthy older speakers. Firstly, the results of the LMM analyses are discussed with respect to the significant differences found between tasks within the groups of young and older speakers, as well as the significant differences found between the two groups. Secondly, the results of the Logistic Regression Analysis are discussed with respect to classification of speaker age.

5.3.2.1 Differences between tasks

When comparing the effects of the six speaking conditions on variability for the young adults, the following notable results were found.

The group of young adults showed one general trend in which variability values were higher in the Increased Length and the Increased Complexity condition, compared to the other speaking conditions. Comparable results have been reported by Kleinow and Smith (2006), who assessed a group of young adults, and found that increases in syntactic complexity and utterance length were associated with an increase in STI values. Sadagopan and Smith (2008) also examined the effects of utterance length and linguistic complexity on the STI, but in their study the young adults did not show a significant overall influence of length or complexity on movement variability.

With respect to the group of older adults, their between-task results were largely similar to the results found in the age-matched control group: higher variability values were observed in the Fast Rate and Slow Rate conditions, when compared to the Habitual rate, Increased Length and Increased Complexity conditions, as well as the presence of higher variability values in the Dual task compared to the Habitual task. This is unsurprising, as the older adults formed a considerable subgroup within the age-matched control group.

5.3.2.2 Differences between groups

The LMM analyses indicated significant differences in variability between young and older speakers across estimators, speech parameters, and speaking conditions.

For the STI of sound pressure level, the group of young adults showed higher variability values in the Increased Length and Increased Complexity tasks, compared to the older adults. In the Dual task, the older adults showed higher variability values. Variability of fundamental frequency was higher in the Slow Rate and Dual tasks in the older adults, compared to the young adults. The young adults displayed higher first formant frequency variability in the Fast Rate and Increased Complexity task. In contrast, Wohlert and Smith (1998) and Kleinow et al. (2001) reported higher spatiotemporal index value of lower lip movements with increasing age, whilst the results of the current study reflect the findings of a study by Dromey et al. (2014), where young adults displayed higher jaw movement spatiotemporal index values in a sentence repetition task with increased complexity compared to older.

The significant results of the spatial variability estimator largely reflected the results of the STI. The group of young adults showed higher sound pressure level variability in the Increased Length and Increased Complexity tasks, compared to the older adults. In contrast, fundamental frequency variability in the Slow, Fast, and Dual tasks was higher in the older adults, compared to the young adults. Furthermore, first formant frequency variability of the Fast Rate and Increased Complexity tasks, and second formant variability in the Slow Rate task were higher in the group of young adults, compared to the older adults.

Temporal variability of sound pressure level was higher in the group of young adults in the Increased Length and Increased Complexity tasks, compared to the older adults. Furthermore, temporal variability values of first formant frequency were higher for the young adults in all speaking tasks except the Dual task.

The age-related differences found in the Dual task generally follow previous studies on speech motor variability in divided attention tasks. Whilst sentence durations were similar across the two groups, the older adults displayed a higher spatiotemporal index and higher spatial variability values for sound pressure level and fundamental frequency. A general finding in earlier studies was that speech production might be affected during the execution of a dual task, with studies reporting a latency in voice onset time (Feyereisen, 1997), a decrease in fluency (Kemper et al., 2005; Kemper et al., 2009), and a decrease in speech motor stability (Dromey & Benson, 2003; Dromey & Bates, 2005; Dromey & Shim, 2008). In addition, ageing is associated with a decline in motor control functions (Krampe, 2002) and cognitive abilities (Salthouse, Fristoe, Lineweaver, & Coon, 1995; Salthouse, 2009), with adversary effects found during dual tasks (Salthouse et al., 1995; Chen et al., 1996; Verhaeghen et al., 2003). Several factors have been suggested to account for age-related differences in dual-task performances, including reduced cognitive processing capacities, loss of sensory and executive functions, and increased cognitive demands (Li & Lindenberger, 2002; Woollacott & Shumway-Cook, 2002; Fraser, Li, & Penhune, 2010). Bailey and Dromey (2015) investigated the effect of divided attention across different age groups by calculating the spatiotemporal index of lower lip movements during a series of sentence repetition tasks. Higher spatiotemporal index values were found during concurrent linguistic and cognitive tasks compared to an isolated speech task, but no age-related differences in speech motor stability were found. This was explained as a possible compensatory strategy in older speakers to reduce speaking rate, as evidenced by longer sentence durations compared to young speakers (Bailey & Dromey, 2015). In the current study, sentence durations of the dual task were not significantly different across groups, whilst variability values were higher for the older adults. This may indicate that the older adults may have chosen a different compensatory strategy in which speaking rates were maintained at the cost of reduced stability of speech motor movements (Smith et al., 1995; Goozee, Stephenson, Murdoch, Darnell, & Lapointe, 2005).

5.3.2.3 Classification of age

Model performance

To further investigate how the variability estimators were able to distinguish between young and older speakers, the estimators were factored into predictors and subjected to a Logistic Regression Analysis to explore the relationship between the predictors and age group.

The results showed that four predictors were able to increase the goodness of fit of the logistic regression model ($p < .001$). The combination of predictors added to the model resulted in 90.0% of the speakers being correctly classified, with a sensitivity of detecting ageing speakers of 92.9%, and a specificity of 87.5%. The overall performance of this model was better compared to the logistic model classifying dysarthria, indicating a higher distinction in variability characteristics between the two groups differing in age. Studies attempting to predict or estimate speaker age on the basis of speech or language production are sparse. Müller (2006) extracted a set of features including fundamental frequency, jitter and shimmer, speech rate, and duration and number of pauses from a speech corpus, and used these to classify four groups of speakers differing in age. Speaker groups included children up to 12 years old, teenagers aged between 13 and 19 years, adults aged between 20 and 64 years, and seniors aged 65 and above. A machine learning method was applied to classify the four groups. When age classes are grouped such that seniors are discriminated from the other classes, an overall accuracy of 94.6% could be reached, with a sensitivity of 97.0% and a specificity of 92.2%. Sedaaghi (2009) extracted a set of features related to formant frequencies, fundamental frequency, intensity, and spectral information from a corpus. A series of machine learning classifiers were tested in their performance on classifying speakers into groups below and above the age of 45 years. Model performances varied between 79.8% and 90.4%, with a sensitivity of detecting older speakers ranging from 80.0% to 88.3%, and a specificity ranging between 80.8% and 92.5%. Dobry, Hecht, Avigal, and Zigel (2011) developed a weighted-pairwise principal components analysis dimension reduction method to classify three different age groups. Groups were defined as young speakers (15-25 years), adults (26-54 years), and seniors (55-80 years). A series of MFCC coefficients was extracted from a speech corpus and used to classify the three groups, which approached a precision of around 65%.

Whilst these above studies mostly used different speech features, classification methodologies, and age brackets to distinguish between speakers of different ages, it can be noted that the performance of the logistic model in the current study can be considered comparable.

Predictors adding to the model

There were four predictors that significantly improved the model.

The first predictor (Factor 1) contained six variability measures: STI and TV of sound pressure level during the IL and IC tasks, and TV of first formant frequency during the IL and IC tasks. Higher values in this predictor were associated with an increased likelihood of being classified as young adult. The LMM analyses confirmed this: all measures showed significantly higher values in the group of young adults. The higher variability values found for the young adults in the Increased Length and Increased Complexity tasks are in contrast with some of the existing studies reporting on speech motor variability in ageing. For example, Wohlert and Smith (1998) and Kleinow et al. (2001) found higher spatiotemporal index value of lower lip movements with increasing age across a range of speaking conditions, indicating an age-related decline in speech motor stability. However, the current results reflect the findings of the study by Dromey et al. (2014), in which a group of young adults displayed the highest jaw movement spatiotemporal index values in a sentence repetition task with increased complexity, whilst older speakers displayed significantly longer utterance durations. Kemper, Herman, and Lian (2003) reported differences between young and older adults when producing language sentences when executing concurrent tasks. Whilst the older adults' speech was less fluent and slower than young adults' speech, young adults reduced sentence length and grammatical complexity during dual-task conditions. This might indicate a preferential strategy that is in line with the current results: younger adults find it acceptable to reduce sentence complexity while maintaining fluency, whilst older adults may prefer to keep the phrase content intact. The higher variability values in the Increased Length and Increased Complexity tasks for the young adults might indicate they are monitoring their complex sentence production less strict compared to older adults.

The second predictor (Factor 4) combined eight variability measures, all related to second formant frequency. These measures included all variability estimators in the Fast Rate and the Increased Length task, and the STI and SV in the Dual task. Similar to the first predictor, higher values were associated with a larger likelihood of being of younger age, in this case measures of second formant frequency variability. It is generally accepted that first formant frequencies are influenced by tongue body height and second formant frequencies by tongue body frontness, although a direct connection between vocal tract anatomies and formant frequencies does not exist, as the vocal tract filter function depends on the interaction of multiple simultaneously resonating cavities. As such, movements of formant frequencies have been used in many studies to indirectly assess vocal tract activity (e.g., Gerratt, 1983; Beverly et al., 2008; Dromey, Jang,

& Hollis, 2013). The variability measures associated with this predictor indicate that variability of second formant frequency has an impact on classifying young and older adult speakers. Further inspection showed that the young adults group displayed higher variability values across the measures, indicating more variable articulation, specifically in tongue frontness / backness movements. A possible explanation for these findings may relate to differences in vowel reduction effects instigated by differences in speaking rate or articulatory strategies. It has been found that variation in second formant (F2) shape depends on vowel durations, i.e., the shape of the acoustic movement between F2 onsets and F2 peaks is affected by rate change (Weismer & Berry, 2003). For example, Agwuele, Sussman, and Lindblom (2008) found greater decreases in F2 onsets during faster rates. However, no significant differences in mean sentence durations were found across groups, indicating that rate-dependent behaviour was most probably not a contributing factor.

The third predictor (Factor 6) contained three variability measures, including TV of fundamental frequency in the Slow Rate task and SV of sound pressure level during the Slow Rate and Increased Complexity task. Higher predictor values were correlated with an increased likelihood of being a member of the young adults group. Group comparisons indicated that spatial variability of sound pressure level in the IC condition was higher for the young adults. The two other measures in this predictor showed a trend towards higher values in the older speaker group. An underlying common pattern amongst the measures of this predictor is difficult to discern. The inclusion of the measure involving sound pressure level variability in the IC task reflects the findings in the first predictor, where the other two variability measures were included, underscoring the prominent role of the longer and more complex sentences in distinguishing young and older adult speakers.

The fourth predictor (Factor 12) contained four variability measures: all variability measures of first formant frequency during the Fast Rate task, and TV of first formant frequency during the Habitual task. Similar to the other predictors, higher values of this predictor were associated with an increased likelihood of being a member of the young adults group. All measures of this group were found to be significantly higher in the group of young adults. It has been found that both first formant and second formant frequencies decrease with increasing age in adult speakers, possibly due to changes in the position of the respiratory system and digestive tract, possibly resulting from vocal tract lengthening with increasing age (Harrington, Palethorpe, Watson, et al., 2007; Reubold, Harrington, & Kleber, 2010). Lower average formant values found with older age might give rise to decreased variances across the formant measures. Another interpretation for these results may be put forward when considering that the contribution of this predictor seems to reflect the involvement of second formant variability measures bundled in the second predictor. The combined elevated measures of formant contour variability found in the young adults may point at differences in articulation of the tongue during vowel production, not only the frontness / backness dimension, but also the height dimension.

The overall results of the logistic regression model showed that estimation of age is largely predicted by higher measures of variability in young adult speakers, compared to older adult speakers. Thus far, studies have reported varying results regarding speech motor control across age groups. A decline in speech motor stability with increasing age has been reported by Wohlert and Smith (1998) and Kleinow et al. (2001), whilst Dromey et al. (2014) reported higher variability measurements in young adults. Low variability values across multiple repetitions of a motor behaviour are usually interpreted as the presence of stable underlying processes involved in movement planning and execution (Kleinow et al., 2001). However, high variability values may indicate that the speaker is using multiple solutions to reach task goals, i.e., the speaker is exploring more of the available movement space to achieve the phonetic goals. In this context, rather than considering lower variability values as optimal, one might view these as evidence of reduced flexibility or plasticity, possibly pointing at more rigid control strategies (Dromey et al., 2014). In the context of the differences found between speakers of distinct age groups as well as between the speakers with hypokinetic dysarthria and healthy control speakers, it should be noted that variability values cannot be interpreted unambiguously. Even if these values are a reflection of variability of a speech parameter across a series of repetitions of a phase, the underlying source and significance of variability should be interpreted in relation to the speakers under investigation.

5.3.3 The relationship between variability estimators and clinical assessments of disordered speech

It is important to know how the measures of variability relate with standard assessments of speech motor control in hypokinetic speech in order to be able to interpret the results in a wider clinical context. The last research question investigated the nature of relationships between linear and nonlinear estimators, intelligibility, acoustical analyses of disordered speech, and quantifiable details of speakers' medical history.

The obtained outcome measures were correlated with each other by means of Pearson Correlations, with a 2-tailed test of significance.

5.3.3.1 Correlations between intelligibility ratings, diadochokinesis results, and medical history details

As a further characterization of the speakers with hypokinetic dysarthria, correlation were first carried out amongst measures of the intelligibility results (ratings of the reading task, ratings of the monologue task, transcriptions of unpredictable sentences), diadochokinesis results (CoV of syllable duration and CoV of maximum vowel intensity) disease duration (years between diagnosis and data collection), medication use (levodopa use in mg / day), and ACE-R score.

Strong significant correlations (all with a significance of $p < .001$) were found amongst the intelligibility measures of transcription and scaling, indicating a coherent assessment of intelligibility in the dysarthric speakers. This indicates that these measures were reliable to use for further correlations with medical history details and variability measures.

The correlations between the ACE-R scores and the three intelligibility measures yielded positive significant relationships, indicating that the speakers with worse cognition outcomes had more severe PD and consequently speech motor symptoms that were more severely affected. Furthermore, a significant negative correlation was found between monologue intelligibility ratings and disease duration: a longer disease duration was associated with a decreased intelligibility in this task, but not with the other two intelligibility measures. The monologue task is probably the most taxing amongst the three intelligibility tasks, and as such most sensitive to speech impediments in (especially) mildly affected speakers (Miller, 2013). In turn, the absence of a significant correlation between ACE-R score and disease duration, indicates a complex interrelationship between intelligibility, cognition, and disease duration. With respect to speakers with hypokinetic dysarthria, some studies have come to similar conclusions, i.e., it has been noted that while cognitive decline is characterized by changes in areas of attention, executive functions, memory, and visuo-spatial functions (Emre et al., 2007), it does not necessarily influence intelligibility or speech performance directly, but might be an indication of general disease progression, which in turn can influence speech performance (Miller et al., 2007; Maetzler, Liepelt, & Berg, 2009; Kulisevsky et al., 2013). The result underscores the degenerative nature of Parkinson's disease and its impact on communication. Furthermore, a significant positive correlation was present between levodopa intake and disease duration. Patients with Parkinson's disease were generally prescribed higher doses with longer disease progression, a common practice in managing motor and non-motor symptoms (Schrag & Quinn, 2000).

Whilst disease duration was correlated both with levodopa intake and monologue intelligibility, effects of levodopa intake on intelligibility were absent. All participants with Parkinson's disease were in their 'on'-state during data collection, and this result could thus be a reflection of the fact that levodopa appears to have little effect on speech performance (Plowman-Prine et al., 2009; Skodda, Visser, & Schlegel, 2010). Alternatively, the current results could have been skewed by the fact that the group included predominantly speakers with relatively mild dysarthria. The current sample is too small and unbalanced across severities to draw any firm conclusions from this result.

Significant results between diadochokinetic performance and intelligibility and medical history details were largely absent, and this is in line with literature reporting an absence of a relationship between diadochokinetic tasks and measures of intelligibility (Weismer, 2006; Kent, 2015). Levodopa intake was not correlated with diadochokinetic performance either, a result that has been reported by Skodda, Grönheit, and Schlegel (2011). However, whilst in the current study no correlation was found between disease duration and diadochokinetic performance, Skodda (2011) and Skodda, Flasskamp, and Schlegel (2011) reported increased coefficient of variation values of syllable length in diadochokinetic tasks with disease progression. Differences in group characteristics may possibly account for the contradicting results. Although having comparable ages to participants in the current study, participants in the study by Skodda, Flasskamp, and Schlegel (2011) were moderately impaired, and thus potentially more affected than the participants in this study.

5.3.3.2 Correlations between variability data and other outcome measures

The results of the correlational analysis of variability data and the other outcome measures are discussed below. Each of the 72 variability outcome measures was correlated with the different quantitative variables.

Variability, ACE-R score, medication use, and disease duration

The correlations between variability results and ACE-R score yielded only significant results in the speaking conditions involving rate change, where low ACE-R scores were associated with higher variability. This is an indication that cognitively affected HD speakers seem to have had more difficulties in repeating sentences at non-habitual rates. Little is reported on the relation between non-habitual rates and cognition in the literature. Lowit et al. (2006) reported that speakers with mild cognitive decline showed smaller amounts of change in speech rate from habitual to slow and fast conditions, compared to speakers with Parkinson's disease without cognitive decline, suggesting a prominent role of cognition in speech performance beyond the presence of dysarthria. The qualitative evaluation of the result of speaker HD22 who had cognitive decline confirmed a link between cognition and variability of speech motor control as this speaker showed the highest level of variability in the Slow Rate, IL, and IC condition of his group. These results give further foundation to the results of the logistic model analysis, which suggested that basal ganglia involvement has consequences for both cognition and speech motor stability.

Only two positive correlational trends were found between medication use and variability measures, exclusively related to the Dual task speaking condition. It has been reported that patients with PD may have problems in executing two tasks simultaneously due to limited attentional resources or problems with executive functions (Holmes et al., 2010). Levodopa treatment is moderately successful in improving basic motor functions in PD patients. However, a cluster of related motor symptoms are know to not improve with levodopa therapy, specifically fine motor control deficits (Kucinski & Sarter, 2016). It is possible that for patients prescribed with higher dosage this might have become ineffective, impacting on the execution of tasks that are both challenging with respect to fine motor control and cognition.

With respect to disease duration: four positive correlations were found between disease duration and outcome measures of variability. A number of these involved the Dual task, of which one was identical to those found during the correlations of variability with medication use, underlining the degenerative nature of PD in executing challenging tasks (Ho et al., 2002). Another notable trend was the involvement of the Slow Rate condition, possibly indicating that patients with a longer disease history have more difficulties in articulating at slower-than-normal rate, as their hypokinesia becomes more severe.

Variability and intelligibility

The correlations of the variability and the intelligibility results showed that relationships between the two outcome measures were largely absent. In total just three notable correlations were found across the three intelligibility tasks, indicating that higher variability values were associated with lower intelligibility score. The correlations involved the temporal variability estimator, the Fast Rate and Increased Length speaking conditions, and the F0 and F2 speech parameters. These limited results might indicate that temporal variability of fundamental frequency and tongue frontness / backness might play a role in perceived intelligibility, and seems to manifest itself most prominently when speakers have to speed up.

With respect to correlating acoustic variability measures with perceived severity in dysarthric speech, it is generally acknowledged that there is a complex relationship between listeners' perceptions and quantitative acoustic measures, in that the assessment of intelligibility is executed along multiple speech dimensions, whilst acoustic analyses are based on the assessment of a single or closed set of factors (Kent, 1996; Bunton, Kent, Kent, & Rosenbek, 2000; Bunton & Weismer, 2001). For example Dromey (2003) used a reading task to compare perceptual ratings with a series of acoustic measures including fundamental frequency, sound pressure level, standard deviation of semitones, harmonics-to-noise ratio, and long-term average spectrum moments in a group of speakers with hypokinetic dysarthria, but found no significant correlations were found between the perceptual ratings and any of the acoustic measures, suggesting that acoustics and perception do not correspond closely in assessing severity in dysarthria (Dromey, 2003). Tjaden, Sussman, and Liu (2010) investigated the relationship between measures of long-term average spectrum (LTAS) moments and perceived speech severity in a reading passage for speakers with Parkinson's disease. The strength of correlations found in their study ranged from weak to moderate for speakers with PD (Tjaden et al., 2010). A more recent study by Feenaughty, Tjaden, and Sussman (2014) investigated the relationships between judgements of intelligibility and selected acoustic measures including the standard deviations of fundamental frequency and sound pressure level in read sentences at the within-speaker level of a group of participants with PD, and found a large variation in the strength of correlation for each of the speakers, varying from moderate negative to moderate positive correlations, underlining the problematic relationship between the two domains. Perhaps the most insightful comparison of the current results with the findings of other studies investigating the relationship between intelligibility and measures of acoustic variability can be made by considering the study by Cummins, Lowit, and van Brenk (2014). A subset of the speaker data (16 speakers with hypokinetic dysarthria, 24 healthy control speakers) employed in the current study was used to assess the suitability of an utterance-to-utterance (UUV) variability index in characterizing dysarthria. A parametric representation of speech, the mel-frequency scaled cepstral coefficients (MFCC), were extracted from the sentence repetitions in the habitual and the fast rate condition. The MFCC information along the sentence tracks was combined with a dynamic time warping algorithm, which allows one sequence to be mapped onto another. A quantitative measure of the amount of time warping was used as an index of utterance-to-utterance variability. Similar to the results found in the current study, it was found that intelligibility was negatively correlated with UUV for the HD group in the habitual, and notably, the fast rate task. Overall, few studies have attempted to correlate variability of repeated utterances with measures of intelligibility (or other measures of speech accuracy), making cross-study comparisons difficult. In addition, a large proportion of the hypokinetic speakers had mild dysarthria, which led to a ceiling effect in intelligibility scores, weakening possible correlations with variability measures.

Variability and diadochokinetic performance

The results of the correlations between the variability results and the coefficient of variation of mean syllable durations in the diadochokinetic task indicated some trends, and these were largely dependent on DDK task. A single correlational trend was found for DDK task /pʌ/, where higher variability in syllable duration was associated with a lower STI for F0. Correlations involving /tʌ/ were absent. A few positive correlations and trends were found between variability measures and the coefficient of variability of syllable durations of /kʌ/ and /pʌtʌkʌ/. These tended to involve temporal variability, and correlations were usually present in the Dual and IC tasks. As temporal variability was the most prominent variability estimator correlating with the CoV of syllable durations, it may be argued that both outcome measures seem to capture shared temporal control characteristics in speakers with HD across quasi-speech and speech tasks. However, considering the small number of notable correlations and the lack of a clear pattern across DDK tasks, a clear-cut link between variability measures and temporal stability of diadochokinetic tasks cannot be established.

Correlations between variability measures and variability of peak vowel intensity of diadochokinetic tasks were more pronounced. A series of positive correlations and trends were found between the coefficient of variation of syllable intensity and the variability results. Particularly, correlations almost always involved sound pressure level: an increase in SPL variability at the sentence level was associated with an increase in SPL peak variability of vowels in DDK tasks. Significant correlations were found for all three variability measures and all six speech tasks, but correlations involving temporal variability and the Habitual Rate and Dual task were more present than in the other tasks. In general, these results showed a more consistent pattern across the two different measures of sound pressure level variability. This indicated that for the speakers in this study difficulties in loudness control extended across tasks, and are further evidence of reduced loudness control in hypokinetic dysarthria (Kleinow et al., 2001; Darling & Huber, 2011).

The above results gave evidence of relationships varying in strength between measurements of diadochokinetic tasks and variability. As such, these results largely mirror the absence of strong correlations of the diadochokinetic results with the other measures employed in this study, with the exception of loudness which appears to permeate all types of speech performance in speakers with hypokinetic dysarthria. These results are not surprising, as it has been argued from theoretical and empirical viewpoints that quasi-speech tasks like DDK are weak or at best equivocal in assessing processes related to actual speech production in speakers with dysarthria (Ziegler, 2002; Weismer, 2006; Kent, 2015). Diadochokinetic tasks possibly recruit different neural control structures from speech due to its simple structure, focus on maximum performance, and because communication is not intended (Bunton & Keintz, 2008; Kent, 2015). A generally accepted model is the task-dependent model (Ziegler, 2002), in which is assumed that speech and nonspeech tasks are different in that they are controlled by distinct motor systems. As such, the diagnostic value of diadochokinetic tasks for speech motor assessment is disputed. Judging the similarities or dissimilarities between DDK results and variability values obtained from a sentence repetition tasks should be done with caution. Therefore, it is acknowledged that DDK tasks have limitations with respect to characterizing speech motor control behaviour in healthy and disordered speech. For example, the usefulness and validity of DDK outcome measures in clinical intervention have been contested (Kent, 2015). However, it has also been argued that experiments with simultaneously employed speech and nonspeech tasks might be informative for the assessment of speech motor involvement (Ballard, Robin, & Folkins, 2003; Maas, 2017). Staiger, Schölderle, Brendel, Bötzel, and Ziegler (2017) showed that differences between speech, quasispeech, and nonspeech tasks were smaller in speakers with dysarthria compared to healthy speakers. Given the previous considerations and the exploratory nature of assessing diadochokinetic characteristics in this study, it was deemed to be justified to evaluate the diadochokinetic tasks together with the variability measures.

The results of the present study demonstrated that the acoustic variability estimators were able to differentiate between dysarthric and unimpaired speech, between young and older speakers, and between speaking conditions within most speaker groups. Furthermore, where significant correlations and trends were found, the variability estimators showed a coherent and interpretative relationship with a number of clinically based assessments. Whilst the majority of the research questions could be answered positively, one needs to remember this was an exploratory study and therefore the results need to be interpreted with caution and are restrained in various aspects.

In the following sections, the limitations of this study will be discussed, together with some recommendations for future research.

5.4 Limitations of the study

A number of limitations arose during the study or were unavoidable considering the scope of the project. The most important issues are concerned with participant recruitment, data collection, methodological limitations and technical limitations.

In relation to the selection of participants, based on the intelligibility results a large number of the speakers in the clinical group had a mild severity of dysarthria, whilst only a few speakers were moderately affected. Therefore, caution should be taken in generalizing findings to speakers with more severe dysarthria. The relatively small number of participants prevented a further grouping into classes of different severity. The heterogeneity within participant groups with respect to severity in the current study has been encountered and acknowledged in many other research reports, and are typically difficult to avoid with limited participant numbers (Feenaughty et al., 2014; Kuo, Tjaden, & Sussman, 2014). Similar speaker numbers have been used in other studies investigating intelligibility or acoustic parameters in dysarthria (Dromey, 2003; Neel, 2009; Tjaden et al., 2010; Tjaden, Lam, & Wilding, 2013). Whilst the group size and characteristics of the clinical participants in the current study could thus have been expanded, they are comparable with existing studies investigating dysarthria, and can therefore still make a contribution to our understanding of the disorder.

Furthermore, the speakers of the age-matched control group were not completely matched in gender with the group of speaker with hypokinetic dysarthria. The HD group comprised a higher proportion of males (18 out of 23), compared to the AMC group (15 out of 24), possibly introducing an effect of gender. The results of the assessment of the effect of gender on variability showed that female speakers showed higher values of the spatiotemporal index in the Habitual and Fast Rate condition of speech parameter First Formant, compared to male speakers. If all other things were equal, one would expect the AMC group to be displaying on average higher variability values for this speech parameter, compared to the HD group. However, when comparing variability measures between the two groups (see table 4.7), a main effect of group was found for the STI and temporal variability, in which the HD group had higher variability across conditions compared to the AMC group. A trend (p = .052) in similar direction could be observed for spatial variability, where the HD group displayed higher values across speaking conditions, compared to the AMC group. Therefore, the effect of gender was biased against the results in this study, indicating that significant results could have possibly been stronger. However, as there were only four speakers in the HD group (HD04, HD05, HD14, HD23) that were not age- and gender-matched, it can be assumed that the different composition of groups in terms of the proportion of males and females did not impact on the eventual result.

To be able to fully evaluate the performance of the participating speakers and to exclude unwanted comorbidities where possible, a thorough clinical examination is advisable. For example, commonly applied tests include the Unified Parkinson's Disease Rating Scale (UPDRS) (Fahn, 1987) and the severity score of the Hoehn and Yahr scale (Hoehn & Yahr, 1967), enabling the assessment of motor complications. It is well known that motor complications have an impact on the quality of life of PD patients (Chapuis, Ouchchane, Metz, Gerbaud, & Durif, 2005). For example, the quality of life of participating speakers may be assessed by means of the 39-item Parkinson's Disease Questionnaire (Peto, Jenkinson, Fitzpatrick, & Greenhall, 1995). As hearing might be affected in older adults, with possible consequences for speech production, it is additionally recommended to perform a pure tone hearing screening (ASHA, 2005). These assessments could have provided more information on the participants, and might have become a predictor of the variability measures used in this study. However, the administration of the UPDRS would have required a neurologist. Data were collected in a single session of about 60 to 90 minutes, including medical history, the ACE-R, reading tasks, monologue, maximum performance tasks, and the sentence repetition tasks. Within the limitations of this study, assessments were therefore limited to patient self-reports and screening measures that did not require extensive qualifications or experience. Finally, the number of variables included in the statistical comparisons throughout this study was already relatively high, with additional measures further increasing the risk of Type I errors. In addition, it is not certain what more refined measures of patient performance would have added in value compared to increasing this statistical risk.

In addition to limiting the amount of baseline tests that could be administered, time restrictions also forced making choices of speaking conditions. The sentence repetition tasks included six speaking conditions. Sentence repetition tasks in which the effect of increased loudness (Kleinow et al., 2001; Tjaden & Wilding, 2004; Darling & Huber, 2011), or altered pitch (de Swart et al., 2003; Tse, Wong, Ma, Whitehill, & Masters, 2013; Tykalova et al., 2014) on speech motor variability are evaluated were therefore not included in the research paradigm in this study, but might be useful to include in future research. However, the set of currently used sentence conditions proved to be successful in bringing about task-related differences.

With hindsight, some additional improvements could also have been made to the elicitation procedure for the sentence repetitions. In the current study, participants were asked to employ self-pacing in producing the sentence repetitions. This might potentially result in a non-uniform, individual, and self-chosen trade-off between speed and accuracy, introducing an extra factor of variation at the level of individual subjects. In addition, the task constraints of the sentence repetition tasks were such that they might not be representative of natural speech. The tasks used in the present study are, in terms of cognitive load, less taxing to execute as they involve reading a single sentence, and less demanding in terms of speech motor control, as they involve the planning and executing the motor program of a memorized phrase. Future studies of language-speech motor interactions should possibly use priming tasks to generate data that are more naturally planned and produced (Sadagopan & Smith, 2008). To further counteract interferences of self-paced speech initiation, a few studies have employed or suggested an experimenter-controlled rate of on-screen stimulus presentation (Walsh & Smith, 2002; MacPherson & Smith, 2013), or other automatic external speech initiation methodologies such as employing auditory (metronome) or visual (oscilloscopic) cues (Pilon, McIntosh, & Thaut, 1998; McHenry, 2003). However, a pacing paradigm may be restrictive and could possible impact on temporal variability results, and the current methodology was therefore deemed to elicit more representative data despite the resulting variability in speech rate.

In the current study, each speaker produced around 20 repetitions in each of the sentence repetition tasks, of which a minimum of 10 error-less, reasonable fluent repetitions were selected. The selection of the utterances from the sentence repetition tasks carries an element of subjective interpretation when deciding which repetitions fulfil these criteria, and might differ across studies. Indeed, other studies employing similar sentence repetition tasks have shown that the selection of eligible utterances is often based on arbitrary criteria. For example, Smith et al. (1995) selected 15 repetitions without disfluencies or errors out of 20 repetitions in each speaking task. Kleinow et al. (2001) instructed the participants to repeat the phrase for approximately one minute of length, and pause for several seconds between utterances. After one minute speaking and a resting period, the participants continued to repeat the utterances for an additional minute to ensure that at least 20 accurate and fluent productions of the phrase were recorded. After that, 15 individual tokens of the phrase were extracted. Nip and Blumenfeld

(2015) recorded 10 sentence repetitions and asked participants to produce additional instances of a sentence if they made any errors or produced any unusual hesitations or pauses. Whilst in the current study an internally consistent and coherent data recording and selection methodology was followed, the differences in methodologies across studies and research labs can make direct comparisons difficult. A universal data collection and processing methodology might improve comparability and help with interpreting variability results across studies.

Another technical limitation was the quality of estimating formant variability. A general difficulty with speech processing software was the accurate tracking of formants across longer stretches of speech. Higher formants tended to blend together, resulting in miscalculations, or were absent altogether. The miscalculations of higher formant values resulted in an unacceptable quality of the extracted third and fourth formant contours. A precise assessment of variability for these formants was not achievable, and these were excluded. With respect to first and second formant data, some optimization steps in computation and signal processing of first and second formant data were undertaken to address this problem. Even then, a fair amount of first formant and mostly second formant frequency contours had to be discarded, potentially impacting on the statistical power of the analysis. The results of the LMM analyses appear to confirm this, as differences in second formant variability between groups and tasks were mostly absent. Previous studies assessing variability in Parkinson's disease have used speaker groups as small as eight (Kleinow et al., 2001) or six speakers (McHenry, 2003, 2004). When using a lower limit of six speakers per group, a few instances would yield insufficient data to compare between groups. Specifically, these are the comparisons between YA and OA speakers in the Slow Rate (4 vs 3 speakers) and Increased Length (8 vs 5 speakers) conditions. However, given the exploratory nature of the study, these data were included for further analysis. In addition, the model of the logistic regression analysis used to classify the groups of young and older adults contained a significantly contributing predictor involving eight measures of second formant variability. This signals that even a relatively smaller second formant frequency data set could bring age-related differences in articulation to light, and was thus worthy of inclusion.

Finally, some limitations of the study involved the manner in which the statistical results were processed. Whilst the results gave evidence of the presence of explanatory relationships between characteristics of sentence variability and other outcome measures, these results should be interpreted with caution, considering the number of significant correlations or trends was rather low across the different comparisons.

Furthermore, large samples are needed in order to optimally conduct logistic regression analyses, as maximum likelihood coefficients are large sample estimates. A small sample size may overestimate odds ratios, and therefore may impact on the validity of the conclusions drawn from analyses involving logistic regression (Nemes, Jonasson, Genell, & Steineck, 2009). Reed and Wu (2013) noted that the suggested minimal sample size for optimal data analysis has been proposed to be around 200 participants, although mentioned also studies that employed sample sizes as low as 66 (Kingston, Huber, Onslow, Jones, & Packman, 2003). The current study employed sample sizes well below that: 47 speakers in the HD and AMC groups, and 30 speakers in the YA and OA groups. An additional critical factor involves the number of covariates employed in the analysis. Calculations of odds ratios might be biased when the number of covariates under examination is high relative to the sample size. In the current study, principal component analyses were partly used to mitigate this problem by reducing the number of covariates from 72 variability outcome measures to 16 (HD vs AMC) and 17 (YA vs OA) principal components, thus reducing the number of predictors relative to the sample size. Taking these limitations into account, it should be noted that there is a risk that the results in the study may have over-estimated the strength of the factors in predicting outcome in the models. However, the concurrently performed LMM analysis largely confirm the findings of the logistic regression models, a finding that validates the various analyses performed with the data, despite the limitations discussed above.

5.5 Suggestions for future research

The results of the research carried out in this study have shown that linear and nonlinear estimators of variability of acoustic data were informative in analysing speech motor behaviour in hypokinetic dysarthria. To further investigate the potential of acoustic variability estimators both in research and in a clinical setting, the following suggestions for future research are discussed. These include: (1) improving the methodological and technical framework; (2) undertaking steps for further validation; (3) evaluating aspects of motor control across dysarthria types and severity; and (4) investigating the potential for clinical use in monitoring therapy outcomes. These issues are expanded on below.

Improving the methodological and technical framework

The current study employed four speech parameters. Although the current study encountered limitations with respect to obtaining accurate F1 and F2 contours and the subsequent impact on statistical power, it is recommended to maintain the current set of speech parameters, as they potentially address different speech subsystems (SPL: respiration and phonation; F0: phonation; F1 and F2: articulation), and as such are intrinsically valuable and complimentary. Further developments in applications that may aid in labeling and manually correcting derived speech signals, in particular formant trajectories (see e.g., Winkelmann and Raess (2014)), would be necessary to obtain accurate and usable formant contours.

When evaluating the suitability of the six speaking conditions used in the current study, it can be concluded that, based on the outcome of the binomial regression analysis, the IC condition most prominently differentiated between speakers with hypokinetic dysarthria and control speakers. Drawing in the results of the linear mixed model analyses, it can be noted that group differentiations involving the IL condition often overlap with the IC condition. As such, the IL condition had little to add and might be left out in future experimentation.

A further point to be considered is that whilst the linear and nonlinear acoustic estimators have proven to be successful in adding to the current understanding of speech motor control issues in disordered or affected speaker populations, the current setup is not sufficiently automated to be considered an easy and reliable analysis tool for everyday use by clinicians. Further developments in signal processing, software automation, and hardware integration are essential to turn the acoustic variability estimator methodology into a fully functioning clinical tool. Ideally, the setup should consist of a laptop equipped with software and hardware capable of high quality voice recording, automated selection of valid stimulus repetitions, automatic identification and annotation of onset and offset points of the stimulus repetitions, automatic extraction of acoustic features and subsequent calculations of variability. However, as discussed before, the current method of automatically deriving formant trajectories, whilst automated, is not sufficiently accurate. Even after the computational steps to stabilise the formant contours, a large proportion of the data had to be discarded. An investigation into the feasibility of manually correcting formant contours could optimize the quality of extracted contours, enabling more data to be included.

Validation of the acoustic variability estimators

For validation purposes, it is important to assess whether variability estimators based on acoustic properties in the speech signal represent variability directly obtained from articulatory movements. A few studies have reported on concurrently measured acoustic and kinematic movement patterns. Howell et al. (2009) examined the relationship between the spatiotemporal index of sound pressure level and the spatiotemporal index of lower lip kinematics during a sentence repetition task executed by speakers who stutter and unimpaired speakers. The results showed a positive correlation between the two variability measures for the group of speakers who stutter, and when taking both speaker groups together. However, a direct correlation between the two variability measures could not be found for the unimpaired speakers. Mefferd and Green (2010) measured tongue movements for vowels in healthy adults during habitual, fast, slow, and loud speech using three-dimensional electromagnetic articulography. Articulatory-to-acoustic relations for phonetic variability were determined by correlating changes in lingual movement variability with changes in formant movement variability, but the authors did not find significant positive linear association for kinematic and acoustic variability. Factors including coarticulation, motor equivalence, and nonlinearities in the linkage between movement and acoustics were thought to account for these findings. It is clear that further research involving an extension of acoustic measurements of variability, (coordinated) articulator movements, and speaker groups are warranted. Future studies should further evaluate kinematic speech movements and contours extracted from the concurrently obtained acoustic signal during sentence repetition tasks. The stimuli used in the current study lend themselves well for this purpose: the sentence "Tony knew you were lying in bed" contains a number of open vowels that bring about lower lip and jaw opening movements, and as such could also be used in articulographic studies.

Evaluating motor control across dysarthria types and severity

An important application of the acoustic variability estimator could be the assessment of severity of speech disorders. As discussed before, the results of the current study are limited by the narrow range of severity present in the participating speakers. In order to investigate whether variability assessments could serve as an objective analysis method to establish speech disorder severity, it is recommended to include larger and more clearly delineated severity groups. The inclusion of speakers with more severe speech impairments might reveal stronger and additional relationships between acoustic measures of variability and intelligibility, for example in vocal tract stability expressed as first formant and second formant variability. The standard reference clinical score quantifying average Parkinson's disease (PD) symptom severity is the Unified Parkinson's Disease Rating Scale (Tsanas, Little, McSharry, & Ramig, 2011), and future studies might use this measure to identify and select study participants with more severe symptoms.

Since the acoustic variability estimators proved to be well suited to analyse variability in speech motor movements, it would be useful to include other neurogenic communication disorders as a focus of research. Dysarthria types other than hypokinesia are most notable to consider, in particular ataxic dysarthria, which is one of the most prevalent dysarthria types and exhibits generally a typical and consistent pattern of speech disorders, enabling the formation and recruitment of clear-cut participants groups (Duffy, 2000). Thus far, a few studies have applied estimators of acoustic variability to study the effect of cerebellar damage related to ataxic dysarthria on speech motor control (Anderson et al., 2008; van Brenk & Lowit, 2012; Cummins et al., 2014). Results of these studies and further research indicated that the acoustic estimators might be more sensitive to ataxic dysarthria than hypokinetic dysarthria, as ataxic speakers show higher degrees of acoustic variability compared to hypokinetic speakers, irrespective of the severity of dysarthria, further demonstrating the important role of the cerebellar control circuit in speech motor control.

A further interesting group to study that are highly likely to show abnormalities in motor control and stability are speakers with apraxia. Apraxia of speech (AOS) and childhood apraxia of speech (CAS), characterized by an inability to translate speech motor plans into motor activity, are also interesting as target groups, as these disorders are typically characterized by inconsistent errors on consonants and vowels in repeated productions of syllables or words, lengthened and disrupted coarticulatory transitions between sounds and syllables, and inappropriate prosody (American Speech-Language-Hearing Association, 2007; Duffy, 2013), and therefore an ideal target for assessing acoustic motor stability. Indeed, measuring speech motor variability in AOS and CAS has already been a topic of research in recent years (van Lieshout, Bose, Square, & Steele, 2007; Moss & Grigos, 2012; Haley, Jacks, & Cunningham, 2013; Grigos, Moss, & Lu, 2015).

Investigating the potential for clinical use

Once the measures have been fully validated, the acoustic variability measures might potentially be used to evaluate treatment effectiveness or act as an outcome measure. Some studies already demonstrated that loud phonation may improve phonatory and articulatory stability in individuals with PD (see e.g., the studies discussed in section 2.7.3), indicating there is clear potential to study acoustic variability in sentence repetitions that are produced in a condition of Increased Loudness, e.g., by instructing patients to speak at ‘twice’ their normal vocal intensity. Employing this condition ties also in with principles of current treatment programs. In particular the LSVT LOUD programs for individuals with PD has been widely used to improve intelligibility by teaching speakers to “think loud” and to produce high-effort loud phonation while constantly monitoring their vocal loudness and effort (Ramig et al., 2001). By employing such speaking condition, the acoustic variability indices may potentially be recruited to monitor participants' progress during LSVT LOUD treatment. Directly obtained measures of intensity and intensity control can be obtained by the acoustic variability estimators, going above and beyond the previously employed kinematic measures of lower-lip variability.

In similar vein, employing a speaking condition with a Clear "repeat this phrase while speaking clearly" or Enunciated "repeat this phrase while enunciating every word" speaking instruction (c.f., Lam and Tjaden (2016) and Park, Theodoros, Finch, and Cardell (2016)) in future research gives the opportunity to evaluate motor stability as a factor of hyperarticulated speech. A clear speech condition might also aid in evaluating outcomes of LSVT ARTIC, a training variant that maintains the same principles of training improved speech via intensity and high-effort tasks but focuses on maximum enunciation instead of loudness (Fox, Ebersbach, Ramig, & Sapir, 2012). As the production of clear speech is accompanied by loudness and rate changes compared to healthy speech, measures of acoustic spatial and temporal variability might incorporate and quantify these confounding factors, and draw a more complete picture of the motor control strategies used to produce clear speech.

5.6 Conclusion

This study set out to determine whether linear and nonlinear estimators of acoustic variability are suitable in the assessment of speech motor control in dysarthric and ageing speakers. The acoustic properties in the speech signal may serve as an indirect measure of speech movements, and circumvent the invasive and technologically demanding nature of directly measured speech movement data. A positive answer would entail that this technology might be further adopted in speech motor control research, and potentially be embedded in clinical practice, adding to the instrumentation available to the speech pathologist and speech researcher when assessing this particular type of speech motor disorders.

The most important results of the variability analyses were the following:

- Variability measures employed in this study could be successfully clustered and serve as predictors in logistic regression models that were able to distinguish between speakers with hypokinetic dysarthria and control speakers, as well as between speakers of different age groups.

- The logistic regression model used for classification of dysarthria had a model performance of 80.9%, and involved one predictor that significantly contributed to the model, containing variability measures related to sound pressure level contours in the Increased Complexity task. An increase of this predictor was associated with an increase in likelihood of having hypokinetic dysarthria.

- The connection between decreased cognitive functioning and increased speech motor variability in speaking conditions of increased length and complexity may be further evidence for the involvement of the basal ganglia in motor planning and control, as well as in cognitive and language-specific functions.

- The logistic regression model classifying young and older adults model resulted in 90.0% of the speakers being correctly classified, and involved four predictors. Variability measures related to these predictors involved sound pressure level and first and second formant variability, indicating age-related differences in phonation and respiration. Higher predictor values were associated with an increase in likelihood of being classified as young adult. The lower variability values found for the older adult speakers may be evidence of more rigid control strategies, i.e., in the light of functional or structural changes, they may be unable to display flexibility.

- Some meaningful correlational trends were present between selected instances of variability data and other outcome measures:

  - Higher variability measures were correlated with increased medication use, possibly pointing at a shared expression of disease severity. Furthermore, higher variability measures were associated with longer disease duration and higher ACE-R scores, signalling the degenerative nature of Parkinson's disease.

- Some measures of variability correlated with intelligibility measures, including variability of fundamental frequency and second formant frequency, and therefore show potention to serve as acoustic based cues of intelligibility of hypokinetic speech.
- Some correlations were present between the coefficient of variation in diadochokinetic syllable duration and temporal variability in the sentence repetition task, as well as between the coefficient of variation of vowel intensity and variability in sound pressure level contours, suggesting that difficulties in timing and loudness control extend across tasks.

The findings of this study have implications both for clinical research and clinical practice, which will be discussed in the following sections.

5.6.1 Implications for clinical research

Research related to the assessment of speech motor control in normal and disordered populations has made great progress in incorporating novel research methodologies in recent years. The use of acoustic based measurements of stability of speech motor movements has several benefits in the assessment of speech motor control, especially in disordered populations. Audio-based signals are cheaper, less invasive and easier to record and analyse compared to kinematic signals. Whilst kinematic measurements are usually concerned with the movement characteristics of single articulators (e.g., lower lip movement) or gestures (e.g., bilabial closure), acoustic properties extracted from the audio signals may describe different aspects of speech production simultaneously, including respiration, voicing, prosody, and articulation. Acoustic data can also be captured in combination with other scanning and imaging systems during the production of speech, something which is not possible with electromagnetic articulography or other motion capture systems.

The current study contributed to the field of speech motor control research by applying an acoustic based method of analysing speech movements in a wide array of speaking conditions and speech parameters, and across different variability estimators. It is widely accepted that lesions to the basal ganglia resulting from Parkinson's disease disrupt speech production (Volkmann et al., 1992; Longworth, Keenan, Barker, Marslen-Wilson, & Tyler, 2005; Wildgruber et al., 2001; Walsh & Smith, 2011). The pattern of results in the current study provides additional evidence of basal ganglia involvement in the programming and coordination of speech movement sequences. The results showed that functional data analysis has significant advantages to the spatiotemporal index, as the predictor that was significant in classifying hypokinetic and normal speech contained mostly measures of temporal variability.

The evaluation of different predictors in the logistic models revealed that sound pressure level is most successful and reliable in distinguishing speaker groups and speaking conditions, whilst fundamental frequency and second formant frequency were the least successful. Overall, some of the current measurement parameters have shown potential in signalling some specific speech motor control difficulties in impaired speakers. In addition, the time and expertise necessary to collect, analyse and interpret data with the current setup is not significantly more demanding compared to currently available measures of kinematics, e.g., electromagnetic articulography.

Based on these observations, acoustic linear and nonlinear estimators of variability show good potential to be included as an additional methodology for clinical research, while at the same time further research is necessary to evaluate to what extent these measures can beneficial in the assessment of speech motor control in disordered populations.

5.6.2 Implications for clinical practice

In addition to the implications for clinical research discussed above, the findings of the current study may have implication for clinical practice as well. The treatment of neurogenic speech disorders benefit from the use of reliable measurements and treatment methods. In recent years, new techniques and methods have been developed that can potentially support differential diagnosis of motor speech problem, serve as outcome measures for treatment, monitoring of disease progression, and detect sub-clinical problems in articulatory control. In the context of applying evidence-based practice in the speech and language therapy clinic, these objective measurement methods are more than welcome. Because of the challenges the speech and language therapist may have in introducing and integrating new instruments and methodologies in daily practice due to a lack of skills, knowledge and time (Baker & McLeod, 2011; Stephens & Upton, 2012), a new assessment method requires to be time-efficient, reliable, and have added value. The current analysis procedure is, as of yet, not sufficiently automated to be able to serve as an easily applicable instrument in daily practice. Further developments in automating recording, signal processing, and hardware integration are essential.

Whilst the variability estimators will require further steps in validation before adding to the clinician's instrumentation toolkit, the current study found robust elevated variability values in speakers with hypokinetic dysarthria (including speakers with low severity) in speech intensity, fundamental frequency, and first formant frequency. These differences came to light in relatively demanding speaking conditions. These results show that further application of the acoustic variability estimators might be able to contribute to evaluating phonatory, articulatory and prosodic deficits in dysarthria, and therefore be a potential indicator in further clinical assessment.

In addition, the current study demonstrated that acoustic measures of variability correlate with measures that are important in the management of the speech disorder in speakers with dysarthria, i.e., selected measures of variability correlated with intelligibility, cognitive status, disease duration, and medication use. This indicates that acoustic measures of variability may potentially be informative in monitoring disease progression.

In conclusion, this study evaluated and made initial steps to validate a novel technique to assess speech motor control in dysarthria and ageing by applying acoustic linear and nonlinear estimators of variability in large speaker groups, and laid a foundation for further studies in this direction by identifying critical issues in the selection and evaluation of tasks and materials. The results of this study showed that the assessment of complex speech movements when evaluating linguistic, cognitive or motor demands within or between speaker groups cannot be reduced to a single task or speech property, but rather calls for a multi-faceted approach in which distinct variability estimators, speech tasks and acoustic properties are evaluated simultaneously.

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Appendix A. Addenbrooke's Cognitive Assessment - Revised

Addenbrooke's Cognitive Assessment - Revised (version A), from Mioshi et al. (2006)

ADDENBROOKE'S COGNITIVE EXAMINATION - ACE-R

Final Revised Version A (2005)

Name :	Date of testing: .... /........ /........
Date of birth :	Tester's name: ....
Hospital no. :	Age at leaving full-time education: ....
	Occupation: ....
Addressograph	Handedness: ....

ORIENTATION — ATTENTION & ORIENTATION

➢ Ask: What is the	Day	Date	Month	Year	Season	[Score 0-5]
	....	....	....	....	....	
➢ Ask: Which	Building	Floor	Town	County	Country	[Score 0-5]
	....	....	....	....	....	

REGISTRATION

[Score 0-3]

➢ Tell: 'I'm going to give you three words and i'd like you to repeat after me: lemon, key and ball'. After subject repeats, say 'Try to remember them because i'm going to ask you later'. Score only the first trial (repeat 3 times if necessary).

Register number of trials ....

ATTENTION & CONCENTRATION

[Score 0-5] (for the best performed task)

➢ Ask the subject: ' could you take 7 away from a 100? After the subject responds, ask him or her to take away another 7 to a total of 5 subtractions. If subject make a mistake, carry on and check the subsequent answer (i.e. 93, 84, 77, 70, 63 -score 4)

Stop after five subtractions (93, 86, 79, 72, 65). ....

➢ Ask: 'could you please spell **WORLD** for me? Then ask him/her to spell it backwards**:**

....

MEMORY - Recall — MEMORY

[Score 0-3]

➢ Ask: 'Which 3 words did I ask you to repeat and remember?'

....

MEMORY - Anterograde Memory

[Score 0-7]

➢ Tell: ' I'm going to give you a name and address and I'd like you to repeat after me. We'll be doing that 3 times, so you have a chance to learn it. I'll be asking you later'

Score only the third trial

	1st Trial	2nd Trial	**3rd Trial**
Harry Barnes	....	....	....
73 Orchard Close	....	....	....
Kingsbridge	....	....	....
Devon	....	....	....

MEMORY - Retrograde Memory

[Score 0 -4]

➢ Name of current Prime Minister ....
➢ Name of the woman who was Prime Minister ....
➢ Name of the USA president ....
➢ Name of the USA president who was assassinated in the 1960's ....

ADDENBROOKE'S COGNITIVE EXAMINATION - ACE-R

Final Revised Version (2005)

V E R B A L F L U E N C Y - Letter 'P' and animals

➢ **Letters**

Say: 'I'm going to give you a letter of the alphabet and I'd like you to generate as many words as you can beginning with that letter, but not names of people or places. Are you ready? You've got a minute and the letter is P'

[Score 0 - 7]

total	correct
>17	7
14-17	6
11-13	5
8-10	4
6-7	3
4-5	2
2-3	1
<2	0

➢ **Animals**

Say: 'Now can you name as many animals as possible, beginning with any letter?

[Score 0 - 7]

total	correct
>21	7
17-21	6
14-16	5
11-13	4
9-10	3
7-8	2
5-6	1
<5	0

F L U E N C Y

L A N G U A G E - Comprehension

➢ Show written instruction:

[Score 0-1]

Close your eyes

➢ 3 stage command:

'Take the paper in your right hand. Fold the paper in half. Put the paper on the floor'

[Score 0-3]

L A N G U A G E - Writing

➢ Ask the subject to make up a sentence and write it in the space below:

Score 1 if sentence contains a subject and a verb (see guide for examples)

[Score 0-1]

L A N G U A G E

ADDENBROOKE'S COGNITIVE EXAMINATION - ACE-R *Final Revised Version (2005)*

L A N G U A G E - Repetition

➢ Ask the subject to repeat: **' hippopotamus'; 'eccentricity; 'unintelligible'; 'statistician'**
Score 2 if all correct; 1 if 3 correct; 0 if 2 or less.

[Score 0-2]

➢ Ask the subject to repeat: **'Above, beyond and below'**

[Score 0-1]

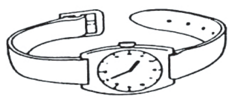
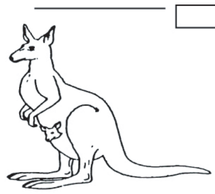
➢ Ask the subject to repeat: **'No ifs, ands or buts'**

[Score 0-1]

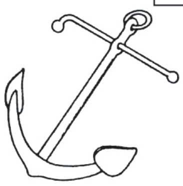
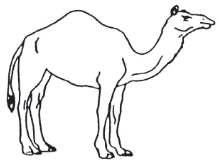
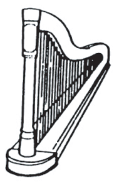
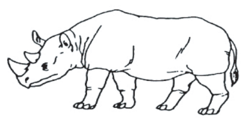
L A N G U A G E - Naming

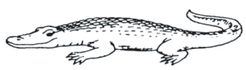
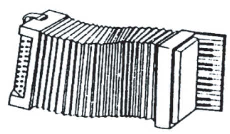
➢ Ask the subject to name the following pictures:

[Score 0-2] pencil + watch

[Score 0-10]

L A N G U A G E - Comprehension

➢ Using the pictures above, ask the subject to:

- Point to the one which is associated with the monarchy
- Point to the one which is a marsupial
- Point to the one which is found in the Antarctic
- Point to the one which has a nautical connection

[Score 0-4]

L A N G U A G E

ADDENBROOKE'S COGNITIVE EXAMINATION - ACE-R *Final Revised Version (2005)*

LANGUAGE - Reading

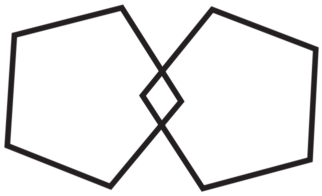
➢ Ask the subject to read the following words: [Score 1 only if all correct] [Score 0-1]

sew
pint
soot
dough
height

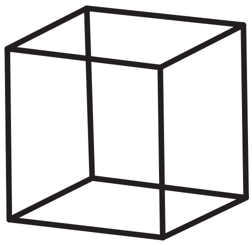
LANGUAGE

VISUOSPATIAL ABILITIES

➢ Overlapping pentagons: Ask the subject to copy this diagram: [Score 0-1]



➢ Wire cube : Ask the subject to copy this drawing (for scoring, see instructions guide) [Score 0-2]



➢ Clock: Ask the subject to draw a clock face with numbers and the hands at ten past five.
(for scoring see instruction guide: circle = 1, numbers = 2, hands = 2 if all correct) [Score 0-5]

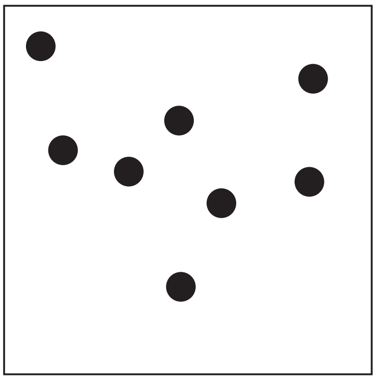
VISUOSPATIAL

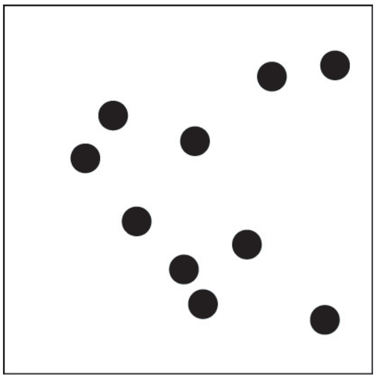
ADDENBROOKE'S COGNITIVE EXAMINATION - ACE-R *Final Revised Version (2005)*

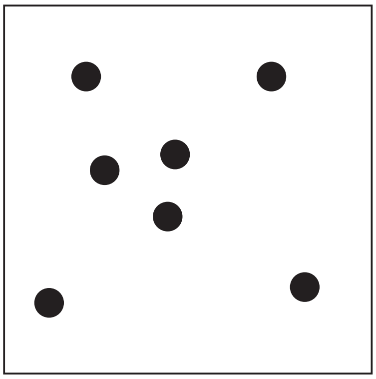
PERCEPTUAL ABILITIES

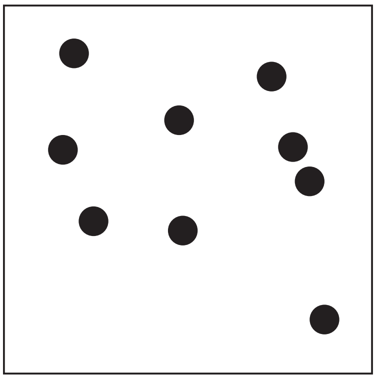
- Ask the subject to count the dots without pointing them

[Score 0-4]









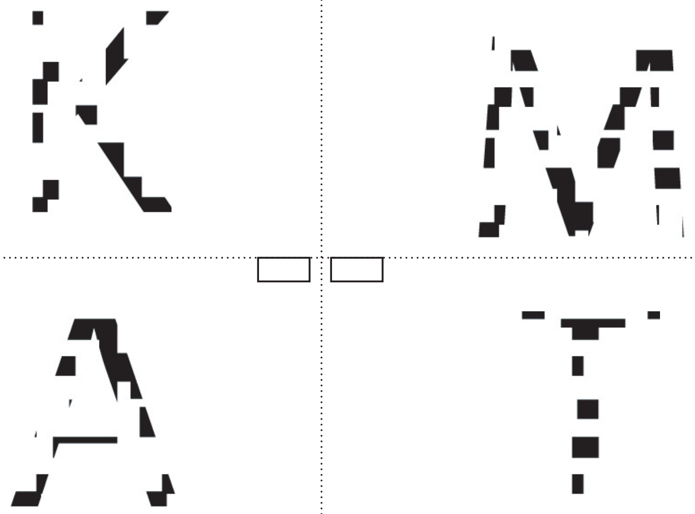
VISUOSPATIAL

ADDENBROOKE'S COGNITIVE EXAMINATION - ACE-R *Final Revised Version A (2005)*

PERCEPTUAL ABILITIES

VISUOSPATIAL

➢ Ask the subject to identify the letters [Score 0-4]



RECALL

MEMORY

➢ Ask "Now tell me what you remember of that name and address we were repeating at the beginning'"

Harry Barnes	....	[Score 0-7]
73 Orchard Close	....	
Kingsbridge	....	
Devon	....	

RECOGNITION

➢ This test should be done if subject failed to recall one or more items. If all items were recalled, skip the test and score 5. If only part is recalled start by ticking items recalled in the shadowed column on the right hand side. Then test not recalled items by telling "ok, I'll give you some hints: was the name X, Y or Z?" and so on. Each recognised item scores one point which is added to the point gained by recalling. [Score 0-5]

Jerry Barnes		Harry Barnes		Harry Bradford		recalled	
37		73		76		recalled	
Orchard Place		Oak Close		Orchard Close		recalled	
Oakhampton		Kingsbridge		Dartington		recalled	
Devon		Dorset		Somerset		recalled	

General Scores

SCORES

MMSE	/30
ACE-R	/100

Subscores

Attention and Orientation	/18
Memory	/26
Fluency	/14
Language	/26
Visuospatial	/16

Normative values based on 63 controls aged 52-75 and 142 dementia patients aged 46-86

Cut-off <88 gives 94% senstivity and 89% specificity for dementia
Cut-off <82 gives 84% sensitivity and 100% specificity for dementia

Appendix B. Reading passage My Grandfather

Reading passage 'My Grandfather', adapted from Van Riper (1963).

You wished to know all about my grandfather. Well, he is nearly ninety-three years old; he dresses himself in an ancient black frock coat, usually minus several buttons; yet he still thinks as swiftly as ever. A long, flowing beard clings to his chin, giving those who observe him a pronounced feeling of the utmost respect. When he speaks, his voice is just a bit cracked and quivers a trifle. Twice each day he plays skilfully and with zest upon our small organ. Except in the winter when the ooze or snow or ice prevents, he slowly takes a short walk in the open air each day. We have often urged him to walk more and smoke less, but he always answers "Banana oil!" Grandfather likes to be modern in his language.

Appendix C. Set of unpredictable sentences

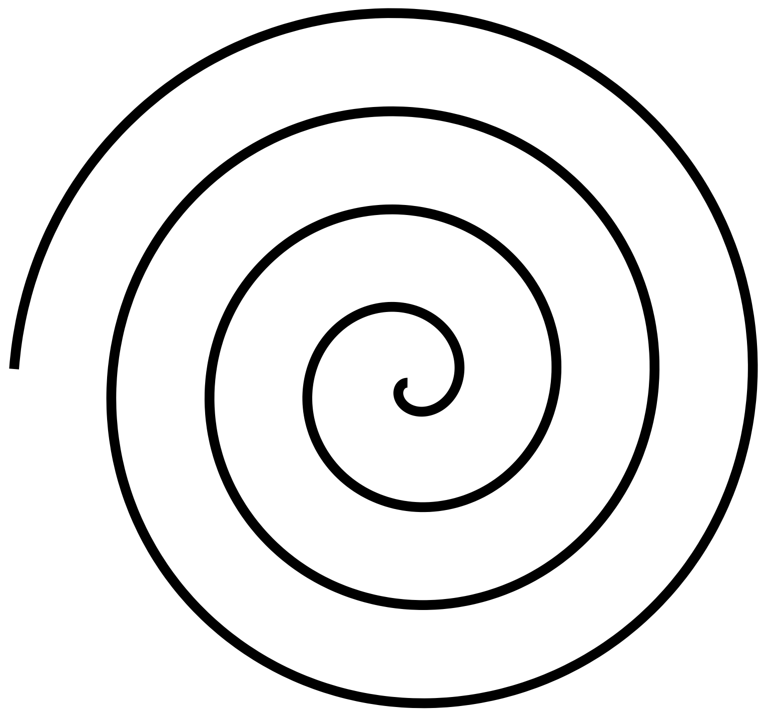
Set of unpredictable sentences for intelligibility testing, c.f. McHenry and Parle (2006).

1. Tim stated she should leave that day.
2. Animals often wander across wooded grassy paths.
3. Dogs with shaggy white coats appear fuzzy.
4. They began mixing dangerous materials by beaches.
5. Math instructors always allow pens before testing.
6. Mark buys baby elephants salty, crunchy cashews.
7. Black, wild, furry creatures act rather mysteriously.
8. Old baking books seem cheaper every summer.
9. Rich bankers enjoy small, rustic, summer homes.
10. Giant plastic bracelets do well each season.
11. Children carrying orange dotted scarves seem weird.
12. Wearing red gloves kept John rather happy.
13. Hot, darting rays dance along grey pavement.
14. Martha's friend bakes banana chips all winter.
15. Fast moving turtles never eat after sleeping.
16. Some creative authors try inventing exotic styles.
17. Lonely birds wander along clammy black caves.
18. Jim began milking venomous reptiles almost daily.
19. Chlorine changed his old clothes two tones.
20. Smashing big juicy apples involves great skill.
21. Many baseball jerseys get worn before winter.

22. Tall guys prefer trim, delicate, pale arms.
23. Four sleepy puppies snore beside that chair.
24. Big people often have old, noisy trucks.
25. Nice man usually grill better fresh vegetables.
26. Lamb seems juicier broiled using light sauces.
27. She always believes corn smells rather salty.
28. They spilled thin, yellow primer over furniture.
29. Happy dogs relish long baths near evening.
30. Red bricks sink quickly through thick mud.
31. Tall professors love ignoring loud, bothersome nephews.
32. Fat, soft marshmallows become tasty, warm desserts.
33. Bob buys instruments, although rarely purchases keyboards.
34. Defensive men often design mittens when relaxing.
35. Juice or candy won't fix his moods.
36. Tina loves making ham using tangy spices.
37. Package black pens using little silver boxes.
38. Boys never hide near big red cars.
39. Mary drove carelessly every rainy Friday afternoon.
40. Three puppies followed Jim's old, blue bike.
41. Steve seldom forgets dusting old card tables.
42. New watches usually display glowing red digits.
43. Four pink bubbles burst under her wand.
44. Playful orange butterflies climb long, green curtains.
45. Lucy's right sneaker sank through thick slime.
46. Biking past hilly pastures creates lovely scenes.
47. Inky dots dance over shimmering new screens.
48. Loud restaurant singers always project harsh attitudes.
49. Spicy cabbage flavoured everyone's favourite meat stew.
50. Andrew's blue notebook broke suddenly that morning.

Appendix D. Archimedean spiral

Template of Archimedean spiral used in the dual task.



Appendix E. Sentence durations in pilot study

Sentence durations (in sec) of sentence repetition tasks for the speakers in the pilot study

Subject	Habitual	Slow	Fast	IL	IC	Dual
S01	1.35	2.43	1.10	1.09	1.11	1.33
S02	1.18	2.49	1.18	1.11	1.06	1.35
S03	1.36	1.27	0.85	1.16	1.31	1.36
S04	1.06	1.90	1.01	1.02	1.10	1.13
S05	1.44	2.52	1.24	1.35	1.34	1.47
S06	1.74	1.49	1.05	1.41	1.16	1.12
S07	1.30	1.54	1.15	1.27	1.24	1.32
S08	1.54	2.14	1.40	1.63	1.66	1.50
S09	1.30	5.17	1.11	1.15	1.23	1.25
S10	1.28	2.25	0.96	1.27	1.21	1.37
S11	1.21	1.83	1.07	1.22	1.19	1.61
S12	1.27	1.77	1.23	1.25	1.40	1.45
S13	1.41	1.83	1.10	1.20	1.26	1.48
S14	1.16	1.71	0.84	0.96	1.06	1.16
S15	1.23	2.94	1.03	0.99	1.10	1.23
S16	1.23	2.67	1.08	1.12	1.19	1.17
S17	1.81	1.61	1.36	1.09	1.21	1.35
Average	1.35	2.21	1.10	1.19	1.23	1.33
SD	0.20	0.89	0.15	0.17	0.15	0.14

Appendix F. Results of spatiotemporal index in pilot study

Results of spatiotemporal index of sound pressure level for the speakers in the pilot study

Subject	Habitual	Slow	Fast	IL	IC	Dual
S01	32.57	31.97	29.16	29.78	32.29	25.74
S02	19.77	29.18	18.05	20.40	23.04	23.97
S03	22.60	22.27	18.77	20.37	30.77	22.68
S04	22.83	24.95	27.23	19.14	26.51	26.39
S05	13.15	25.85	15.23	17.30	16.53	20.34
S06	20.17	22.43	16.97	23.72	22.39	18.21
S07	14.16	32.25	17.85	20.45	15.34	19.11
S08	22.14	28.17	23.59	27.11	29.86	17.58
S09	17.06	28.61	11.27	14.37	11.16	11.07
S10	17.82	19.02	19.32	17.19	26.93	24.94
S11	17.65	27.15	20.75	18.99	21.37	22.26
S12	24.29	25.71	27.30	28.67	24.46	25.05
S13	20.76	30.95	22.51	19.75	31.19	14.02
S14	27.26	27.28	19.96	24.77	27.97	24.39
S15	21.61	34.13	23.92	29.86	31.86	18.56
S16	20.49	22.62	13.11	21.54	23.19	16.72
S17	19.62	25.03	20.16	30.00	30.04	21.95
Average	20.82	26.92	20.30	22.55	24.99	20.76
SD	4.61	4.07	4.93	4.97	6.22	4.35

Results of spatiotemporal index of fundamental frequency for the speakers in the pilot study

Subject	Habitual	Slow	Fast	IL	IC	Dual
S01	27.58	31.51	14.34	16.77	30.69	25.97
S02	22.10	37.22	22.13	22.49	30.51	31.09
S03	13.83	25.45	11.25	12.93	27.10	14.08
S04	17.93	16.48	24.92	16.94	17.00	20.35
S05	12.25	26.48	21.78	32.44	15.19	21.98
S06	19.01	23.74	16.38	21.30	19.17	9.30
S07	12.42	15.40	9.47	18.15	18.45	11.63
S08	15.57	14.63	16.90	22.24	24.29	12.85
S09	8.87	19.22	11.39	10.75	13.69	9.78
S10	9.42	23.10	11.11	9.41	14.50	28.41
S11	10.38	10.44	9.73	8.11	14.05	7.80
S12	11.62	13.77	17.88	15.99	24.45	15.73
S13	10.15	23.87	12.04	12.32	20.22	8.05
S14	15.72	21.19	11.22	17.41	18.85	14.24
S15	11.03	18.22	14.37	18.59	24.87	12.11
S16	8.10	29.91	8.48	12.53	21.81	8.65
S17	10.35	13.68	12.29	28.16	19.68	18.81
Average	13.90	21.43	14.45	17.44	20.85	15.93
SD	5.24	7.25	4.86	6.49	5.42	7.34

Results of spatiotemporal index of first formant frequency for the speakers in the pilot study

Subject	Habitual	Slow	Fast	IL	IC	Dual
S01	22.35	28.65	22.07	21.83	26.85	29.47
S02	17.17	31.09	21.45	15.57	19.93	33.82
S03	25.57	39.11	30.30	30.95	36.35	26.25
S04	31.22	23.91	31.13	27.55	29.63	29.28
S05	28.10	33.23	30.06	27.70	29.41	27.28
S06	33.37	37.61	27.09	29.30	32.10	28.74
S07	29.89	30.82	22.05	29.58	28.90	18.73
S08	29.67	30.40	31.51	34.83	33.31	30.21
S09	26.60	37.28	23.51	27.00	26.73	25.95
S10	21.70	36.05	31.52	21.50	31.86	30.06
S11	13.21	30.29	14.04	14.26	15.20	27.66
S12	33.62	30.87	27.50	30.61	30.01	24.68
S13	30.98	30.75	29.48	21.56	27.56	34.71
S14	19.82	25.96	17.67	17.56	16.97	17.87
S15	13.64	16.57	11.98	18.70	18.89	16.66
S16	25.76	33.40	16.11	29.71	32.50	30.45
S17	27.53	34.40	27.95	26.88	28.06	26.85
Average	25.31	31.20	24.44	25.01	27.31	26.98
SD	6.41	5.51	6.45	6.02	6.06	5.11

Results of spatiotemporal index of second formant frequency for the speakers in the pilot study

Subject	Habitual	Slow	Fast	IL	IC	Dual
S01	31.40	27.37	21.76	22.49	28.12	28.43
S02	18.41	31.38	23.23	19.27	19.96	29.03
S03	22.21	28.24	23.73	21.37	33.66	21.85
S04	37.34	29.09	44.35	31.90	39.64	37.75
S05	30.36	34.83	39.65	41.09	35.95	39.70
S06	36.12	38.48	27.52	34.74	20.89	22.17
S07	37.80	39.98	44.17	40.01	38.19	33.47
S08	36.91	32.69	34.50	35.08	39.64	32.70
S09	29.46	42.05	35.84	36.64	30.83	38.86
S10	17.64	32.27	28.37	17.51	23.04	17.61
S11	18.36	20.87	22.93	16.71	15.03	20.19
S12	30.37	21.48	26.87	26.95	27.61	23.74
S13	26.76	30.25	29.67	19.97	18.71	31.56
S14	31.53	37.07	29.50	21.62	27.60	27.49
S15	26.20	26.64	28.03	27.51	32.30	29.48
S16	30.96	36.48	33.27	30.99	32.50	30.64
S17	29.66	32.66	34.80	36.61	37.83	35.81
Average	28.91	31.87	31.07	28.26	29.50	29.44
SD	6.59	5.98	7.05	8.21	7.79	6.66

Appendix G. Results of spatial variability in pilot study

Results of spatial variability of sound pressure level for the speakers in the pilot study

Subject	Habitual	Slow	Fast	IL	IC	Dual
S01	0.462	0.445	0.407	0.405	0.376	0.326
S02	0.336	0.405	0.268	0.303	0.355	0.367
S03	0.347	0.383	0.309	0.320	0.505	0.347
S04	0.382	0.346	0.437	0.314	0.461	0.462
S05	0.215	0.305	0.234	0.269	0.262	0.311
S06	0.272	0.353	0.278	0.389	0.376	0.303
S07	0.231	0.507	0.264	0.334	0.240	0.303
S08	0.345	0.393	0.380	0.419	0.482	0.302
S09	0.273	0.293	0.172	0.224	0.172	0.164
S10	0.296	0.276	0.293	0.285	0.362	0.391
S11	0.295	0.441	0.327	0.313	0.352	0.366
S12	0.395	0.388	0.436	0.463	0.406	0.415
S13	0.346	0.466	0.380	0.321	0.517	0.234
S14	0.388	0.454	0.331	0.408	0.436	0.382
S15	0.322	0.470	0.359	0.480	0.518	0.310
S16	0.351	0.362	0.226	0.359	0.361	0.293
S17	0.325	0.341	0.337	0.495	0.472	0.377
Average	0.328	0.390	0.320	0.359	0.391	0.333
SD	0.062	0.067	0.075	0.077	0.100	0.070

Results of spatial variability of fundamental frequency for the speakers in the pilot study

Subject	Habitual	Slow	Fast	IL	IC	Dual
S01	0.430	0.525	0.246	0.273	0.495	0.359
S02	0.350	0.621	0.314	0.346	0.537	0.536
S03	0.210	0.356	0.183	0.201	0.405	0.211
S04	0.324	0.261	0.407	0.294	0.278	0.332
S05	0.206	0.371	0.288	0.575	0.209	0.263
S06	0.261	0.370	0.235	0.319	0.278	0.136
S07	0.195	0.222	0.162	0.277	0.256	0.185
S08	0.251	0.237	0.270	0.368	0.382	0.219
S09	0.149	0.302	0.182	0.195	0.220	0.160
S10	0.154	0.362	0.146	0.153	0.204	0.451
S11	0.166	0.147	0.141	0.137	0.223	0.127
S12	0.197	0.237	0.279	0.250	0.375	0.226
S13	0.155	0.421	0.176	0.175	0.332	0.134
S14	0.221	0.291	0.175	0.288	0.287	0.214
S15	0.168	0.298	0.247	0.325	0.429	0.196
S16	0.124	0.415	0.114	0.179	0.297	0.140
S17	0.183	0.231	0.214	0.494	0.341	0.317
Average	0.220	0.333	0.222	0.285	0.326	0.247
SD	0.081	0.118	0.075	0.117	0.099	0.117

Results of spatial variability of first formant frequency for the speakers in the pilot study

Subject	Habitual	Slow	Fast	IL	IC	Dual
S01	0.265	0.410	0.224	0.239	0.329	0.478
S02	0.202	0.355	0.194	0.156	0.222	0.468
S03	0.391	0.665	0.454	0.392	0.601	0.395
S04	0.518	0.363	0.467	0.441	0.466	0.462
S05	0.455	0.531	0.486	0.456	0.430	0.442
S06	0.531	0.611	0.415	0.417	0.570	0.455
S07	0.504	0.457	0.348	0.446	0.504	0.304
S08	0.447	0.480	0.482	0.548	0.529	0.462
S09	0.413	0.668	0.384	0.423	0.401	0.416
S10	0.330	0.601	0.464	0.322	0.471	0.457
S11	0.176	0.452	0.148	0.165	0.168	0.435
S12	0.519	0.502	0.408	0.470	0.469	0.360
S13	0.430	0.476	0.410	0.338	0.416	0.583
S14	0.234	0.299	0.266	0.220	0.241	0.243
S15	0.174	0.233	0.142	0.231	0.275	0.176
S16	0.398	0.551	0.242	0.440	0.524	0.464
S17	0.430	0.613	0.410	0.385	0.424	0.396
Average	0.377	0.486	0.350	0.358	0.414	0.412
SD	0.124	0.126	0.121	0.117	0.127	0.096

Results of spatial variability of second formant frequency for the speakers in the pilot study

Subject	Habitual	Slow	Fast	IL	IC	Dual
S01	0.478	0.449	0.346	0.367	0.393	0.407
S02	0.299	0.458	0.333	0.288	0.279	0.418
S03	0.326	0.460	0.355	0.326	0.467	0.326
S04	0.638	0.455	0.844	0.569	0.737	0.644
S05	0.479	0.494	0.651	0.734	0.620	0.747
S06	0.539	0.578	0.447	0.558	0.307	0.323
S07	0.597	0.635	0.823	0.630	0.610	0.498
S08	0.575	0.524	0.539	0.562	0.608	0.505
S09	0.462	0.681	0.557	0.619	0.437	0.627
S10	0.264	0.521	0.453	0.254	0.311	0.233
S11	0.246	0.275	0.312	0.204	0.187	0.301
S12	0.469	0.310	0.371	0.414	0.384	0.341
S13	0.401	0.540	0.456	0.267	0.237	0.570
S14	0.478	0.578	0.441	0.310	0.418	0.413
S15	0.397	0.454	0.439	0.373	0.502	0.472
S16	0.424	0.604	0.570	0.459	0.464	0.401
S17	0.487	0.556	0.557	0.663	0.674	0.571
Average	0.445	0.504	0.500	0.447	0.449	0.459
SD	0.113	0.105	0.158	0.165	0.160	0.139

Appendix H. Results of temporal variability in pilot study

Results of temporal variability of sound pressure level for the speakers in the pilot study

Subject	Habitual	Slow	Fast	IL	IC	Dual
S01	0.0315	0.0233	0.0254	0.0273	0.0302	0.0246
S02	0.0151	0.0237	0.0192	0.0152	0.0176	0.0242
S03	0.0182	0.0140	0.0199	0.0196	0.0274	0.0187
S04	0.0199	0.0225	0.0207	0.0126	0.0188	0.0351
S05	0.0121	0.0275	0.0144	0.0163	0.0118	0.0175
S06	0.0266	0.0270	0.0159	0.0191	0.0178	0.0166
S07	0.0159	0.0399	0.0252	0.0246	0.0220	0.0203
S08	0.0199	0.0247	0.0243	0.0220	0.0238	0.0183
S09	0.0165	0.0152	0.0174	0.0178	0.0166	0.0162
S10	0.0103	0.0147	0.0121	0.0096	0.0221	0.0170
S11	0.0097	0.0145	0.0182	0.0106	0.0097	0.0129
S12	0.0132	0.0204	0.0196	0.0200	0.0145	0.0210
S13	0.0151	0.0272	0.0170	0.0118	0.0155	0.0129
S14	0.0173	0.0219	0.0254	0.0190	0.0147	0.0158
S15	0.0175	0.0211	0.0191	0.0293	0.0218	0.0193
S16	0.0265	0.0127	0.0167	0.0235	0.0225	0.0205
S17	0.0135	0.0177	0.0128	0.0202	0.0163	0.0168
Average	0.0176	0.0216	0.0190	0.0187	0.0190	0.0193
SD	0.0059	0.0068	0.0042	0.0057	0.0054	0.0052

Results of temporal variability of fundamental frequency for the speakers in the pilot study

Subject	Habitual	Slow	Fast	IL	IC	Dual
S01	0.0453	0.0274	0.0386	0.0514	0.0498	0.0564
S02	0.0377	0.0405	0.0270	0.0214	0.0292	0.0262
S03	0.0247	0.0278	0.0215	0.0371	0.0334	0.0257
S04	0.0250	0.0247	0.0521	0.0391	0.0232	0.0481
S05	0.0136	0.0289	0.0363	0.0437	0.0228	0.0399
S06	0.0229	0.0316	0.0225	0.0414	0.0269	0.0132
S07	0.0224	0.0322	0.0225	0.0448	0.0320	0.0204
S08	0.0250	0.0374	0.0443	0.0210	0.0296	0.0272
S09	0.0127	0.0291	0.0300	0.0181	0.0168	0.0193
S10	0.0111	0.0186	0.0157	0.0110	0.0305	0.0465
S11	0.0155	0.0183	0.0287	0.0130	0.0238	0.0121
S12	0.0226	0.0164	0.0336	0.0391	0.0522	0.0211
S13	0.0185	0.0334	0.0185	0.0180	0.0293	0.0111
S14	0.0233	0.0248	0.0196	0.0157	0.0193	0.0231
S15	0.0253	0.0220	0.0234	0.0212	0.0293	0.0272
S16	0.0119	0.0238	0.0159	0.0169	0.0377	0.0174
S17	0.0125	0.0151	0.0183	0.0385	0.0182	0.0217
Average	0.0218	0.0266	0.0276	0.0289	0.0296	0.0269
SD	0.0092	0.0072	0.0104	0.0132	0.0098	0.0132

Results of temporal variability of first formant frequency for the speakers in the pilot study

Subject	Habitual	Slow	Fast	IL	IC	Dual
S01	0.0212	0.0228	0.0234	0.0232	0.0313	0.0353
S02	0.0144	0.0222	0.0209	0.0136	0.0181	0.0344
S03	0.0222	0.0201	0.0224	0.0247	0.0335	0.0250
S04	0.0361	0.0352	0.0360	0.0343	0.0291	0.0475
S05	0.0239	0.0241	0.0280	0.0225	0.0369	0.0296
S06	0.0296	0.0246	0.0223	0.0192	0.0268	0.0214
S07	0.0363	0.0372	0.0258	0.0400	0.0265	0.0304
S08	0.0285	0.0318	0.0239	0.0296	0.0375	0.0387
S09	0.0130	0.0272	0.0135	0.0208	0.0167	0.0249
S10	0.0133	0.0138	0.0197	0.0135	0.0267	0.0265
S11	0.0101	0.0163	0.0136	0.0137	0.0180	0.0273
S12	0.0457	0.0317	0.0320	0.0363	0.0360	0.0270
S13	0.0348	0.0278	0.0441	0.0128	0.0229	0.0302
S14	0.0199	0.0239	0.0215	0.0157	0.0126	0.0162
S15	0.0151	0.0131	0.0186	0.0205	0.0183	0.0168
S16	0.0361	0.0221	0.0319	0.0353	0.0345	0.0521
S17	0.0330	0.0148	0.0300	0.0312	0.0251	0.0257
Average	0.0255	0.0240	0.0252	0.0239	0.0265	0.0299
SD	0.0105	0.0072	0.0079	0.0090	0.0078	0.0095

Results of temporal variability of second formant frequency for the speakers in the pilot study

Subject	Habitual	Slow	Fast	IL	IC	Dual
S01	0.0279	0.0192	0.0182	0.0221	0.0354	0.0290
S02	0.0178	0.0257	0.0234	0.0155	0.0220	0.0325
S03	0.0325	0.0242	0.0360	0.0404	0.0629	0.0336
S04	0.0372	0.0446	0.0506	0.0366	0.0629	0.0408
S05	0.0237	0.0269	0.0266	0.0236	0.0224	0.0348
S06	0.0236	0.0315	0.0284	0.0185	0.0144	0.0284
S07	0.0237	0.0329	0.0366	0.0352	0.0340	0.0259
S08	0.0320	0.0297	0.0491	0.0338	0.0323	0.0339
S09	0.0169	0.0306	0.0298	0.0227	0.0204	0.0194
S10	0.0193	0.0140	0.0403	0.0195	0.0332	0.0197
S11	0.0144	0.0261	0.0180	0.0134	0.0153	0.0170
S12	0.0280	0.0165	0.0244	0.0309	0.0333	0.0305
S13	0.0243	0.0239	0.0372	0.0258	0.0205	0.0278
S14	0.0248	0.0266	0.0275	0.0215	0.0188	0.0197
S15	0.0227	0.0138	0.0278	0.0342	0.0226	0.0229
S16	0.0339	0.0222	0.0316	0.0329	0.0298	0.0322
S17	0.0211	0.0212	0.0327	0.0402	0.0445	0.0264
Average	0.0249	0.0253	0.0317	0.0275	0.0309	0.0279
SD	0.0063	0.0076	0.0093	0.0086	0.0145	0.0066

Appendix I. Mean syllable repetition rates in 4 diadochokinetic tasks

DDK mean syllable repetition rates of HD and AMC groups

Subject	/pa/	/ta/	/ka/	/pataka/
HD01	7.06	7.49	5.62	2.79
HD02	6.58	6.59	5.78	2.23
HD03	6.69	6.50	5.87	2.31
HD04	8.81	8.22	6.97	2.11
HD05	4.19	4.59	3.35	1.48
HD06	6.50	6.14	6.34	1.82
HD07	6.85	6.90	6.11	2.17
HD08	7.72	6.36	6.49	2.22
HD09	5.23	6.22	6.41	2.38
HD10	5.68	4.85	5.38	1.79
HD11	5.25	7.50	5.10	1.70
HD12	6.57	5.70	5.42	1.74
HD13	6.85	6.29	6.36	1.59
HD14	5.86	5.83	5.41	1.80
HD15	6.06	5.17	5.21	1.54
HD16	7.97	5.89	5.41	2.61
HD17	7.45	6.76	6.30	2.45
HD18	4.75	4.92	4.55	1.48
HD19	6.72	5.70	5.89	2.40
HD20	6.93	6.67	5.76	2.12
HD21	8.53	7.48	8.68	2.51
HD22	7.35	7.72	6.94	2.14
HD23	6.11	4.86	5.16	2.00
Average	6.60	6.28	5.85	2.06
SD	1.14	1.00	1.00	0.38

Subject	/pa/	/ta/	/ka/	/pataka/
AMC01	7.87	8.35	7.28	2.54
AMC02	7.85	7.49	7.19	2.61
AMC03	5.69	6.30	5.59	2.28
AMC04	7.13	6.32	5.03	2.11
AMC05	7.77	6.84	6.69	2.50
AMC06	6.82	5.75	5.86	2.26
AMC07	6.64	6.36	5.73	2.19
AMC08	7.19	7.64	6.96	2.67
AMC09	6.06	6.51	6.41	2.48
AMC10	6.42	6.62	5.75	2.22
AMC11	6.83	6.82	5.44	2.65
AMC12	6.90	5.98	5.53	2.49
AMC13	6.08	5.50	5.06	2.11
AMC14	7.05	6.58	6.13	2.42
AMC15	7.34	6.45	5.86	2.27
AMC16	6.47	6.02	5.33	2.62
AMC17	6.77	6.24	6.14	2.51
AMC18	7.86	7.05	6.74	2.75
AMC19	7.08	6.94	5.51	1.84
AMC20	6.34	6.59	4.98	1.85
AMC21	7.02	6.59	6.34	2.18
AMC22	6.73	6.77	5.93	2.16
AMC23	6.55	6.74	6.29	2.47
AMC24	6.02	6.22	5.46	2.63
Average	6.85	6.61	5.97	2.37
SD	0.61	0.61	0.66	0.25

DDK mean syllable repetition rates of YA and OA groups

Subject	/pa/	/ta/	/ka/	/pataka/
YA01	6.33	6.21	5.79	2.57
YA02	6.32	8.35	2.76	1.88
YA03	2.88	4.73	3.68	2.13
YA04	4.80	3.37	2.52	1.61
YA05	3.58	3.62	3.73	2.25
YA06	3.91	2.42	4.44	2.07
YA07	2.41	4.70	4.04	2.52
YA08	5.92	4.49	6.36	2.45
YA09	4.16	4.89	5.49	2.19
YA10	7.01	6.57	5.73	2.33
YA11	7.02	6.36	4.98	2.09
YA12	6.14	5.81	6.33	2.84
YA13	5.66	6.32	7.28	2.54
YA14	7.50	5.69	6.69	2.50
YA15	5.92	6.00	5.86	2.26
YA16	6.30	6.36	6.48	2.53
Average	5.37	5.06	4.76	2.27
SD	1.55	1.40	1.30	0.33

Subject	/pa/	/ta/	/ka/	/pataka/
OA01	7.19	7.64	6.96	2.67
OA02	6.06	6.51	6.41	2.48
OA03	6.42	6.62	5.75	2.22
OA04	6.83	6.82	5.44	2.65
OA05	6.90	5.98	5.53	2.49
OA06	6.08	5.50	5.06	2.11
OA07	7.05	6.58	6.13	2.42
OA08	7.34	6.45	5.86	2.27
OA09	6.47	6.02	5.33	2.62
OA10	6.77	6.24	6.14	2.51
OA11	7.86	7.05	6.74	2.75
OA12	6.34	6.59	4.98	1.85
OA13	7.02	6.59	6.34	2.18
OA14	6.55	6.74	6.29	2.47
Average	6.78	6.52	5.93	2.41
SD	0.50	0.51	0.61	0.25

Appendix J. CoV of mean syllable length in 4 diadochokinetic tasks

DDK CoV of mean syllable length of HD and AMC groups

Subject	/pa/	/ta/	/ka/	/pataka/
HD01	9.86	30.56	21.31	10.18
HD02	8.84	4.30	11.27	8.12
HD03	9.42	8.09	11.17	5.25
HD04	12.66	23.16	10.82	24.28
HD05	15.70	20.54	9.02	7.99
HD06	4.97	6.43	6.81	34.80
HD07	11.78	7.37	9.40	14.27
HD08	8.15	6.57	5.10	5.24
HD09	14.60	8.13	25.65	30.40
HD10	12.35	10.90	8.88	4.70
HD11	17.21	17.44	16.03	45.87
HD12	12.59	24.70	35.46	21.75
HD13	12.87	15.60	16.67	5.54
HD14	15.90	9.54	5.61	4.44
HD15	5.92	4.76	8.91	15.15
HD16	10.35	9.96	6.28	25.75
HD17	12.86	10.47	7.99	2.25
HD18	20.57	9.10	5.19	7.28
HD19	18.06	5.70	5.12	21.29
HD20	8.81	9.92	8.84	4.28
HD21	7.84	10.89	16.60	19.18
HD22	10.23	14.31	12.26	13.57
HD23	7.82	7.09	8.26	4.13
Average	11.71	11.98	11.85	14.60
SD	3.97	6.96	7.39	11.59

Subject	/pa/	/ta/	/ka/	/pataka/
AMC01	7.31	7.11	8.20	4.28
AMC02	5.72	6.87	7.25	7.32
AMC03	4.49	8.06	5.82	4.74
AMC04	9.64	11.06	7.15	5.88
AMC05	8.12	12.75	8.58	2.28
AMC06	9.40	7.64	7.95	4.48
AMC07	8.26	14.19	9.29	12.96
AMC08	6.34	7.44	6.91	3.40
AMC09	5.63	8.78	7.88	3.47
AMC10	4.82	5.32	5.37	12.44
AMC11	7.10	8.78	6.01	5.72
AMC12	7.04	5.60	8.55	4.27
AMC13	8.10	14.82	19.62	4.07
AMC14	5.44	5.53	5.82	16.67
AMC15	8.44	6.62	7.88	7.98
AMC16	9.29	7.70	7.41	3.11
AMC17	7.28	7.14	10.70	17.85
AMC18	6.50	10.23	6.41	5.62
AMC19	4.35	3.71	11.01	15.09
AMC20	11.18	6.19	6.14	7.63
AMC21	5.54	6.19	6.21	3.13
AMC22	5.24	10.72	8.03	12.87
AMC23	6.22	7.34	9.03	3.63
AMC24	4.96	9.30	10.54	4.23
Average	6.93	8.30	8.24	7.21
SD	1.82	2.79	2.89	4.72

DDK CoV of mean syllable length of YA and OA groups

Subject	/pa/	/ta/	/ka/	/pataka/
YA01	8.61	11.36	10.39	4.26
YA02	8.04	11.61	9.84	7.21
YA03	3.36	6.55	2.95	2.56
YA04	8.55	6.47	9.03	7.59
YA05	6.21	6.05	6.52	2.69
YA06	6.87	4.63	7.22	4.01
YA07	7.93	2.81	2.51	5.78
YA08	24.52	6.63	9.85	16.68
YA09	10.05	7.24	8.71	5.04
YA10	14.09	15.35	16.10	6.42
YA11	8.51	8.97	8.24	9.16
YA12	12.44	12.20	9.08	22.52
YA13	10.88	15.67	18.03	15.89
YA14	6.64	10.48	8.74	5.43
YA15	10.01	12.19	36.67	11.34
YA16	4.78	5.86	5.51	7.43
Average	9.47	9.00	10.59	8.38
SD	4.84	3.80	8.01	5.60

Subject	/pa/	/ta/	/ka/	/pataka/
OA01	6.34	7.44	6.91	3.40
OA02	5.63	8.78	7.88	3.47
OA03	4.82	5.32	5.37	12.44
OA04	7.10	8.78	6.01	5.72
OA05	7.04	5.60	8.55	4.27
OA06	8.10	14.82	19.62	4.07
OA07	5.44	5.53	5.82	16.67
OA08	8.44	6.62	7.88	7.98
OA09	9.29	7.70	7.41	3.11
OA10	7.28	7.14	10.70	17.85
OA11	6.50	10.23	6.41	5.62
OA12	11.18	6.19	6.14	7.63
OA13	5.54	6.19	6.21	3.13
OA14	6.22	7.34	9.03	3.63
Average	7.07	7.69	8.14	7.07
SD	1.72	2.49	3.61	5.03

Appendix K. CoV of peak syllable intensity in 4 diadochokinetic tasks

DDK CoV of peak syllable intensity of HD and AMC groups

Subject	/pa/	/ta/	/ka/	/pataka/
HD01	3.39	11.83	4.68	3.41
HD02	4.48	3.73	1.97	4.37
HD03	3.35	3.37	2.13	3.19
HD04	2.14	1.73	2.15	2.95
HD05	3.12	2.03	2.07	2.87
HD06	3.11	3.01	3.73	3.09
HD07	4.95	3.95	8.42	2.94
HD08	2.00	2.08	1.89	1.77
HD09	7.83	4.29	10.05	8.17
HD10	3.55	3.29	2.50	3.78
HD11	2.59	3.60	4.54	3.92
HD12	4.14	3.36	3.90	2.03
HD13	1.51	1.61	1.16	2.28
HD14	4.06	6.78	3.57	6.91
HD15	1.58	1.37	1.56	2.64
HD16	2.56	1.55	1.46	2.30
HD17	2.24	1.70	2.15	1.90
HD18	4.34	2.26	2.17	3.61
HD19	2.45	2.37	2.58	1.57
HD20	3.89	3.89	4.08	2.86
HD21	2.99	2.35	2.37	2.96
HD22	2.76	2.89	2.46	2.49
HD23	2.22	2.88	1.56	4.92
Average	3.27	3.30	3.18	3.34
SD	1.37	2.22	2.17	1.57

Subject	/pa/	/ta/	/ka/	/pataka/
AMC01	1.82	1.44	1.57	2.56
AMC02	1.43	2.06	2.41	3.23
AMC03	2.31	2.70	1.92	2.70
AMC04	1.89	2.15	1.74	2.25
AMC05	3.13	1.83	1.65	1.16
AMC06	1.81	2.83	2.28	2.59
AMC07	4.35	4.12	3.85	6.56
AMC08	2.50	1.75	1.67	2.20
AMC09	2.07	1.50	1.43	4.32
AMC10	2.76	3.71	4.14	4.32
AMC11	3.32	3.58	3.89	3.37
AMC12	1.28	3.77	2.25	1.41
AMC13	2.64	5.05	3.79	3.18
AMC14	4.22	2.01	2.13	2.01
AMC15	1.67	2.40	2.44	1.78
AMC16	2.23	3.40	3.15	3.59
AMC17	2.97	3.52	4.39	2.13
AMC18	3.13	2.87	3.28	3.41
AMC19	2.44	2.65	3.61	3.42
AMC20	3.72	8.71	3.30	3.17
AMC21	2.59	4.86	4.69	2.80
AMC22	2.23	1.35	1.96	3.86
AMC23	3.40	2.43	2.79	4.33
AMC24	2.43	1.70	4.22	2.54
Average	2.60	3.02	2.86	3.04
SD	0.81	1.60	1.03	1.15

DDK CoV of peak syllable intensity of YA and OA groups

Subject	/pa/	/ta/	/ka/	/pataka/
YA01	4.39	3.78	2.68	5.83
YA02	3.57	3.23	2.73	2.40
YA03	3.60	1.94	1.01	2.39
YA04	5.00	3.93	2.84	5.82
YA05	3.00	2.63	2.24	3.97
YA06	1.67	2.35	3.19	1.27
YA07	3.03	2.95	2.81	2.14
YA08	4.55	3.49	2.40	4.38
YA09	3.09	4.94	3.67	3.13
YA10	2.74	3.15	3.31	3.60
YA11	4.83	3.80	2.83	3.80
YA12	3.69	3.38	4.00	2.84
YA13	4.04	4.28	4.64	4.91
YA14	3.45	2.52	1.81	3.09
YA15	3.89	5.81	3.33	4.06
YA16	2.90	2.44	2.08	1.58
Average	3.59	3.41	2.85	3.45
SD	0.86	1.01	0.87	1.36

Subject	/pa/	/ta/	/ka/	/pataka/
OA01	2.50	1.75	1.67	2.20
OA02	2.07	1.50	1.43	4.32
OA03	2.76	3.71	4.14	4.32
OA04	3.32	3.58	3.89	3.37
OA05	1.28	3.77	2.25	1.41
OA06	2.64	5.05	3.79	3.18
OA07	4.22	2.01	2.13	2.01
OA08	1.67	2.40	2.44	1.78
OA09	2.23	3.40	3.15	3.59
OA10	2.97	3.52	4.39	2.13
OA11	3.13	2.87	3.28	3.41
OA12	3.72	8.71	3.30	3.17
OA13	2.59	4.86	4.69	2.80
OA14	3.40	2.43	2.79	4.33
Average	2.75	3.54	3.10	3.00
SD	0.79	1.83	1.02	0.98

Appendix L. Sentence durations in sentence repetition tasks

Sentence durations (in sec) of sentence repetition task for the HD and AMC groups

Subject	Slow	Hab	Fast	IL	IC	Dual
HD01	1.54	1.00	0.89	0.83	0.97	0.96
HD02	1.28	1.20	1.18	1.11	1.16	1.19
HD03	2.20	1.38	1.04	1.06	1.62	1.33
HD04	1.24	1.19	1.07	1.06	0.98	1.16
HD05	2.75	1.84	1.76	1.74	1.92	.
HD06	1.50	1.44	1.26	1.25	1.34	1.36
HD07	1.05	1.15	0.94	0.90	0.97	0.86
HD08	1.79	1.58	1.20	1.20	1.26	1.33
HD09	1.05	1.01	0.70	0.73	0.72	0.70
HD10	1.59	1.41	1.22	1.20	1.18	1.52
HD11	1.21	1.02	0.69	0.71	1.18	0.79
HD12	1.24	1.06	0.98	0.94	1.38	0.87
HD13	1.63	1.76	1.06	1.05	1.19	1.36
HD14	1.99	1.88	1.55	1.81	1.69	1.86
HD15	3.62	1.90	1.47	1.58	1.85	1.72
HD16	1.83	1.16	1.03	0.98	1.02	1.18
HD17	2.30	1.59	1.42	1.27	1.38	1.56
HD18	1.24	1.20	1.12	1.01	1.07	1.15
HD19	2.45	1.06	0.82	0.91	1.00	0.90
HD20	1.57	1.22	1.07	1.09	1.08	1.07
HD21	2.15	1.16	0.78	0.79	0.84	0.94
HD22	0.67	0.92	0.72	0.73	0.77	0.86
HD23	2.85	1.63	1.34	1.53	1.37	1.64
Avg	1.77	1.34	1.10	1.11	1.21	1.20
SD	0.69	0.31	0.28	0.31	0.32	0.32

Subject	Slow	Hab	Fast	IL	IC	Dual
AMC01	1.06	0.96	0.68	0.76	0.87	0.75
AMC02	2.39	1.11	0.75	1.39	1.14	1.08
AMC03	2.29	1.25	0.90	0.99	1.06	1.25
AMC04	1.37	0.91	0.85	0.82	0.88	0.95
AMC05	4.44	1.52	1.13	1.58	1.39	1.61
AMC06	3.54	1.26	0.86	1.08	1.12	0.87
AMC07	1.63	1.02	1.02	0.95	1.02	1.11
AMC08	2.23	1.36	0.88	1.18	1.12	1.30
AMC09	1.21	1.13	1.02	1.14	1.15	1.27
AMC10	3.52	1.51	1.09	1.70	1.34	1.36
AMC11	1.25	1.39	0.98	1.16	1.50	1.06
AMC12	2.00	1.57	0.86	1.12	0.98	1.21
AMC13	2.64	1.59	1.39	1.30	1.47	2.17
AMC14	1.64	1.92	1.21	1.07	1.77	1.15
AMC15	1.61	1.08	0.88	1.08	1.01	1.14
AMC16	2.18	1.59	1.29	1.37	1.57	1.64
AMC17	1.31	1.27	0.96	1.07	1.12	1.17
AMC18	4.54	1.29	1.01	1.15	1.09	1.07
AMC19	2.17	1.26	1.13	1.80	1.14	1.54
AMC20	5.07	1.70	1.28	1.65	1.62	1.75
AMC21	1.90	1.57	1.19	1.14	1.31	1.40
AMC22	1.82	1.53	1.24	1.16	1.34	1.67
AMC23	4.87	1.66	1.31	1.71	1.52	1.56
AMC24	3.47	1.27	0.95	0.99	1.04	0.98
Avg	2.51	1.36	1.04	1.22	1.23	1.29
SD	1.23	0.26	0.19	0.28	0.25	0.33

Sentence durations (in sec) of sentence repetition task for the YA and OA groups

Subject	Slow	Hab	Fast	IL	IC	Dual
YA01	2.16	1.48	1.26	1.58	1.45	1.48
YA02	1.61	1.28	0.92	1.33	1.19	1.38
YA03	2.93	1.37	1.03	1.17	1.11	1.29
YA04	2.70	1.28	1.03	1.28	1.15	1.27
YA05	1.65	1.13	0.92	1.09	1.09	1.10
YA06	2.88	1.37	0.89	1.12	1.09	1.09
YA07	1.90	1.48	0.96	1.35	1.20	1.47
YA08	1.76	1.33	0.93	1.11	1.21	1.26
YA09	2.72	1.46	1.15	1.15	1.13	1.26
YA10	2.21	1.25	1.10	1.50	1.18	1.15
YA11	5.00	1.42	0.99	1.27	1.10	1.33
YA12	3.46	1.29	1.01	1.14	1.18	1.29
YA13	2.13	1.79	0.92	1.59	1.58	1.60
YA14	1.78	1.02	0.90	0.99	1.05	0.99
YA15	2.19	1.08	0.87	1.05	0.99	1.10
YA16	2.84	1.10	0.92	1.15	1.03	1.15
Avg	2.50	1.32	0.99	1.24	1.17	1.26
SD	0.86	0.19	0.11	0.18	0.15	0.16

Subject	Slow	Hab	Fast	IL	IC	Dual
OA01	2.23	1.36	0.88	1.18	1.12	1.30
OA02	1.21	1.13	1.02	1.14	1.15	1.27
OA03	3.52	1.51	1.09	1.70	1.34	1.36
OA04	1.25	1.39	0.98	1.16	1.50	1.06
OA05	2.00	1.57	0.86	1.12	0.98	1.21
OA06	2.64	1.59	1.39	1.30	1.47	2.17
OA07	1.64	1.92	1.21	1.07	1.77	1.15
OA08	1.61	1.08	0.88	1.08	1.01	1.14
OA09	2.18	1.59	1.29	1.37	1.57	1.64
OA10	1.31	1.27	0.96	1.07	1.12	1.17
OA11	4.54	1.29	1.01	1.15	1.09	1.07
OA12	5.07	1.70	1.28	1.65	1.62	1.75
OA13	1.90	1.57	1.19	1.14	1.31	1.40
OA14	4.87	1.66	1.31	1.71	1.52	1.56
Avg	2.57	1.47	1.10	1.27	1.33	1.38
SD	1.37	0.23	0.18	0.24	0.25	0.31

Appendix M. Spatiotemporal index of intensity

Spatiotemporal index of intensity for the HD and AMC groups

Subject	Slow	Hab	Fast	IL	IC	Dual
HD01	24.73	31.44	36.87	38.02	28.95	26.88
HD02	25.97	25.46	22.84	23.53	22.80	29.73
HD03	30.06	17.86	16.60	20.50	17.64	23.55
HD04	17.00	13.91	15.57	22.92	19.52	.
HD05	34.84	22.49	24.84	21.57	26.45	.
HD06	25.99	24.08	19.88	24.60	25.72	21.61
HD07	23.20	27.67	24.70	25.98	37.27	33.30
HD08	20.67	18.03	17.25	23.63	16.92	23.12
HD09	31.57	34.24	27.72	30.73	31.27	42.87
HD10	19.45	25.28	12.02	18.12	19.27	21.28
HD11	32.65	25.77	25.99	27.29	39.45	24.23
HD12	19.22	13.27	11.92	15.30	22.41	27.86
HD13	22.57	24.98	29.89	34.29	32.38	30.30
HD14	27.16	29.05	28.34	26.70	33.26	30.09
HD15	22.80	22.83	15.50	21.79	29.73	20.14
HD16	17.23	14.24	18.34	20.85	19.05	22.84
HD17	22.94	19.51	15.86	18.46	16.59	17.15
HD18	21.02	18.42	20.16	23.57	19.39	16.24
HD19	28.65	17.54	28.77	23.26	19.93	30.15
HD20	17.34	15.07	15.24	24.09	19.91	23.79
HD21	23.47	23.73	38.97	38.25	33.18	27.41
HD22	41.30	30.17	36.16	37.81	33.71	34.43
HD23	21.72	18.35	25.13	25.44	18.23	22.43
Avg	24.85	22.32	22.98	25.51	25.35	26.16
SD	6.11	5.93	7.84	6.36	7.17	6.23

Subject	Slow	Hab	Fast	IL	IC	Dual
AMC01	21.70	20.02	23.60	21.59	23.81	19.30
AMC02	28.48	21.86	30.32	24.80	22.75	22.59
AMC03	16.39	23.45	26.82	26.06	24.49	23.49
AMC04	26.38	23.41	21.28	25.15	26.94	22.35
AMC05	22.34	17.28	16.83	27.84	20.30	16.86
AMC06	22.57	12.84	23.64	23.50	17.97	20.94
AMC07	14.30	17.22	13.70	20.64	19.04	13.11
AMC08	23.23	15.44	22.25	18.65	19.60	15.99
AMC09	21.79	26.11	19.38	15.50	21.60	24.65
AMC10	28.65	23.49	26.57	32.74	19.01	24.85
AMC11	13.15	11.99	39.60	20.52	19.49	38.61
AMC12	21.83	16.39	18.23	18.72	20.89	22.89
AMC13	33.43	21.79	23.36	19.62	18.96	27.96
AMC14	28.72	13.64	24.65	23.16	22.93	30.39
AMC15	19.51	15.39	12.47	17.64	17.36	21.27
AMC16	30.21	18.23	13.83	16.04	22.46	21.43
AMC17	18.25	20.99	24.72	32.53	23.33	20.70
AMC18	27.89	15.80	18.64	18.92	15.75	18.55
AMC19	27.18	22.45	16.01	27.81	14.64	32.05
AMC20	23.05	15.62	13.63	14.65	16.38	17.82
AMC21	23.86	12.33	22.14	20.63	28.94	19.86
AMC22	28.50	26.20	27.22	28.87	28.88	31.96
AMC23	24.33	23.72	17.33	21.85	21.42	35.95
AMC24	29.08	20.39	21.13	18.52	16.09	29.99
Avg	23.95	19.00	21.56	22.33	20.96	23.90
SD	5.16	4.37	6.19	5.03	3.89	6.46

Spatiotemporal index of intensity for the YA and OA groups

Subject	Slow	Hab	Fast	IL	IC	Dual
YA01	21.31	22.40	21.10	26.76	25.38	16.50
YA02	25.36	27.11	22.42	26.42	27.51	26.39
YA03	29.62	27.42	22.10	30.04	26.91	23.38
YA04	19.87	17.28	15.63	18.16	20.79	19.10
YA05	20.39	15.46	20.46	30.66	21.26	22.08
YA06	22.07	21.27	15.39	25.39	25.02	17.78
YA07	18.63	16.50	21.15	23.40	21.94	19.43
YA08	20.54	15.25	16.55	18.98	23.53	20.63
YA09	23.00	21.54	23.15	26.08	29.11	27.69
YA10	19.44	17.88	12.24	20.18	25.81	22.27
YA11	.	18.22	18.81	26.31	21.53	18.49
YA12	17.53	21.61	21.23	24.42	21.30	18.73
YA13	15.34	15.36	17.42	16.67	25.88	19.37
YA14	17.15	14.93	21.88	24.78	26.18	23.01
YA15	24.50	17.73	22.37	41.09	35.68	21.42
YA16	22.14	14.01	13.12	17.01	17.19	19.93
Avg	21.13	19.00	19.06	24.77	24.69	21.01
SD	3.59	4.17	3.54	6.14	4.26	3.04

Subject	Slow	Hab	Fast	IL	IC	Dual
OA01	23.23	15.44	22.25	18.65	19.60	15.99
OA02	21.79	26.11	19.38	15.50	21.60	24.65
OA03	28.65	23.49	26.57	32.74	19.01	24.85
OA04	13.15	11.99	39.60	20.52	19.49	38.61
OA05	21.83	16.39	18.23	18.72	20.89	22.89
OA06	33.43	21.79	23.36	19.62	18.96	27.96
OA07	28.72	13.64	24.65	23.16	22.93	30.39
OA08	19.51	15.39	12.47	17.64	17.36	21.27
OA09	30.21	18.23	13.83	16.04	22.46	21.43
OA10	18.25	20.99	24.72	32.53	23.33	20.70
OA11	27.89	15.80	18.64	18.92	15.75	18.55
OA12	23.05	15.62	13.63	14.65	16.38	17.82
OA13	23.86	12.33	22.14	20.63	28.94	19.86
OA14	24.33	23.72	17.33	21.85	21.42	35.95
Avg	24.14	17.92	21.20	20.80	20.58	24.35
SD	5.32	4.52	6.91	5.54	3.36	6.72

Appendix N. Spatiotemporal index of fundamental frequency

Spatiotemporal index of fundamental frequency for the HD and AMC groups

Subject	Slow	Hab	Fast	IL	IC	Dual
HD01	10.26	21.11	8.20	20.13	18.35	9.91
HD02	41.49	41.26	38.06	25.15	15.69	37.48
HD03	23.77	9.26	8.39	10.67	.	7.15
HD04	16.73	10.16	13.38	12.58	15.74	13.44
HD05	16.48	9.31	9.87	12.60	20.48	.
HD06	35.39	34.12	35.53	40.93	41.33	.
HD07	20.20	26.91	19.00	16.27	23.30	18.73
HD08	16.84	9.85	6.64	8.61	19.72	17.14
HD09	7.25	8.22	9.11	12.27	11.01	13.04
HD10	13.86	13.30	10.02	16.80	17.25	12.25
HD11	15.69	13.14	14.02	13.05	34.24	10.28
HD12	7.69	7.39	6.26	13.99	13.14	19.81
HD13	21.42	13.87	19.85	19.43	20.69	16.24
HD14	12.02	13.06	12.95	18.47	21.40	24.58
HD15	22.03	18.24	9.69	14.07	26.61	14.41
HD16	9.09	5.90	6.66	7.94	13.05	7.48
HD17	14.17	14.46	6.54	7.25	16.70	9.75
HD18	6.60	7.78	11.53	14.59	10.32	6.12
HD19	12.29	6.54	5.31	10.74	8.68	14.61
HD20	10.56	8.41	6.87	14.01	14.66	10.27
HD21	9.09	8.00	9.57	15.11	14.27	16.83
HD22	20.88	13.45	24.42	16.46	15.89	10.59
HD23	27.79	29.85	42.58	40.27	22.17	28.24
Avg	17.03	14.94	14.54	16.58	18.85	15.16
SD	8.89	9.53	10.74	8.62	7.64	7.57

Subject	Slow	Hab	Fast	IL	IC	Dual
AMC01	13.99	15.04	11.85	9.86	25.79	4.51
AMC02	12.64	19.74	16.66	21.11	28.34	29.86
AMC03	6.78	10.25	9.48	15.62	10.12	7.91
AMC04	8.73	6.39	5.56	7.00	8.83	5.98
AMC05	31.29	9.12	7.00	21.23	22.47	12.81
AMC06	23.86	16.48	10.54	9.94	14.67	11.65
AMC07	7.76	6.53	5.21	7.47	9.51	8.35
AMC08	15.96	9.58	10.79	9.35	24.30	16.39
AMC09	25.09	18.56	14.66	11.66	35.21	13.83
AMC10	26.52	21.75	34.96	19.34	13.79	23.86
AMC11	10.88	8.00	36.05	23.35	14.04	24.35
AMC12	9.26	9.84	5.99	17.96	11.82	15.32
AMC13	35.19	21.89	15.26	22.06	21.78	23.25
AMC14	23.17	10.03	16.34	9.59	23.10	36.51
AMC15	19.39	9.89	6.67	18.13	19.96	11.81
AMC16	26.30	12.43	9.04	8.82	23.65	14.59
AMC17	8.09	10.61	6.81	27.44	10.09	21.67
AMC18	14.15	10.68	10.48	12.77	12.32	12.17
AMC19	18.90	10.72	8.67	13.97	15.09	18.72
AMC20	17.48	9.34	7.65	16.42	20.09	13.23
AMC21	12.26	14.71	11.60	12.24	18.86	12.38
AMC22	15.29	12.50	7.23	15.99	11.00	10.81
AMC23	20.86	12.95	7.48	13.28	17.79	14.63
AMC24	25.05	9.79	9.35	7.59	9.43	12.76
Avg	17.87	12.37	11.89	14.67	17.59	15.72
SD	7.89	4.45	7.99	5.69	7.00	7.57

Spatiotemporal index of fundamental frequency for the YA and OA groups

Subject	Slow	Hab	Fast	IL	IC	Dual
YA01	16.92	25.60	26.46	20.75	19.14	13.32
YA02	9.05	7.32	4.98	9.60	20.52	12.32
YA03	10.35	6.65	5.32	10.30	11.96	9.06
YA04	17.14	8.79	8.87	16.24	17.30	14.19
YA05	17.18	9.24	23.94	29.15	12.95	17.35
YA06	12.78	12.39	9.30	19.00	14.72	11.38
YA07	11.24	6.72	8.55	13.90	11.31	9.87
YA08	8.95	7.36	6.25	9.98	13.08	5.84
YA09	10.28	10.55	9.50	15.95	21.56	10.31
YA10	7.32	6.96	5.62	11.34	31.08	11.58
YA11	15.98	16.50	12.18	23.20	10.89	14.78
YA12	7.31	13.03	6.97	10.60	14.16	9.08
YA13	4.76	10.67	5.53	8.67	18.83	8.39
YA14	9.21	5.49	5.66	25.61	30.06	10.48
YA15	18.83	10.82	9.82	27.14	15.93	11.78
YA16	12.13	5.85	10.55	5.63	9.16	7.52
Avg	11.84	10.25	9.97	16.07	17.04	11.08
SD	4.23	5.07	6.34	7.30	6.39	2.92

Subject	Slow	Hab	Fast	IL	IC	Dual
OA01	15.96	9.58	10.79	9.35	24.30	16.39
OA02	25.09	18.56	14.66	11.66	35.21	13.83
OA03	26.52	21.75	34.96	19.34	13.79	23.86
OA04	10.88	8.00	36.05	23.35	14.04	24.35
OA05	9.26	9.84	5.99	17.96	11.82	15.32
OA06	35.19	21.89	15.26	22.06	21.78	23.25
OA07	23.17	10.03	16.34	9.59	23.10	36.51
OA08	19.39	9.89	6.67	18.13	19.96	11.81
OA09	26.30	12.43	9.04	8.82	23.65	14.59
OA10	8.09	10.61	6.81	27.44	10.09	21.67
OA11	14.15	10.68	10.48	12.77	12.32	12.17
OA12	17.48	9.34	7.65	16.42	20.09	13.23
OA13	12.26	14.71	11.60	12.24	18.86	12.38
OA14	20.86	12.95	7.48	13.28	17.79	14.63
Avg	18.90	12.88	13.84	15.89	19.06	18.14
SD	7.80	4.63	9.76	5.74	6.61	6.99

Appendix O. Spatiotemporal index of first formant frequency

Spatiotemporal index of first formant frequency for the HD and AMC groups

Subject	Slow	Hab	Fast	IL	IC	Dual
HD01	20.24	22.20	22.12	20.52	18.31	23.57
HD02	28.92	14.69	15.47	23.54	18.09	28.54
HD03	.	32.73	12.35	36.47	32.27	29.72
HD04	19.58	19.98	19.96	19.05	19.95	21.78
HD05	.	26.85	37.38	16.81	17.79	.
HD06	31.10	28.55	21.81	27.04	25.69	23.12
HD07	34.25	35.46	31.71	27.14	39.50	33.47
HD08	.	22.20	23.55	18.89	20.72	31.63
HD09	26.32	24.37	32.53	30.27	31.75	41.62
HD10	23.66	27.04	18.45	22.45	21.78	23.80
HD11	30.29	33.36	38.15	39.71	.	27.94
HD12	28.33	28.68	29.25	31.37	31.12	31.84
HD13	25.88	23.96	35.83	31.71	35.01	34.32
HD14	30.41	22.80	29.46	28.21	21.67	26.68
HD15	29.50	23.90	20.52	25.02	.	24.88
HD16	18.60	33.42	34.98	30.88	19.31	33.88
HD17	21.25	16.86	9.96	15.14	10.07	15.43
HD18	20.89	18.91	20.85	28.00	18.83	17.43
HD19	37.87	31.20	25.40	32.35	21.89	29.24
HD20	14.99	12.12	23.04	15.01	14.60	17.11
HD21	15.23	22.41	36.27	24.23	36.31	29.83
HD22	37.14	28.21	22.75	32.61	19.43	38.11
HD23	23.03	20.43	27.01	26.11	21.39	23.71
Avg	25.87	24.80	25.60	26.20	23.59	27.62
SD	6.70	6.19	8.03	6.64	7.74	6.70

Subject	Slow	Hab	Fast	IL	IC	Dual
AMC01	16.52	16.19	23.00	18.66	19.96	20.78
AMC02	.	29.99	29.91	32.70	32.03	39.71
AMC03	.	28.89	37.10	.	22.84	.
AMC04	22.91	18.93	20.80	16.77	19.29	20.75
AMC05	.	24.13	24.08	23.51	24.90	22.12
AMC06	26.84	25.00	17.76	15.36	12.21	27.83
AMC07	.	27.44	32.29	25.56	19.24	27.86
AMC08	28.03	15.64	18.37	15.37	17.87	24.61
AMC09	26.24	25.12	29.95	25.16	16.57	36.15
AMC10	.	.	44.52	.	29.13	29.18
AMC11	18.56	14.73	25.14	18.47	22.31	25.93
AMC12	19.23	16.54	16.75	14.23	16.49	17.46
AMC13	31.76	20.98	19.23	15.24	15.15	25.00
AMC14	.	20.56	17.34	21.28	25.90	23.58
AMC15	.	24.68	23.14	25.41	23.44	.
AMC16	19.91	11.23	9.70	9.55	14.07	17.24
AMC17	22.83	25.62	26.86	22.73	17.65	23.44
AMC18	21.29	18.62	18.03	14.32	11.86	21.82
AMC19	.	21.57	19.27	.	24.22	.
AMC20	.	16.77	14.94	13.75	9.94	15.27
AMC21	15.16	17.50	13.42	12.49	17.31	13.28
AMC22	.	.	30.11	19.63	25.19	31.28
AMC23	17.49	27.50	24.27	17.81	.	29.47
AMC24	.	20.11	22.50	12.47	21.02	25.72
Avg	22.06	21.26	23.27	18.59	19.94	24.69
SD	4.97	5.12	7.88	5.66	5.59	6.49

Spatiotemporal index of first formant frequency for the YA and OA groups

Subject	Slow	Hab	Fast	IL	IC	Dual
YA01	20.90	22.34	32.22	23.53	23.21	18.98
YA02	.	27.56	.	.	.	19.28
YA03	.	.	.	.	30.78	25.87
YA04	27.76	16.07	19.95	17.57	.	20.75
YA05	27.19	25.31	39.30	18.39	27.66	10.19
YA06	22.82	19.50	15.71	19.30	21.58	21.55
YA07	28.31	25.26	32.28	.	.	.
YA08	20.93	26.30	30.44	12.65	16.53	24.44
YA09	.	26.46	28.92	29.81	25.45	30.18
YA10	36.03	31.30	27.42	28.70	30.06	24.29
YA11	.	19.01	18.73	16.31	15.00	17.26
YA12	.	22.09	18.21	22.94	22.90	21.92
YA13	31.80	.	25.18	.	.	.
YA14	.	.	.	.	.	33.54
YA15	.	18.15	24.49	28.27	22.96	21.00
YA16	14.69	20.32	.	18.15	24.65	30.39
Avg	25.60	23.05	26.07	21.42	23.71	22.83
SD	6.45	4.39	7.03	5.65	4.93	6.00

Subject	Slow	Hab	Fast	IL	IC	Dual
OA01	28.03	15.64	18.37	15.37	17.87	24.61
OA02	26.24	25.12	29.95	25.16	16.57	36.15
OA03	.	.	44.52	.	29.13	29.18
OA04	18.56	14.73	25.14	18.47	22.31	25.93
OA05	19.23	16.54	16.75	14.23	16.49	17.46
OA06	31.76	20.98	19.23	15.24	15.15	25.00
OA07	.	20.56	17.34	21.28	25.90	23.58
OA08	.	24.68	23.14	25.41	23.44	.
OA09	19.91	11.23	9.70	9.55	14.07	17.24
OA10	22.83	25.62	26.86	22.73	17.65	23.44
OA11	21.29	18.62	18.03	14.32	11.86	21.82
OA12	.	16.77	14.94	13.75	9.94	15.27
OA13	15.16	17.50	13.42	12.49	17.31	13.28
OA14	17.49	27.50	24.27	17.81	.	29.47
Avg	22.05	19.65	21.55	17.37	18.28	23.26
SD	5.18	4.92	8.63	4.97	5.51	6.37

Appendix P. Spatiotemporal index of second formant frequency

Spatiotemporal index of second formant frequency for the HD and AMC groups

Subject	Slow	Hab	Fast	IL	IC	Dual
HD01	.	31.89	22.54	27.90	30.13	24.24
HD02	25.83	10.23	9.39	12.83	12.46	16.21
HD03	.	.	.	.	.	.
HD04	.	18.22	18.20	29.99	18.59	21.16
HD05	.	19.44	19.29	12.82	19.26	.
HD06	.	.	.	.	.	.
HD07	34.44	33.76	33.89	.	35.27	.
HD08	.	36.12	26.62	22.93	26.02	.
HD09	25.39	23.82	21.40	22.31	19.24	.
HD10	23.77	36.56	31.02	.	20.63	27.45
HD11	24.41	33.88	22.65	28.57	.	33.76
HD12	.	.	14.96	35.00	30.86	.
HD13	25.19	.	30.48	26.20	.	.
HD14	.	.	.	.	.	.
HD15	.	35.26	27.65	.	40.76	.
HD16	17.07	.	15.72	22.31	.	19.23
HD17	.	14.45	11.94	10.40	18.24	15.25
HD18	29.34	23.71	17.78	25.81	21.66	21.91
HD19	.	35.21	14.86	14.02	16.63	25.49
HD20	13.07	16.57	17.06	12.84	14.80	13.26
HD21	.	.	31.80	.	.	.
HD22	19.85	12.86	18.05	26.16	13.19	.
HD23	.	25.86	30.13	26.08	23.16	28.41
Avg	23.84	25.49	21.77	22.26	22.56	22.40
SD	6.04	9.29	7.22	7.43	8.07	6.23

Subject	Slow	Hab	Fast	IL	IC	Dual
AMC01	18.18	21.41	15.75	17.00	14.45	.
AMC02	.	14.87	10.71	.	.	.
AMC03	19.59	11.19	13.98	11.74	13.42	14.56
AMC04	23.93	20.34	15.91	25.19	31.38	19.34
AMC05	.	.	17.54	19.45	.	15.74
AMC06	27.31	29.84	20.10	24.02	26.66	21.58
AMC07	25.98	20.95	.	15.03	18.48	.
AMC08	.	17.10	16.14	.	.	.
AMC09	.	.	15.74	.	.	.
AMC10	.	.	18.77	.	.	.
AMC11	.	17.57	21.95	.	22.27	19.44
AMC12	20.77	26.07	23.84	29.90	22.91	30.87
AMC13	.	.	31.08	.	.	.
AMC14	.	.	.	.	.	.
AMC15	.	.	.	.	21.48	.
AMC16	27.25	.	11.41	11.04	21.15	14.31
AMC17	.	13.47	.	.	19.53	18.98
AMC18	.	.	.	.	.	.
AMC19	.	.	.	.	.	.
AMC20	.	.	12.74	18.85	.	.
AMC21	13.51	13.26	17.61	13.63	18.24	15.06
AMC22	.	.	20.85	.	.	.
AMC23	.	.	.	.	39.18	28.03
AMC24	.	19.44	.	.	.	.
Avg	22.07	18.79	17.76	18.59	22.43	19.79
SD	4.92	5.44	5.11	6.20	7.18	5.69

Spatiotemporal index of second formant frequency for the YA and OA groups

Subject	Slow	Hab	Fast	IL	IC	Dual
YA01	.	13.02	18.23	21.40	16.19	15.50
YA02	28.88	.	.	25.05	32.68	.
YA03	.	.	.	.	21.92	.
YA04	.	.	37.48	31.02	27.43	34.81
YA05	.	24.43	22.14	20.18	16.84	22.30
YA06	32.65	23.51	19.84	26.62	.	.
YA07	28.86	.	.	.	.	.
YA08	23.58	19.80	16.10	11.21	18.44	19.76
YA09	.	21.66	.	13.31	15.74	11.62
YA10	.	.	.	.	25.64	.
YA11	.	27.18	15.38	19.11	26.85	.
YA12	.	.	.	.	.	.
YA13	.	.	11.61	.	.	.
YA14	.	.	.	.	.	29.82
YA15	.	11.93	19.37	26.73	14.67	18.25
YA16	.	18.67	21.77	.	.	21.67
Avg	28.49	20.03	20.21	21.63	21.64	21.72
SD	3.73	5.37	7.27	6.49	6.19	7.50

Subject	Slow	Hab	Fast	IL	IC	Dual
OA01	.	17.10	16.14	.	.	.
OA02	.	.	15.74	.	.	.
OA03	.	.	18.77	.	.	.
OA04	.	17.57	21.95	.	22.27	19.44
OA05	20.77	26.07	23.84	29.90	22.91	30.87
OA06	.	.	31.08	.	.	.
OA07	.	.	.	.	.	.
OA08	.	.	.	.	21.48	.
OA09	27.25	.	11.41	11.04	21.15	14.31
OA10	.	13.47	.	.	19.53	18.98
OA11	.	.	.	.	.	.
OA12	.	.	12.74	18.85	.	.
OA13	13.51	13.26	17.61	13.63	18.24	15.06
OA14	.	.	.	.	39.18	28.03
Avg	20.51	17.49	18.81	18.36	23.54	21.12
SD	6.87	5.19	6.08	8.35	7.08	6.83

Appendix Q. Spatial variability of intensity

Spatial variability of intensity for the HD and AMC groups

Subject	Slow	Hab	Fast	IL	IC	Dual
HD01	0.385	0.533	0.633	0.613	0.437	0.455
HD02	0.374	0.387	0.332	0.342	0.337	0.474
HD03	0.467	0.255	0.277	0.294	0.245	0.391
HD04	0.284	0.230	0.251	0.375	0.320	.
HD05	0.539	0.357	0.409	0.338	0.398	.
HD06	0.410	0.382	0.336	0.426	0.417	0.354
HD07	0.421	0.489	0.398	0.428	0.599	0.508
HD08	0.294	0.250	0.255	0.355	0.253	0.345
HD09	0.539	0.593	0.436	0.495	0.505	0.710
HD10	0.222	0.291	0.173	0.202	0.224	0.269
HD11	0.486	0.364	0.405	0.384	0.647	0.390
HD12	0.223	0.175	0.179	0.242	0.430	0.493
HD13	0.346	0.319	0.430	0.401	0.377	0.439
HD14	0.453	0.465	0.446	0.453	0.554	0.454
HD15	0.306	0.275	0.203	0.265	0.456	0.265
HD16	0.229	0.223	0.282	0.316	0.305	0.363
HD17	0.307	0.246	0.226	0.231	0.220	0.254
HD18	0.269	0.261	0.255	0.323	0.290	0.248
HD19	0.321	0.271	0.462	0.348	0.317	0.458
HD20	0.296	0.260	0.266	0.395	0.332	0.390
HD21	0.333	0.326	0.657	0.594	0.465	0.381
HD22	0.606	0.404	0.511	0.605	0.433	0.518
HD23	0.353	0.301	0.397	0.424	0.320	0.383
Avg	0.368	0.333	0.357	0.385	0.386	0.407
SD	0.107	0.107	0.133	0.113	0.117	0.108

Subject	Slow	Hab	Fast	IL	IC	Dual
AMC01	0.326	0.297	0.359	0.349	0.389	0.284
AMC02	0.347	0.311	0.495	0.327	0.310	0.355
AMC03	0.247	0.374	0.424	0.444	0.421	0.393
AMC04	0.342	0.352	0.345	0.376	0.398	0.356
AMC05	0.340	0.268	0.273	0.372	0.309	0.239
AMC06	0.265	0.177	0.336	0.377	0.277	0.336
AMC07	0.251	0.288	0.220	0.310	0.339	0.211
AMC08	0.294	0.193	0.346	0.272	0.283	0.239
AMC09	0.340	0.431	0.325	0.269	0.368	0.391
AMC10	0.453	0.336	0.397	0.514	0.264	0.379
AMC11	0.227	0.204	0.705	0.366	0.326	0.694
AMC12	0.287	0.223	0.281	0.263	0.309	0.329
AMC13	0.399	0.267	0.258	0.267	0.249	0.367
AMC14	0.463	0.164	0.390	0.388	0.305	0.499
AMC15	0.227	0.229	0.201	0.300	0.274	0.342
AMC16	0.512	0.306	0.247	0.289	0.369	0.371
AMC17	0.280	0.326	0.387	0.496	0.374	0.331
AMC18	0.433	0.240	0.240	0.258	0.223	0.299
AMC19	0.431	0.332	0.234	0.441	0.230	0.537
AMC20	0.342	0.243	0.218	0.224	0.264	0.294
AMC21	0.342	0.172	0.350	0.314	0.471	0.291
AMC22	0.439	0.322	0.358	0.466	0.418	0.436
AMC23	0.404	0.388	0.284	0.304	0.309	0.627
AMC24	0.442	0.322	0.331	0.291	0.255	0.499
Avg	0.351	0.282	0.334	0.345	0.322	0.379
SD	0.082	0.072	0.108	0.080	0.066	0.119

Spatial variability of intensity for the YA and OA groups

Subject	Slow	Hab	Fast	IL	IC	Dual
YA01	0.341	0.371	0.325	0.430	0.425	0.256
YA02	0.413	0.412	0.386	0.396	0.398	0.434
YA03	0.492	0.501	0.347	0.523	0.470	0.397
YA04	0.280	0.270	0.254	0.300	0.337	0.305
YA05	0.317	0.250	0.295	0.464	0.329	0.362
YA06	0.315	0.326	0.243	0.359	0.366	0.288
YA07	0.314	0.286	0.355	0.399	0.344	0.310
YA08	0.353	0.248	0.260	0.313	0.381	0.355
YA09	0.342	0.339	0.384	0.423	0.468	0.433
YA10	0.327	0.286	0.209	0.325	0.431	0.382
YA11	.	0.277	0.297	0.396	0.301	0.290
YA12	0.277	0.347	0.356	0.411	0.369	0.317
YA13	0.244	0.194	0.278	0.204	0.376	0.283
YA14	0.248	0.251	0.365	0.446	0.420	0.386
YA15	0.427	0.318	0.376	0.768	0.592	0.373
YA16	0.414	0.245	0.208	0.280	0.286	0.350
Avg	0.340	0.308	0.309	0.402	0.393	0.345
SD	0.070	0.075	0.061	0.125	0.076	0.054

Subject	Slow	Hab	Fast	IL	IC	Dual
OA01	0.294	0.193	0.346	0.272	0.283	0.239
OA02	0.340	0.431	0.325	0.269	0.368	0.391
OA03	0.453	0.336	0.397	0.514	0.264	0.379
OA04	0.227	0.204	0.705	0.366	0.326	0.694
OA05	0.287	0.223	0.281	0.263	0.309	0.329
OA06	0.399	0.267	0.258	0.267	0.249	0.367
OA07	0.463	0.164	0.390	0.388	0.305	0.499
OA08	0.227	0.229	0.201	0.300	0.274	0.342
OA09	0.512	0.306	0.247	0.289	0.369	0.371
OA10	0.280	0.326	0.387	0.496	0.374	0.331
OA11	0.433	0.240	0.240	0.258	0.223	0.299
OA12	0.342	0.243	0.218	0.224	0.264	0.294
OA13	0.342	0.172	0.350	0.314	0.471	0.291
OA14	0.404	0.388	0.284	0.304	0.309	0.627
Avg	0.357	0.266	0.331	0.323	0.313	0.390
SD	0.089	0.081	0.126	0.088	0.065	0.130

Appendix R. Spatial variability of fundamental frequency

Spatial variability of fundamental frequency for the HD and AMC groups

Subject	Slow	Hab	Fast	IL	IC	Dual
HD01	0.173	0.299	0.142	0.324	0.282	0.161
HD02	0.737	0.734	0.558	0.354	0.245	0.630
HD03	0.316	0.142	0.142	0.172	.	0.120
HD04	0.266	0.170	0.208	0.211	0.237	0.207
HD05	0.269	0.162	0.167	0.212	0.356	.
HD06	0.534	0.544	0.527	0.703	0.708	.
HD07	0.283	0.395	0.250	0.228	0.318	0.246
HD08	0.237	0.140	0.095	0.130	0.236	0.257
HD09	0.123	0.120	0.135	0.178	0.167	0.218
HD10	0.162	0.205	0.152	0.232	0.261	0.161
HD11	0.249	0.206	0.223	0.218	0.466	0.167
HD12	0.116	0.122	0.102	0.212	0.200	0.282
HD13	0.311	0.237	0.301	0.263	0.285	0.263
HD14	0.177	0.220	0.215	0.262	0.369	0.377
HD15	0.311	0.252	0.153	0.239	0.401	0.216
HD16	0.150	0.098	0.111	0.122	0.144	0.124
HD17	0.237	0.190	0.108	0.114	0.237	0.151
HD18	0.112	0.129	0.182	0.204	0.149	0.100
HD19	0.226	0.118	0.090	0.187	0.145	0.228
HD20	0.180	0.141	0.107	0.209	0.225	0.177
HD21	0.162	0.135	0.146	0.209	0.237	0.270
HD22	0.291	0.192	0.609	0.233	0.242	0.168
HD23	0.442	0.480	0.819	0.639	0.341	0.438
Avg	0.264	0.236	0.241	0.255	0.284	0.236
SD	0.145	0.159	0.195	0.143	0.127	0.122

Subject	Slow	Hab	Fast	IL	IC	Dual
AMC01	0.220	0.238	0.194	0.153	0.418	0.067
AMC02	0.223	0.340	0.226	0.316	0.391	0.538
AMC03	0.100	0.147	0.135	0.224	0.162	0.130
AMC04	0.133	0.102	0.092	0.107	0.144	0.096
AMC05	0.569	0.138	0.116	0.299	0.341	0.195
AMC06	0.388	0.220	0.142	0.137	0.198	0.191
AMC07	0.119	0.107	0.084	0.119	0.155	0.125
AMC08	0.194	0.104	0.132	0.132	0.388	0.269
AMC09	0.383	0.270	0.223	0.162	0.627	0.174
AMC10	0.362	0.323	0.446	0.286	0.209	0.370
AMC11	0.149	0.101	0.805	0.366	0.192	0.373
AMC12	0.131	0.145	0.098	0.287	0.165	0.254
AMC13	0.518	0.329	0.229	0.336	0.256	0.313
AMC14	0.347	0.172	0.209	0.158	0.360	0.660
AMC15	0.271	0.151	0.107	0.258	0.295	0.190
AMC16	0.377	0.208	0.155	0.139	0.374	0.243
AMC17	0.130	0.162	0.110	0.326	0.172	0.325
AMC18	0.236	0.162	0.165	0.182	0.175	0.186
AMC19	0.264	0.180	0.111	0.205	0.240	0.239
AMC20	0.265	0.155	0.121	0.255	0.316	0.215
AMC21	0.203	0.199	0.148	0.141	0.276	0.189
AMC22	0.237	0.185	0.106	0.240	0.165	0.158
AMC23	0.372	0.204	0.118	0.206	0.288	0.228
AMC24	0.420	0.130	0.135	0.126	0.143	0.200
Avg	0.275	0.186	0.184	0.215	0.269	0.247
SD	0.128	0.070	0.152	0.080	0.118	0.134

Spatial variability of fundamental frequency for the YA and OA groups

Subject	Slow	Hab	Fast	IL	IC	Dual
YA01	0.224	0.393	0.378	0.300	0.274	0.175
YA02	0.156	0.120	0.078	0.153	0.285	0.193
YA03	0.186	0.116	0.090	0.173	0.191	0.144
YA04	0.279	0.155	0.155	0.260	0.278	0.246
YA05	0.209	0.106	0.272	0.396	0.139	0.198
YA06	0.193	0.169	0.130	0.251	0.213	0.158
YA07	0.190	0.107	0.114	0.242	0.173	0.155
YA08	0.145	0.117	0.097	0.137	0.177	0.081
YA09	0.173	0.179	0.154	0.244	0.383	0.154
YA10	0.123	0.103	0.096	0.192	0.440	0.184
YA11	0.287	0.259	0.202	0.367	0.165	0.229
YA12	0.127	0.214	0.119	0.180	0.237	0.154
YA13	0.083	0.175	0.088	0.146	0.229	0.140
YA14	0.151	0.095	0.093	0.374	0.425	0.166
YA15	0.306	0.173	0.154	0.518	0.241	0.186
YA16	0.199	0.093	0.143	0.093	0.123	0.121
Avg	0.189	0.161	0.148	0.252	0.248	0.168
SD	0.062	0.078	0.079	0.115	0.096	0.040

Subject	Slow	Hab	Fast	IL	IC	Dual
OA01	0.194	0.104	0.132	0.132	0.388	0.269
OA02	0.383	0.270	0.223	0.162	0.627	0.174
OA03	0.362	0.323	0.446	0.286	0.209	0.370
OA04	0.149	0.101	0.805	0.366	0.192	0.373
OA05	0.131	0.145	0.098	0.287	0.165	0.254
OA06	0.518	0.329	0.229	0.336	0.256	0.313
OA07	0.347	0.172	0.209	0.158	0.360	0.660
OA08	0.271	0.151	0.107	0.258	0.295	0.190
OA09	0.377	0.208	0.155	0.139	0.374	0.243
OA10	0.130	0.162	0.110	0.326	0.172	0.325
OA11	0.236	0.162	0.165	0.182	0.175	0.186
OA12	0.265	0.155	0.121	0.255	0.316	0.215
OA13	0.203	0.199	0.148	0.141	0.276	0.189
OA14	0.372	0.204	0.118	0.206	0.288	0.228
Avg	0.281	0.192	0.219	0.231	0.292	0.285
SD	0.116	0.071	0.191	0.081	0.123	0.127

Appendix S. Spatial variability of first formant frequency

Spatial variability of first formant frequency for the HD and AMC groups

Subject	Slow	Hab	Fast	IL	IC	Dual
HD01	0.278	0.308	0.349	0.279	0.267	0.337
HD02	0.470	0.202	0.225	0.334	0.254	0.512
HD03	.	0.531	0.165	0.536	0.487	0.440
HD04	0.312	0.304	0.334	0.291	0.333	0.326
HD05	.	0.509	0.653	0.247	0.233	.
HD06	0.508	0.407	0.258	0.314	0.373	0.390
HD07	0.584	0.642	0.518	0.401	0.670	0.487
HD08	.	0.348	0.388	0.220	0.288	0.597
HD09	0.489	0.311	0.452	0.471	0.543	0.645
HD10	0.247	0.276	0.220	0.213	0.224	0.256
HD11	0.482	0.542	0.694	0.690	.	0.434
HD12	0.309	0.420	0.473	0.425	0.611	0.450
HD13	0.445	0.365	0.564	0.481	0.566	0.525
HD14	0.584	0.340	0.456	0.433	0.339	0.443
HD15	0.344	0.299	0.340	0.364	.	0.333
HD16	0.254	0.589	0.625	0.497	0.295	0.540
HD17	0.226	0.185	0.122	0.172	0.147	0.178
HD18	0.281	0.209	0.221	0.293	0.269	0.213
HD19	0.574	0.533	0.370	0.507	0.356	0.486
HD20	0.225	0.170	0.455	0.194	0.206	0.245
HD21	0.202	0.275	0.647	0.337	0.601	0.473
HD22	0.544	0.401	0.284	0.469	0.249	0.666
HD23	0.395	0.373	0.464	0.475	0.427	0.421
Avg	0.388	0.371	0.403	0.376	0.368	0.427
SD	0.134	0.134	0.164	0.130	0.153	0.133

Subject	Slow	Hab	Fast	IL	IC	Dual
AMC01	0.239	0.223	0.310	0.253	0.297	0.284
AMC02	.	0.486	0.479	0.485	0.544	0.729
AMC03	.	0.499	0.614	.	0.269	.
AMC04	0.264	0.279	0.304	0.235	0.257	0.302
AMC05	.	0.425	0.428	0.346	0.422	0.359
AMC06	0.381	0.334	0.409	0.211	0.164	0.409
AMC07	.	0.394	0.505	0.325	0.260	0.335
AMC08	0.439	0.202	0.252	0.207	0.213	0.376
AMC09	0.431	0.338	0.520	0.376	0.205	0.578
AMC10	.	.	0.841	.	0.499	0.476
AMC11	0.254	0.189	0.336	0.248	0.263	0.332
AMC12	0.235	0.214	0.195	0.147	0.203	0.180
AMC13	0.515	0.252	0.192	0.205	0.173	0.356
AMC14	.	0.258	0.226	0.316	0.295	0.344
AMC15	.	0.379	0.349	0.401	0.313	.
AMC16	0.207	0.142	0.125	0.117	0.175	0.236
AMC17	0.351	0.392	0.373	0.325	0.276	0.378
AMC18	0.261	0.262	0.256	0.156	0.155	0.268
AMC19	.	0.342	0.288	.	0.419	.
AMC20	.	0.259	0.228	0.207	0.133	0.205
AMC21	0.187	0.237	0.171	0.172	0.224	0.166
AMC22	.	.	0.326	0.281	0.504	0.546
AMC23	0.279	0.433	0.372	0.283	.	0.500
AMC24	.	0.346	0.353	0.140	0.318	0.378
Avg	0.311	0.313	0.352	0.259	0.286	0.368
SD	0.102	0.099	0.159	0.095	0.117	0.138

Spatial variability of first formant frequency for the YA and OA groups

Subject	Slow	Hab	Fast	IL	IC	Dual
YA01	0.362	0.378	0.553	0.377	0.374	0.295
YA02	.	0.435	.	.	.	0.350
YA03	.	.	.	.	0.571	0.437
YA04	0.397	0.222	0.227	0.207	.	0.216
YA05	0.475	0.498	0.679	0.282	0.577	0.163
YA06	0.367	0.303	0.242	0.292	0.282	0.325
YA07	0.491	0.329	0.448	.	.	.
YA08	0.343	0.514	0.619	0.224	0.275	0.486
YA09	.	0.361	0.408	0.425	0.425	0.468
YA10	0.566	0.505	0.443	0.416	0.477	0.368
YA11	.	0.214	0.281	0.180	0.154	0.283
YA12	.	0.308	0.259	0.354	0.376	0.386
YA13	0.510	.	0.328	.	.	.
YA14	.	.	.	.	.	0.423
YA15	.	0.313	0.428	0.396	0.222	0.308
YA16	0.225	0.319	.	0.290	0.404	0.483
Avg	0.415	0.361	0.410	0.313	0.376	0.357
SD	0.105	0.100	0.150	0.086	0.136	0.099

Subject	Slow	Hab	Fast	IL	IC	Dual
OA01	0.439	0.202	0.252	0.207	0.213	0.376
OA02	0.431	0.338	0.520	0.376	0.205	0.578
OA03	.	.	0.841	.	0.499	0.476
OA04	0.254	0.189	0.336	0.248	0.263	0.332
OA05	0.235	0.214	0.195	0.147	0.203	0.180
OA06	0.515	0.252	0.192	0.205	0.173	0.356
OA07	.	0.258	0.226	0.316	0.295	0.344
OA08	.	0.379	0.349	0.401	0.313	.
OA09	0.207	0.142	0.125	0.117	0.175	0.236
OA10	0.351	0.392	0.373	0.325	0.276	0.378
OA11	0.261	0.262	0.256	0.156	0.155	0.268
OA12	.	0.259	0.228	0.207	0.133	0.205
OA13	0.187	0.237	0.171	0.172	0.224	0.166
OA14	0.279	0.433	0.372	0.283	.	0.500
Avg	0.316	0.274	0.317	0.243	0.241	0.338
SD	0.112	0.087	0.183	0.090	0.095	0.127

Appendix T. Spatial variability of second formant frequency

Spatial variability of second formant frequency for the HD and AMC groups

Subject	Slow	Hab	Fast	IL	IC	Dual
HD01	.	0.477	0.229	0.391	0.387	0.356
HD02	0.349	0.118	0.122	0.169	0.173	0.248
HD03	.	.	.	.	.	.
HD04	.	0.243	0.300	0.428	0.269	0.303
HD05	.	0.213	0.234	0.161	0.258	.
HD06	.	.	.	.	.	.
HD07	0.512	0.529	0.597	.	0.540	.
HD08	.	0.638	0.405	0.334	0.372	.
HD09	0.373	0.335	0.285	0.237	0.245	.
HD10	0.320	0.491	0.509	.	0.351	0.366
HD11	0.353	0.418	0.270	0.295	.	0.603
HD12	.	.	0.233	0.421	0.428	.
HD13	0.350	.	0.453	0.355	.	.
HD14	.	.	.	.	.	.
HD15	.	0.599	0.410	.	0.679	.
HD16	0.214	.	0.185	0.308	.	0.202
HD17	.	0.179	0.169	0.122	0.241	0.188
HD18	0.511	0.351	0.231	0.525	0.339	0.323
HD19	.	0.459	0.164	0.177	0.274	0.315
HD20	0.191	0.261	0.226	0.166	0.218	0.198
HD21	.	.	0.368	.	.	.
HD22	0.203	0.141	0.193	0.274	0.129	.
HD23	.	0.436	0.491	0.414	0.359	0.410
Avg	0.338	0.368	0.304	0.299	0.329	0.319
SD	0.114	0.163	0.133	0.119	0.138	0.120

Subject	Slow	Hab	Fast	IL	IC	Dual
AMC01	0.266	0.297	0.197	0.199	0.178	.
AMC02	.	0.180	0.144	.	.	.
AMC03	0.315	0.142	0.159	0.159	0.200	0.219
AMC04	0.376	0.305	0.230	0.303	0.415	0.305
AMC05	.	.	0.272	0.248	.	0.213
AMC06	0.439	0.417	0.260	0.323	0.427	0.305
AMC07	0.427	0.300	.	0.201	0.242	.
AMC08	.	0.227	0.201	.	.	.
AMC09	.	.	0.204	.	.	.
AMC10	.	.	0.283	.	.	.
AMC11	.	0.298	0.299	.	0.236	0.273
AMC12	0.282	0.418	0.258	0.368	0.234	0.435
AMC13	.	.	0.340	.	.	.
AMC14	.	.	.	.	.	.
AMC15	.	.	.	.	0.339	.
AMC16	0.311	.	0.144	0.171	0.292	0.192
AMC17	.	0.188	.	.	0.304	0.290
AMC18	.	.	.	.	.	.
AMC19	.	.	.	.	.	.
AMC20	.	.	0.145	0.237	.	.
AMC21	0.148	0.197	0.243	0.189	0.252	0.209
AMC22	.	.	0.233	.	.	.
AMC23	.	.	.	.	0.741	0.428
AMC24	.	0.302	.	.	.	.
Avg	0.321	0.273	0.226	0.240	0.322	0.287
SD	0.095	0.089	0.059	0.070	0.153	0.087

Spatial variability of second formant frequency for the YA and OA groups

Subject	Slow	Hab	Fast	IL	IC	Dual
YA01	.	0.173	0.261	0.237	0.228	0.215
YA02	0.496	.	.	0.364	0.539	.
YA03	.	.	.	.	0.362	.
YA04	.	.	0.578	0.340	0.378	0.542
YA05	.	0.403	0.345	0.320	0.265	0.313
YA06	0.534	0.376	0.305	0.403	.	.
YA07	0.416	.	.	.	.	.
YA08	0.381	0.334	0.216	0.151	0.302	0.294
YA09	.	0.273	.	0.140	0.210	0.150
YA10	.	.	.	.	0.419	.
YA11	.	0.464	0.199	0.291	0.413	.
YA12	.	.	.	.	.	.
YA13	.	.	0.130	.	.	.
YA14	.	.	.	.	.	0.381
YA15	.	0.170	0.247	0.274	0.203	0.254
YA16	.	0.279	0.332	.	.	0.310
Avg	0.457	0.309	0.290	0.280	0.332	0.307
SD	0.070	0.106	0.127	0.091	0.109	0.118

Subject	Slow	Hab	Fast	IL	IC	Dual
OA01	.	0.227	0.201	.	.	.
OA02	.	.	0.204	.	.	.
OA03	.	.	0.283	.	.	.
OA04	.	0.298	0.299	.	0.236	0.273
OA05	0.282	0.418	0.258	0.368	0.234	0.435
OA06	.	.	0.340	.	.	.
OA07	.	.	.	.	.	.
OA08	.	.	.	.	0.339	.
OA09	0.311	.	0.144	0.171	0.292	0.192
OA10	.	0.188	.	.	0.304	0.290
OA11	.	.	.	.	.	.
OA12	.	.	0.145	0.237	.	.
OA13	0.148	0.197	0.243	0.189	0.252	0.209
OA14	.	.	.	.	0.741	0.428
Avg	0.247	0.266	0.235	0.241	0.343	0.305
SD	0.087	0.096	0.068	0.089	0.180	0.105

Appendix U. Temporal variability of intensity

Temporal variability of intensity for the HD and AMC groups

Subject	Slow	Hab	Fast	IL	IC	Dual
HD01	0.0206	0.0156	0.0254	0.0261	0.0141	0.0263
HD02	0.0111	0.0144	0.0090	0.0101	0.0120	0.0091
HD03	0.0288	0.0159	0.0106	0.0141	0.0232	0.0289
HD04	0.0114	0.0154	0.0200	0.0393	0.0205	.
HD05	0.0287	0.0115	0.0123	0.0102	0.0144	.
HD06	0.0289	0.0221	0.0144	0.0162	0.0237	0.0187
HD07	0.0233	0.0146	0.0297	0.0277	0.0347	0.0509
HD08	0.0148	0.0112	0.0125	0.0206	0.0136	0.0179
HD09	0.0265	0.0203	0.0418	0.0369	0.0318	0.0536
HD10	0.0184	0.0199	0.0102	0.0168	0.0153	0.0174
HD11	0.0368	0.0248	0.0236	0.0258	0.0354	0.0293
HD12	0.0180	0.0117	0.0088	0.0093	0.0245	0.0135
HD13	0.0120	0.0164	0.0216	0.0286	0.0244	0.0287
HD14	0.0322	0.0356	0.0369	0.0379	0.0315	0.0508
HD15	0.0206	0.0126	0.0064	0.0108	0.0157	0.0124
HD16	0.0159	0.0137	0.0216	0.0200	0.0174	0.0277
HD17	0.0137	0.0135	0.0066	0.0104	0.0080	0.0128
HD18	0.0137	0.0120	0.0154	0.0190	0.0104	0.0117
HD19	0.0228	0.0114	0.0180	0.0123	0.0093	0.0179
HD20	0.0097	0.0092	0.0092	0.0142	0.0148	0.0124
HD21	0.0107	0.0158	0.0308	0.0267	0.0238	0.0282
HD22	0.0411	0.0173	0.0283	0.0347	0.0268	0.0258
HD23	0.0217	0.0148	0.0418	0.0215	0.0134	0.0260
Avg	0.0209	0.0161	0.0198	0.0213	0.0199	0.0248
SD	0.0088	0.0057	0.0110	0.0096	0.0082	0.0131

Subject	Slow	Hab	Fast	IL	IC	Dual
AMC01	0.0141	0.0148	0.0215	0.0142	0.0146	0.0152
AMC02	0.0185	0.0092	0.0161	0.0112	0.0111	0.0111
AMC03	0.0104	0.0176	0.0209	0.0145	0.0196	0.0217
AMC04	0.0164	0.0150	0.0141	0.0123	0.0142	0.0113
AMC05	0.0085	0.0091	0.0091	0.0185	0.0086	0.0097
AMC06	0.0117	0.0105	0.0134	0.0101	0.0123	0.0148
AMC07	0.0175	0.0218	0.0228	0.0300	0.0147	0.0199
AMC08	0.0186	0.0138	0.0160	0.0117	0.0115	0.0101
AMC09	0.0364	0.0368	0.0196	0.0111	0.0118	0.0347
AMC10	0.0153	0.0094	0.0131	0.0184	0.0093	0.0099
AMC11	0.0140	0.0102	0.0523	0.0225	0.0139	0.0498
AMC12	0.0173	0.0094	0.0141	0.0113	0.0130	0.0144
AMC13	0.0248	0.0166	0.0173	0.0115	0.0117	0.0199
AMC14	0.0244	0.0101	0.0138	0.0139	0.0246	0.0158
AMC15	0.0197	0.0156	0.0178	0.0122	0.0170	0.0095
AMC16	0.0256	0.0095	0.0071	0.0087	0.0150	0.0131
AMC17	0.0095	0.0080	0.0127	0.0136	0.0100	0.0161
AMC18	0.0173	0.0112	0.0126	0.0152	0.0108	0.0154
AMC19	0.0207	0.0331	0.0218	0.0218	0.0128	0.0327
AMC20	0.0177	0.0118	0.0168	0.0104	0.0114	0.0125
AMC21	0.0141	0.0123	0.0126	0.0113	0.0183	0.0142
AMC22	0.0155	0.0330	0.0189	0.0190	0.0168	0.0227
AMC23	0.0103	0.0099	0.0109	0.0102	0.0106	0.0138
AMC24	0.0116	0.0164	0.0173	0.0136	0.0102	0.0218
Avg	0.0171	0.0152	0.0172	0.0145	0.0135	0.0179
SD	0.0062	0.0081	0.0085	0.0050	0.0037	0.0095

Temporal variability of intensity for the YA and OA groups

Subject	Slow	Hab	Fast	IL	IC	Dual
YA01	0.0149	0.0229	0.0194	0.0246	0.0175	0.0141
YA02	0.0230	0.0145	0.0312	0.0177	0.0170	0.0128
YA03	0.0139	0.0244	0.0185	0.0126	0.0151	0.0210
YA04	0.0157	0.0134	0.0150	0.0106	0.0147	0.0164
YA05	0.0203	0.0222	0.0456	0.0413	0.0320	0.0174
YA06	0.0117	0.0127	0.0136	0.0186	0.0172	0.0144
YA07	0.0125	0.0088	0.0300	0.0120	0.0159	0.0320
YA08	0.0149	0.0168	0.0198	0.0156	0.0187	0.0114
YA09	0.0147	0.0148	0.0154	0.0142	0.0175	0.0168
YA10	0.0250	0.0223	0.0108	0.0157	0.0183	0.0288
YA11	.	0.0105	0.0138	0.0148	0.0162	0.0143
YA12	0.0137	0.0152	0.0175	0.0110	0.0114	0.0136
YA13	0.0124	0.0176	0.0170	0.0114	0.0382	0.0145
YA14	0.0147	0.0150	0.0219	0.0107	0.0172	0.0255
YA15	0.0166	0.0151	0.0311	0.0451	0.0489	0.0270
YA16	0.0219	0.0187	0.0174	0.0256	0.0288	0.0163
Avg	0.0164	0.0166	0.0211	0.0188	0.0215	0.0185
SD	0.0041	0.0045	0.0090	0.0105	0.0102	0.0064

Subject	Slow	Hab	Fast	IL	IC	Dual
OA01	0.0186	0.0138	0.0160	0.0117	0.0115	0.0101
OA02	0.0364	0.0368	0.0196	0.0111	0.0118	0.0347
OA03	0.0153	0.0094	0.0131	0.0184	0.0093	0.0099
OA04	0.0140	0.0102	0.0523	0.0225	0.0139	0.0498
OA05	0.0173	0.0094	0.0141	0.0113	0.0130	0.0144
OA06	0.0248	0.0166	0.0173	0.0115	0.0117	0.0199
OA07	0.0244	0.0101	0.0138	0.0139	0.0246	0.0158
OA08	0.0197	0.0156	0.0178	0.0122	0.0170	0.0095
OA09	0.0256	0.0095	0.0071	0.0087	0.0150	0.0131
OA10	0.0095	0.0080	0.0127	0.0136	0.0100	0.0161
OA11	0.0173	0.0112	0.0126	0.0152	0.0108	0.0154
OA12	0.0177	0.0118	0.0168	0.0104	0.0114	0.0125
OA13	0.0141	0.0123	0.0126	0.0113	0.0183	0.0142
OA14	0.0103	0.0099	0.0109	0.0102	0.0106	0.0138
Avg	0.0189	0.0132	0.0169	0.0130	0.0135	0.0178
SD	0.0070	0.0072	0.0107	0.0036	0.0041	0.0111

Appendix V. Temporal variability of fundamental frequency

Temporal variability of fundamental frequency for the HD and AMC groups

Subject	Slow	Hab	Fast	IL	IC	Dual
HD01	0.0475	0.0853	0.0239	0.0586	0.0439	0.0484
HD02	0.0826	0.0920	0.0571	0.0857	0.0474	0.0777
HD03	0.0637	0.0181	0.0203	0.0181	.	0.0191
HD04	0.0244	0.0182	0.0256	0.0194	0.0327	0.0267
HD05	0.0434	0.0185	0.0213	0.0456	0.0619	.
HD06	0.0510	0.0537	0.0633	0.0455	0.0471	.
HD07	0.0342	0.0548	0.0333	0.0394	0.0451	0.0348
HD08	0.0343	0.0173	0.0171	0.0298	0.0413	0.0519
HD09	0.0185	0.0292	0.0365	0.0550	0.0526	0.0579
HD10	0.0214	0.0185	0.0155	0.0237	0.0186	0.0172
HD11	0.0468	0.0504	0.0576	0.0434	0.0770	0.0383
HD12	0.0276	0.0177	0.0157	0.0265	0.0200	0.0404
HD13	0.0637	0.0267	0.0488	0.0531	0.0387	0.0413
HD14	0.0197	0.0312	0.0378	0.0504	0.0484	0.0559
HD15	0.0222	0.0272	0.0152	0.0169	0.0269	0.0260
HD16	0.0175	0.0164	0.0175	0.0252	0.0237	0.0261
HD17	0.0152	0.0330	0.0101	0.0115	0.0207	0.0200
HD18	0.0130	0.0145	0.0388	0.0327	0.0155	0.0135
HD19	0.0363	0.0158	0.0211	0.0259	0.0144	0.0420
HD20	0.0179	0.0223	0.0251	0.0479	0.0559	0.0330
HD21	0.0209	0.0217	0.0370	0.0596	0.0357	0.0583
HD22	0.0943	0.0488	0.0806	0.0702	0.0569	0.0416
HD23	0.0317	0.0626	0.0542	0.0822	0.0434	0.0417
Avg	0.0369	0.0345	0.0336	0.0420	0.0394	0.0387
SD	0.0220	0.0224	0.0187	0.0206	0.0166	0.0162

Subject	Slow	Hab	Fast	IL	IC	Dual
AMC01	0.0336	0.0385	0.0317	0.0337	0.0539	0.0214
AMC02	0.0184	0.0454	0.0443	0.0584	0.0834	0.0798
AMC03	0.0125	0.0177	0.0249	0.0397	0.0282	0.0155
AMC04	0.0237	0.0194	0.0124	0.0239	0.0195	0.0202
AMC05	0.0186	0.0229	0.0224	0.0307	0.0330	0.0262
AMC06	0.0236	0.0279	0.0185	0.0163	0.0244	0.0217
AMC07	0.0294	0.0175	0.0182	0.0249	0.0211	0.0296
AMC08	0.0166	0.0144	0.0201	0.0176	0.0689	0.0198
AMC09	0.0415	0.0613	0.0583	0.0385	0.0197	0.0373
AMC10	0.0220	0.0649	0.0924	0.0435	0.0213	0.0629
AMC11	0.0254	0.0158	0.0685	0.0877	0.0212	0.0846
AMC12	0.0161	0.0271	0.0208	0.0236	0.0166	0.0280
AMC13	0.0301	0.0478	0.0223	0.0657	0.0319	0.0215
AMC14	0.0690	0.0146	0.0471	0.0241	0.0312	0.0807
AMC15	0.0404	0.0248	0.0182	0.0705	0.0355	0.0300
AMC16	0.0306	0.0202	0.0112	0.0104	0.0297	0.0153
AMC17	0.0153	0.0238	0.0234	0.0932	0.0279	0.0464
AMC18	0.0156	0.0182	0.0181	0.0172	0.0179	0.0202
AMC19	0.0189	0.0200	0.0167	0.0155	0.0302	0.0244
AMC20	0.0342	0.0263	0.0199	0.0281	0.0471	0.0433
AMC21	0.0182	0.0343	0.0202	0.0200	0.0247	0.0228
AMC22	0.0217	0.0310	0.0237	0.0283	0.0178	0.0182
AMC23	0.0238	0.0167	0.0159	0.0150	0.0202	0.0171
AMC24	0.0263	0.0360	0.0324	0.0322	0.0331	0.0638
Avg	0.0261	0.0286	0.0292	0.0358	0.0316	0.0354
SD	0.0120	0.0141	0.0196	0.0230	0.0166	0.0223

Temporal variability of fundamental frequency for the YA and OA groups

Subject	Slow	Hab	Fast	IL	IC	Dual
YA01	0.0157	0.0619	0.0402	0.0208	0.0207	0.0209
YA02	0.0176	0.0196	0.0179	0.0269	0.0426	0.0591
YA03	0.0168	0.0184	0.0174	0.0373	0.0449	0.0326
YA04	0.0285	0.0183	0.0250	0.0394	0.0307	0.0336
YA05	0.0180	0.0204	0.0510	0.1155	0.0212	0.0234
YA06	0.0117	0.0162	0.0152	0.0275	0.0189	0.0164
YA07	0.0254	0.0159	0.0443	0.0218	0.0317	0.0322
YA08	0.0183	0.0199	0.0148	0.0242	0.0562	0.0151
YA09	0.0174	0.0306	0.0366	0.0569	0.0392	0.0445
YA10	0.0245	0.0274	0.0144	0.0305	0.0582	0.0304
YA11	0.0122	0.0460	0.0290	0.0264	0.0180	0.0435
YA12	0.0150	0.0419	0.0241	0.0326	0.0424	0.0274
YA13	0.0135	0.0271	0.0190	0.0244	0.0324	0.0271
YA14	0.0220	0.0178	0.0214	0.0507	0.0660	0.0443
YA15	0.0597	0.0243	0.0399	0.0736	0.0545	0.0419
YA16	0.0434	0.0240	0.0442	0.0224	0.0335	0.0303
Avg	0.0225	0.0269	0.0284	0.0394	0.0382	0.0327
SD	0.0126	0.0128	0.0124	0.0250	0.0150	0.0117

Subject	Slow	Hab	Fast	IL	IC	Dual
OA01	0.0166	0.0144	0.0201	0.0176	0.0689	0.0198
OA02	0.0415	0.0613	0.0583	0.0385	0.0197	0.0373
OA03	0.0220	0.0649	0.0924	0.0435	0.0213	0.0629
OA04	0.0254	0.0158	0.0685	0.0877	0.0212	0.0846
OA05	0.0161	0.0271	0.0208	0.0236	0.0166	0.0280
OA06	0.0301	0.0478	0.0223	0.0657	0.0319	0.0215
OA07	0.0690	0.0146	0.0471	0.0241	0.0312	0.0807
OA08	0.0404	0.0248	0.0182	0.0705	0.0355	0.0300
OA09	0.0306	0.0202	0.0112	0.0104	0.0297	0.0153
OA10	0.0153	0.0238	0.0234	0.0932	0.0279	0.0464
OA11	0.0156	0.0182	0.0181	0.0172	0.0179	0.0202
OA12	0.0342	0.0263	0.0199	0.0281	0.0471	0.0433
OA13	0.0182	0.0343	0.0202	0.0200	0.0247	0.0228
OA14	0.0238	0.0167	0.0159	0.0150	0.0202	0.0171
Avg	0.0285	0.0293	0.0326	0.0397	0.0296	0.0379
SD	0.0147	0.0169	0.0243	0.0281	0.0140	0.0232

Appendix W. Temporal variability of first formant frequency

Temporal variability of first formant frequency for the HD and AMC groups

Subject	Slow	Hab	Fast	IL	IC	Dual
HD01	0.0178	0.0224	0.0214	0.0288	0.0157	0.0232
HD02	0.0192	0.0114	0.0115	0.0188	0.0162	0.0211
HD03	.	0.0270	0.0109	0.0541	0.0204	0.0268
HD04	0.0135	0.0140	0.0119	0.0136	0.0110	0.0205
HD05	.	0.0349	0.0351	0.0224	0.0193	.
HD06	0.0348	0.0208	0.0362	0.0726	0.0176	0.0243
HD07	0.0726	0.0212	0.0240	0.0494	0.0447	0.0535
HD08	.	0.0310	0.0159	0.0170	0.0160	0.0390
HD09	0.0409	0.0243	0.0459	0.0341	0.0335	0.0773
HD10	0.0194	0.0185	0.0114	0.0165	0.0153	0.0163
HD11	0.0378	0.0268	0.0604	0.0309	.	0.0749
HD12	0.0333	0.0272	0.0269	0.0322	0.0434	0.0548
HD13	0.0116	0.0130	0.0250	0.0277	0.0213	0.0310
HD14	0.0343	0.0336	0.0504	0.0258	0.0212	0.0229
HD15	0.0200	0.0140	0.0084	0.0120	.	0.0118
HD16	0.0151	0.0233	0.0357	0.0351	0.0183	0.0461
HD17	0.0138	0.0145	0.0065	0.0122	0.0071	0.0117
HD18	0.0146	0.0141	0.0164	0.0248	0.0117	0.0110
HD19	0.0244	0.0162	0.0304	0.0259	0.0125	0.0263
HD20	0.0141	0.0117	0.0517	0.0128	0.0131	0.0127
HD21	0.0183	0.0260	0.0383	0.0319	0.0396	0.0643
HD22	0.0506	0.0204	0.0328	0.0400	0.0174	0.0320
HD23	0.0175	0.0210	0.0229	0.0214	0.0385	0.0296
Avg	0.0262	0.0212	0.0274	0.0287	0.0216	0.0332
SD	0.0155	0.0069	0.0152	0.0147	0.0112	0.0202

Subject	Slow	Hab	Fast	IL	IC	Dual
AMC01	0.0162	0.0151	0.0191	0.0162	0.0246	0.0220
AMC02	.	0.0122	0.0201	0.0183	0.0170	0.0437
AMC03	.	0.0174	0.0291	.	0.0233	.
AMC04	0.0171	0.0156	0.0199	0.0278	0.0183	0.0178
AMC05	.	0.0130	0.0098	0.0150	0.0134	0.0132
AMC06	0.0107	0.0194	0.0486	0.0111	0.0102	0.0205
AMC07	.	0.0332	0.0353	0.0315	0.0206	0.0536
AMC08	0.0168	0.0116	0.0147	0.0114	0.0127	0.0258
AMC09	0.0177	0.0245	0.0182	0.0252	0.0183	0.0585
AMC10	.	.	0.0230	.	0.0127	0.0187
AMC11	0.0133	0.0127	0.0292	0.0155	0.0232	0.0337
AMC12	0.0188	0.0112	0.0126	0.0100	0.0115	0.0144
AMC13	0.0247	0.0172	0.0184	0.0112	0.0112	0.0209
AMC14	.	0.0112	0.0115	0.0109	0.0152	0.0150
AMC15	.	0.0149	0.0147	0.0145	0.0188	.
AMC16	0.0163	0.0081	0.0073	0.0081	0.0115	0.0127
AMC17	0.0148	0.0184	0.0332	0.0167	0.0151	0.0219
AMC18	0.0177	0.0153	0.0210	0.0131	0.0096	0.0177
AMC19	.	0.0113	0.0183	.	0.0216	.
AMC20	.	0.0170	0.0295	0.0149	0.0113	0.0135
AMC21	0.0147	0.0104	0.0236	0.0159	0.0154	0.0147
AMC22	.	.	0.0230	0.0163	0.0184	0.0291
AMC23	0.0090	0.0247	0.0316	0.0162	.	0.0198
AMC24	.	0.0087	0.0179	0.0122	0.0140	0.0323
Avg	0.0160	0.0156	0.0221	0.0158	0.0160	0.0247
SD	0.0039	0.0059	0.0093	0.0059	0.0045	0.0130

Temporal variability of first formant frequency for the YA and OA groups

Subject	Slow	Hab	Fast	IL	IC	Dual
YA01	0.0185	0.0175	0.0373	0.0215	0.0220	0.0230
YA02	.	0.0169	.	.	.	0.0235
YA03	.	.	.	.	0.0257	0.0418
YA04	0.0201	0.0122	0.0182	0.0133	.	0.0182
YA05	0.0224	0.0298	0.0641	0.0275	0.0423	0.0249
YA06	0.0225	0.0170	0.0227	0.0167	0.0211	0.0214
YA07	0.0374	0.0503	0.0815	.	.	.
YA08	0.0191	0.0314	0.0799	0.0188	0.0151	0.0287
YA09	.	0.0194	0.0391	0.0355	0.0197	0.0231
YA10	0.0292	0.0170	0.0152	0.0165	0.0201	0.0194
YA11	.	0.0187	0.0157	0.0153	0.0179	0.0123
YA12	.	0.0252	0.0248	0.0279	0.0213	0.0312
YA13	0.0177	.	0.0241	.	.	.
YA14	.	.	.	.	.	0.0546
YA15	.	0.0359	0.0763	0.0328	0.0447	0.0219
YA16	0.0194	0.0156	.	0.0130	0.0202	0.0255
Avg	0.0229	0.0236	0.0416	0.0217	0.0246	0.0264
SD	0.0064	0.0107	0.0264	0.0080	0.0097	0.0106

Subject	Slow	Hab	Fast	IL	IC	Dual
OA01	0.0168	0.0116	0.0147	0.0114	0.0127	0.0258
OA02	0.0177	0.0245	0.0182	0.0252	0.0183	0.0585
OA03	.	.	0.0230	.	0.0127	0.0187
OA04	0.0133	0.0127	0.0292	0.0155	0.0232	0.0337
OA05	0.0188	0.0112	0.0126	0.0100	0.0115	0.0144
OA06	0.0247	0.0172	0.0184	0.0112	0.0112	0.0209
OA07	.	0.0112	0.0115	0.0109	0.0152	0.0150
OA08	.	0.0149	0.0147	0.0145	0.0188	.
OA09	0.0163	0.0081	0.0073	0.0081	0.0115	0.0127
OA10	0.0148	0.0184	0.0332	0.0167	0.0151	0.0219
OA11	0.0177	0.0153	0.0210	0.0131	0.0096	0.0177
OA12	.	0.0170	0.0295	0.0149	0.0113	0.0135
OA13	0.0147	0.0104	0.0236	0.0159	0.0154	0.0147
OA14	0.0090	0.0247	0.0316	0.0162	.	0.0198
Avg	0.0164	0.0152	0.0206	0.0141	0.0143	0.0221
SD	0.0041	0.0052	0.0081	0.0043	0.0039	0.0124

Appendix X. Temporal variability of second formant frequency

Temporal variability of second formant frequency for the HD and AMC groups

Subject	Slow	Hab	Fast	IL	IC	Dual
HD01	.	0.0283	0.0379	0.0232	0.0341	0.0227
HD02	0.0301	0.0120	0.0101	0.0132	0.0109	0.0142
HD03	.	.	.	.	.	.
HD04	.	0.0254	0.0279	0.0367	0.0204	0.0377
HD05	.	0.0361	0.0275	0.0156	0.0250	.
HD06	.	.	.	.	.	.
HD07	0.0362	0.0334	0.0479	.	0.0268	.
HD08	.	0.0540	0.0257	0.0218	0.0194	.
HD09	0.0283	0.0240	0.0266	0.0352	0.0279	.
HD10	0.0258	0.0473	0.0258	.	0.0181	0.0254
HD11	0.0241	0.0557	0.0308	0.0417	.	0.0506
HD12	.	.	0.0136	0.0661	0.0305	.
HD13	0.0255	.	0.0348	0.0279	.	.
HD14	.	.	.	.	.	.
HD15	.	0.0196	0.0270	.	0.0445	.
HD16	0.0193	.	0.0252	0.0223	.	0.0303
HD17	.	0.0143	0.0114	0.0099	0.0201	0.0136
HD18	0.0389	0.0373	0.0235	0.0591	0.0369	0.0293
HD19	.	0.0585	0.0186	0.0146	0.0122	0.0337
HD20	0.0102	0.0159	0.0260	0.0117	0.0131	0.0114
HD21	.	.	0.0467	.	.	.
HD22	0.0335	0.0164	0.0275	0.0519	0.0207	.
HD23	.	0.0127	0.0222	0.0245	0.0235	0.0321
Avg	0.0272	0.0307	0.0268	0.0297	0.0240	0.0274
SD	0.0084	0.0161	0.0098	0.0173	0.0092	0.0117

Subject	Slow	Hab	Fast	IL	IC	Dual
AMC01	0.0151	0.0225	0.0183	0.0209	0.0169	.
AMC02	.	0.0215	0.0113	.	.	.
AMC03	0.0139	0.0102	0.0172	0.0096	0.0099	0.0103
AMC04	0.0358	0.0414	0.0213	0.0485	0.0557	0.0295
AMC05	.	.	0.0148	0.0230	.	0.0213
AMC06	0.0232	0.0264	0.0281	0.0361	0.0269	0.0232
AMC07	0.0206	0.0320	.	0.0155	0.0272	.
AMC08	.	0.0206	0.0185	.	.	.
AMC09	.	.	0.0175	.	.	.
AMC10	.	.	0.0138	.	.	.
AMC11	.	0.0092	0.0210	.	0.0208	0.0334
AMC12	0.0238	0.0281	0.0362	0.0446	0.0293	0.0233
AMC13	.	.	0.0297	.	.	.
AMC14	.	.	.	.	.	.
AMC15	.	.	.	.	0.0131	.
AMC16	0.0262	.	0.0080	0.0070	0.0194	0.0098
AMC17	.	0.0100	.	.	0.0146	0.0158
AMC18	.	.	.	.	.	.
AMC19	.	.	.	.	.	.
AMC20	.	.	0.0105	0.0175	.	.
AMC21	0.0134	0.0086	0.0244	0.0194	0.0234	0.0137
AMC22	.	.	0.0294	.	.	.
AMC23	.	.	.	.	0.0497	0.0259
AMC24	.	0.0116	.	.	.	.
Avg	0.0215	0.0202	0.0200	0.0242	0.0256	0.0206
SD	0.0076	0.0106	0.0079	0.0142	0.0140	0.0080

Temporal variability of second formant frequency for the YA and OA groups

Subject	Slow	Hab	Fast	IL	IC	Dual
YA01	.	0.0113	0.0111	0.0167	0.0102	0.0116
YA02	0.0159	.	.	0.0204	0.0220	.
YA03	.	.	.	.	0.0191	.
YA04	.	.	0.0468	0.0461	0.0195	0.0213
YA05	.	0.0142	0.0199	0.0153	0.0139	0.0231
YA06	0.0330	0.0256	0.0185	0.0356	.	.
YA07	0.0332	.	.	.	.	.
YA08	0.0156	0.0128	0.0165	0.0105	0.0139	0.0206
YA09	.	0.0185	.	0.0150	0.0160	0.0103
YA10	.	.	.	.	0.0198	.
YA11	.	0.0541	0.0178	0.0176	0.0304	.
YA12	.	.	.	.	.	.
YA13	.	.	0.0154	.	.	.
YA14	.	.	.	.	.	0.0563
YA15	.	0.0103	0.0288	0.0427	0.0129	0.0171
YA16	.	0.0124	0.0149	.	.	0.0167
Avg	0.0244	0.0199	0.0211	0.0244	0.0178	0.0221
SD	0.0100	0.0147	0.0108	0.0133	0.0058	0.0145

Subject	Slow	Hab	Fast	IL	IC	Dual
OA01	.	0.0206	0.0185	.	.	.
OA02	.	.	0.0175	.	.	.
OA03	.	.	0.0138	.	.	.
OA04	.	0.0092	0.0210	.	0.0208	0.0334
OA05	0.0238	0.0281	0.0362	0.0446	0.0293	0.0233
OA06	.	.	0.0297	.	.	.
OA07	.	.	.	.	.	.
OA08	.	.	.	.	0.0131	.
OA09	0.0262	.	0.0080	0.0070	0.0194	0.0098
OA10	.	0.0100	.	.	0.0146	0.0158
OA11	.	.	.	.	.	.
OA12	.	.	0.0105	0.0175	.	.
OA13	0.0134	0.0086	0.0244	0.0194	0.0234	0.0137
OA14	.	.	.	.	0.0497	0.0259
Avg	0.0211	0.0153	0.0200	0.0221	0.0243	0.0203
SD	0.0068	0.0087	0.0091	0.0159	0.0124	0.0088