Motor and Cognitive influences on speech production

in Huntington's disease and Parkinson's disease

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To Jane: my greatest lesson yet-
always remember to be
the nerd

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CHAPTER I

INTRODUCTION

Statement of the Problem

Although it is common to consider cognition and speech motor functioning as separate processes, evidence has emerged to support the interaction of both systems during speech production (Feenaughty et al., 2014; Lowit et al., 2006; Rodgers et al., 2013). Yet, limited information exists to describe the interaction of these systems in speech production and guide speech-language pathologists in providing appropriate services for patients with co-occurring motor and cognitive deficits. Specifically, speech production is likely mediated by multiple exertive mechanisms (i.e., attention, effort, arousal, focus, motivation) which can directly interact with speech motor control (Tilsen, 2017). Although some of our current insights into the interactions between cognition and speech motor control stem from studies investigating healthy individuals across the lifespan (i.e., developmental and aging effects) (Dromey & Bates, 2005; Dromey & Benson, 2003; Maner et al., 2014; Sadagopan & Smith, 2008), there is also emerging evidence from research in neurological populations (Arnett et al., 2008; Feenaughty et al., 2013; Huber & Darling, 2011; Lowit et al., 2006; MacKenzie & Green, 2009; Noffs et al., 2018; Östberg et al., 2009; Rodgers et al., 2013; M. M. Smith & Arnett, 2007) (i.e., multiple sclerosis [MS], Parkinson's disease [PD], Huntington's disease [HD]).

A comprehensive understanding about how cognitive and/or speech motor impairment affect speech production is particularly important because one or both of these processes are commonly affected to varying degrees in neurodegenerative diseases (e.g., HD, PD). Patients with HD and PD experience progressive decline in cognition and motor functioning due to damage to the basal ganglia and associated frontostriatal dysfunction (Dominguez et al., 2017; Fennema-Notestine et al., 2004; Lewis et al., 2003; Rodda, 1981; Watkins et al., 2000; Wolf et al., 2008; Zgaljardic et al., 2003). While they are both degenerative in nature and involve similar neurological regions, they differ in terms of their motor speech classification (hyperkinetic dysarthria for HD and hypokinetic dysarthria for PD) and the nature of cognitive decline. Yet, within the populations of HD and PD, the motor speech characteristics for all patients are not uniform. There is variability in presentation of hyperkinetic and hypokinetic dysarthria, which results in heterogenous speech profiles (e.g., rate differences) among individuals with the same medical diagnosis and the same general motor speech classification (Darley et al., 1969; Diehl et al., 2019; Kim et al., 2022; Lansford et al., 2014; Ludlow et al., 1987; Metter & Hanson, 1986; Netsell et al., 1975; Skodda & Schlegel, 2008; Weismer et al., 2001). It is possible that this heterogeneity might reflect the interaction of cognitive impairment and speech motor impairment on the process of speech production. Speech-language pathologists must be able to evaluate patient performance on speech assessments with an understanding of the influence of cognitive ability and speech motor control on task performance. Improved understanding of the influence of cognition and motor control during a speech evaluation will help to optimize interpretation of patient abilities and allow for the development of targeted interventions.

Speech Timing

One way to determine the impact of cognitive ability and motor functioning on speech production is by studying aspects of speech timing, a feature that can be influenced by both motor ability and cognitive functioning. Methods of studying speech timing, for example, include direct examination of motor performance (i.e., speed of articulators), acoustic analyses of either global speech timing measures (i.e., articulation rate, speech rate, pause durations) or segmental measures (i.e., segment durations), or perceptual ratings (i.e., perceptual judgment of speech rate). Most clinicians do not have access to the specialized equipment used to evaluate speech motor performance directly and, therefore, kinematic measures are not often used in clinical practice. Software for acoustic analysis, however, is freely available to clinicians and is more feasible in clinical practice and research. Thus, acoustic analyses are often used to examine speech timing via these global measures of speech rate, articulating rate, and pausing behavior.

Acoustic analyses are often used to examine global measures of speech timing, including articulation rate and speech rate. Articulation rate is calculated by removing pauses from a speech production sample and determining the rate of only sound production in syllables per second or words per minute. Conversely, speech rate is calculated by determining the time, in syllables per second or words per minute, that an individual produces the speech sample of interest. While articulation rate is a primarily motor-based measure, speech rate accounts for both time spent articulating as well as the pauses within the given sample. Pause time (i.e., average pause duration, total pause time, etc.) is an acoustic variable that can represent either cognitive-linguistic processing (Rochester, 1971; Walker, 1988) or motor-related processes (i.e., speech breathing) and may be used to speculate about the cognitive and motor influences of a task. Filled pauses (i.e., “um”, “uh”) have been associated with speakers’ ability to predict an upcoming delay (Clark & Fox Tree, 2002), and ungrammatical pauses occur more in spontaneous speech rather than reading tasks (Y. Wang et al., 2010).

These measures of articulation rate and speech rate may have unique value in the evaluation of individuals with degenerative disorders that are characterized by cognitive or motor speech deficits. Articulation rate may decline with age-related reduction in motor function in the absence of reduced intelligibility (Amerman & Parnell, 1990; Lowit et al., 2006; Ramig, 1983) or due to underlying motor disorder (i.e., dysarthria). Pause timing (i.e., pause length, speech rate), however, can be used to determine the potential for further cognitive disruption of speech timing beyond that of slower motor functioning due to age or motor speech disorder. For example, in older adults and individuals with dysarthria, evidence suggests that speech rate may be reduced as a compensatory strategy for reduced articulatory control or linguistic formulation (i.e., word finding) (Feenaughty et al., 2013; Mefferd & Corder, 2014). Articulation rate and speech rate can be used to attempt to parse out the cognitive and motor impairments impacting an individual's speech timing. Although all measures of speech timing (i.e., speech rate, articulation rate, pausing behavior) may be impaired to some degree in degenerative disorders, they may not be impaired equally or in the same manner across individuals.

For example, if a patient is found to have an abnormally slow speech rate, it is possible that impaired motor speech function (i.e., dysarthria) and/or cognitive function impacted performance. The pause-related variables in speech rate, such as the percent of time spent articulating versus pausing, might allow assumptions to be made regarding the influence of cognition. If the patient has 'normal' pausing behavior, the slow articulation rate and speech rate are likely the result of a pure motor problem (i.e., dysarthria), as changes in articulation rate are often the result of impaired movement. Conversely, a patient may have 'normal' articulation rate but have lengthy pauses in their sample that leads to a reduced speech rate. This would suggest a greater interference of cognition rather than motor functioning on the individual's speech production system. Finally, it is possible that an individual with slow speech rate may present with both slow articulation rate and long pause times. If the slow speech rate happens to be a result of very long pause times, in addition to the slowed articulation, this would suggest that cognition does play a role in the patient's performance beyond that of slowed articulation and normal pausing behavior. The ability to examine both articulation and pause timing in speech production is therefore crucial in order to tease apart the influences of co-occurring cognitive and motor impairments on speech production.

Task Specific Demands

The study of speech timing (i.e., articulation rate and speech rate) requires careful consideration of the motor speech and cognitive demands of selected experimental tasks. Given that speech production may vary based upon cognitive-linguistic and speech motor demands, researchers may be able to compare performance across tasks to achieve a better understanding of the influences of each on speech timing. A variety of tasks have been used in the evaluation of motor speech disorders including non-speech [i.e., syllable repetition tasks, alternating and sequential motion rate tasks (AMRs/SMRs)] and speech tasks (i.e., connected speech tasks such as reading aloud or narrative production). Syllable repetition tasks can be particularly useful in understanding the basic oral motor performance which underlies speech production without the addition of cognitive-linguistic demands (Maas, 2017; Y. T. Wang et al., 2005) that occur in more natural speech. Conversely, connected speech tasks such as reading passages aloud or generating narratives place a higher level of cognitive-linguistic demand on patient performance. For example, reading aloud involves underlying skillsets such as decoding, self-monitoring and revising errors while narratives might involve the cognitive load of perceiving a pictured scene, retrieving words, and/or developing and producing a personal story in an efficient manner. These task differences can directly impact interpretation of patient performance. If a patient has reduced performance on a syllable repetition task, this may suggest a primarily motor-based deficit such as dysarthria. However, if the patient also has reduced performance, or a greater degree of reduced performance, on measures of speech timing (i.e., increased pausing) in connected speech this might indicate both motor and cognitive dysfunction.

As connected speech tasks draw upon both underlying cognitive-linguistic and motor skills, interpretation of performance on these tasks is more complex. Some of this complexity stems from reports of differential task performance between types of connected speech. Comparisons of speech timing have been made between reading aloud and self-generated or spontaneous speech, with a lack of consensus across studies (Huber & Darling, 2011; Jaewicz et al., 2010; Walker, 1988) or no differences in rate reported (Barik, 1979; Lowit-Leuschel & Docherty, 2001). When completing spontaneous speech tasks, speech rate has been shown to be slower due to increased pause time, (Huber, 2007; Huber & Darling, 2011; Walker, 1988) and articulation rate (i.e., the rate of sound production) has been shown to be faster (Jaewicz et al., 2010) compared to reading aloud in neurotypical adults and individuals with PD. Researchers have speculated that the reduced articulatory rate when reading aloud could indicate a more formal style of speaking or a possible compensatory strategy used to promote intelligibility by persons with dysarthria (Feenaughty et al., 2013). However, the increased pause time in spontaneous speech is thought to reflect additional time for message formulation and cognitive-linguistic processing (Rochester, 1971; Walker, 1988). Therefore, some researchers may assume that spontaneous speech is more demanding than reading aloud and more susceptible to reduced performance in patients with other neurodegenerative diseases. It is also possible that variation in task types (i.e., reading length or complexity) may differ in terms of cognitive demand. Ultimately, it is likely that the combination of cognitive and motor deficits experienced by an individual with degenerative disease could lead to unique challenges for each specific connected speech task.

Similar to tasks used to assess motor speech disorders, tasks used to assess cognitive functioning may also vary in the level of demand placed upon extraneous skills (i.e., language, motor speech). For example, certain cognitive tasks rely upon rapid spoken response (Arnett et al., 2008; Kent et al., 1987; M. M. Smith & Arnett, 2007) , such as verbal fluency tasks and the oral version of timed tasks such as the symbol digit modalities test. Reduced performance on these tasks in the MS population has been associated with increased perceived severity of dysarthria (M. M. Smith & Arnett, 2007) and reduced syllable repetition rate (Kent et al., 1987). If motor speech performance is impaired, it is more likely that decreased speech rate may be a confound in interpreting performance on cognitive measures that require timed speech production. Similarly, studies that have examined cognition using language-based tasks only (MacKenzie & Green, 2009) with comparisons to motor speech performance must be interpreted in relation to the individual's language ability. It may be less linguistically taxing to name pictures or describe cartoon sequences than to generate unfamiliar narratives without visuals to aid in language retrieval/production. The same may be true for motor speech tasks as some involve greater cognitive-linguistic demands than others. Considering the heterogeneity of task performance reported above, it is important to include tasks eliciting speech production at varying levels of cognitive-linguistic demand such as syllable repetition tasks, a variety of reading-based tasks, and/or narrative or monologue elicitation tasks when possible.

The Impact of Cognitive Demands on Articulatory Performance

To better understand the relationship between motor speech and cognition in degenerative disease, it is important to determine how these processes interact in neurotypical individuals. Speech kinematic performance has been shown to be impacted by cognitive-linguistic functioning throughout typical child development and on tasks that require increased cognitive-linguistic load in adults (Dromey & Bates, 2005; Dromey & Benson, 2003; Maner et al., 2014; Sadagopan & Smith, 2008). For example, the speech motor performance of children has been found to decrease relative to the linguistic complexity of task (e.g., utterance length) (Maner et al., 2014; Sadagopan & Smith, 2008), and speech rate increases with age due to decreased pausing and increased efficiency of articulatory movements (Nip & Green, 2013). This suggests that the capacity for higher level cognitive-linguistic functioning may play a role in increased rate of speech production in typical development. This suspected interaction of motor speech control and cognitive-linguistic ability is also found for adults under dual-task conditions (e.g., speaking while performing a fine motor or cognitive task) and with increased linguistic complexity (Dromey & Bates, 2005; Dromey & Benson, 2003). These changes in kinematic performance observed with competing, dual-task, demands support the theory that motor planning in healthy adults may be impacted to some degree by cognitive load. Though not specifically focused on cognition, all of the kinematic studies above support the idea that greater task complexity, and likely greater processing demands, influence motor speech production. This viewpoint is not unique to motor speech dysfunction as resource allocation (i.e., cognitive skill; particularly attention) has been suggested to negatively influence language functioning in aphasia (McNeil et al., 1991). Therefore, it is possible to speculate that speech motor control may be impacted negatively if normal cognitive-linguistic abilities are diminished due to progressive neurological disease.

Speech Timing in Neurological Disorders

Similar to the kinematic literature reviewed above, acoustic measures of global speech timing (i.e., syllable repetition duration, articulation rate, speech rate, pause variables) may be influenced by the interaction between motor speech performance and cognitive functioning in acquired (Y. T. Wang et al., 2004, 2005) or degenerative (Arnett et al., 2008; Chan et al., 2022; Feenaughty et al., 2013; Huber & Darling, 2011; Lowit et al., 2006; MacKenzie & Green, 2009; Noffs et al., 2018; Östberg et al., 2009; Rodgers et al., 2013; M. M. Smith & Arnett, 2007) neurological disorders. In chronic dysarthria secondary to traumatic brain injury (TBI); a disorder which commonly coincides with cognitive impairment (Y. T. Wang et al., 2004, 2005), cognition has been suggested to exacerbate the already slowed articulatory movements stemming from underlying dysarthria. Patients with TBI were shown to have lengthened syllable durations resulting in reduced rate on AMRs and reduced speech rate (in syllables per second) and articulation rate (in syllables per second excluding pauses) during sentence production tasks. Further, those with more severe TBI were found to have the highest percentage of pause time and reduced ability to alter speech and articulation rate (i.e., change rate from habitual to fast or slow). One possible explanation for the reduction in performance on rate measures is that patients with TBI had difficulty initiating and coordinating speech movement due to motor dysfunction. However, the changes in speech rate, in particular, may also indicate increased pausing which can result from higher-level cognitive impairment (Y. T. Wang et al., 2005). Unfortunately, this study did not directly test or report the cognitive performance of the participants, but the authors proposed that cognitive impairments could be at least partially responsible for the reduced rate in this population. Therefore, it is possible that individuals with other diagnoses associated with cognitive dysfunction may also present with impairments of speech timing that are not solely due to dysarthria.

In neurodegenerative conditions, additional evidence for the interaction of motor speech and cognitive functioning in speech production exists with more systematic testing of cognition relative to performance on speech timing measures. An early study included patients with PD and MCI (Lowit et al., 2006) separated into high and low cognitive groups using the Addenbrooke's Cognitive Examination (Mathuranath et al., 2000). Measures of speech timing were examined for recorded reading tasks at the paragraph and sentence levels (e.g., articulation rate in syllables per second, articulation to pause time ratio, and ability to alter rate of articulation). Overall, the group with PD had a similar articulation rate to the control sample while those with MCI were found to be slower (Lowit et al., 2006). One exception is that the group with PD had faster rate in the slow reading condition. The finding of slowed speaking rate in the MCI group is consistent with previous reports of reduced syllable repetition rate for patients with mild dementia but no dysarthria on a task of low cognitive-linguistic demand (Östberg et al., 2009) potentially reflecting the influence of normal aging. Although seemingly unimpaired in articulation rate, pause time was greatest in the group with PD (Lowit et al., 2006). This might suggest that patients with PD had similar rate of actual speech movements but required additional time to pause and process their message. All groups reflected an ability to alter articulation rate but to varying degrees. Those with PD and MCI had more difficulty both increasing and decreasing speed compared to the control group with the amount of change in articulation rate greater for those with PD than MCI across conditions (Lowit et al., 2006). As the group with MCI, but no dysarthria, was more impaired than the group with PD in multiple variables of speech timing, the authors suggest factors beyond motor control (i.e., age and cognition) influenced the durations of pause times and the ability to manipulate rate (Lowit et al., 2006). Significant speech timing differences between high and low cognitive groups within each population were not found, although this may be due to the fact that the groups were created using a limited screening tool with an arbitrary cutoff value. Results revealed significant positive correlations between performance on speech variables and measures of cognition, which suggests speech timing may be impacted to a greater degree by cognition beyond the influence of participant age (Lowit et al., 2006). With the potential influence of cognitive ability on measures of speech timing in individuals with and without overt motor speech impairment, it is likely that it also mediates speech timing in other unstudied populations that experience co-occurring motor and cognitive decline.

A more recent study (Chan et al., 2022) found a similar relationship between habitual rate measures and performance on the Symbol Digit Modalities Test (SDMT) for a cohort of participants with pre-manifest and early HD. While the emphasis of this study compared perceived motor speech impairment to acoustic analyses, a select set of speech timing measures on reading and monologue tasks were found to be correlated with SDMT score. Specifically, they identified that a decline in speech rate on the paragraph-level reading task was associated with lower score (i.e., greater cognitive impairment) on the SDMT (Chan et al., 2022). Further, an increase in SDMT score was associated with a decrease in the percent of silent time during a monologue task (Chan et al., 2022), further suggesting the importance of pausing behavior and its association with cognitive ability. Although a valuable first link of speech timing and cognition in HD, these findings are limited as the control sample did not complete cognitive testing and the researchers examined different speech timing measures across tasks, limiting the ability to explore task-related differences.

Further evidence suggests that the variability in reported patient performance on measures of speech timing (e.g., speech rate, articulation rate) across tasks may be a direct result of differing task demands (Feenaughty et al., 2013; Rodgers et al., 2013). Feenaughty and colleagues (2013) found that speech rate and pause characteristics differed across tasks with generally faster articulation rate and slower speech rate during the narrative condition compared to reading regardless of cognitive status (Feenaughty et al., 2013). It was observed that additional pause time during the narrative led to slower speech rate compared to reading aloud (Feenaughty et al., 2013). Similarly, Rodgers and colleagues (2013) found that patients with MS had significantly slower speech rate and articulation rate for the reading passage but only significantly slower speech rate for the narrative compared to neurotypical controls.

In addition, both studies highlight the impact of the degree of cognitive dysfunction on participant performance on measures of speech timing in MS (Feenaughty et al., 2013; Rodgers et al., 2013). Feenaughty and colleagues (2013) separated participants into low- and high-cognitive status groups based on neuropsychological testing. Patients in the low-cognitive status group had overall slower speech rate than other groups despite similar severity of dysarthria. However, nonsignificant task by group interactions occurred. The authors propose that there may be greater than anticipated cognitive-linguistic load associated with reading aloud for patients with MS, and that topic familiarity may have reduced the demands for self-generated speech; particularly for the low cognitive group (Feenaughty et al., 2013). While Rodgers and colleagues (2013) did not separate participants by cognitive status, they found that an information processing speed composite score (including scores from the oral form of Symbol Digit Modalities Test, Paced Auditory Serial Addition Test) was the strongest predictor of rate related measures. As the patients were all intelligible, they concluded that cognition (e.g., degree of processing speed deficit) was likely driving slow rate rather than motor impairment alone (Rodgers et al., 2013). Beyond interpretations of task complexity, Feenaughty and colleagues (2013) suggest that compensatory behavior for reduced processing speed, poor motor planning, or word retrieval might explain the longer silent pauses on the narrative task (Feenaughty et al., 2013). Changes in speech rate as a compensatory strategy is not unique to this study, as work with aging adults reported the possibility of slowed speech to compensate for reduced articulatory control (Mefferd & Corder, 2014). It is possible that some of the heterogeneity of speech rate in HD or PD also reflects a compensatory mechanism, reduced processing speed, or general decline of motoric functioning.

Modification of Speech Timing

In addition to performance on speech tasks using habitual rate, assessing ability to modify rate in both directions (i.e., speak faster or slower) may be crucial to determine what volitional control patients have when habitual speech is abnormal. Ability to modify speaking rate has been studied in neurotypical individuals (Goozée et al., 2003; Mefferd & Green, 2010) and has also been found to be impaired to some degree in people with motor speech disorders resulting from neurological conditions (i.e., TBI, PD, MS, ALS) (Hammen & Yorkston, 1996; Lowit et al., 2006; Tjaden et al., 2014; Tjaden & Wilding, 2011, 2004; Turner & Weismer, 1993; Van Nuffelen et al., 2009, 2010; Weismer et al., 2000; K. M. Yorkston et al., 1990). These studies typically involve completion of a syllable repetition or reading task at habitual (e.g., typical rate), fast (i.e., twice as fast as habitual), or slow (half of habitual) rates. The purpose is to then calculate an index of rate change from the habitual condition (i.e., percent change; statistical comparisons between habitual and fast/slow rates). While these tasks have been studied for decades, there has been little consistency in condition or task selection to elicit speech. For example, some investigate the reduced rate condition and do not assess ability to increase speaking rate voluntarily (Tjaden & Wilding, 2011) or vice versa (Goozée et al., 2003; Tjaden & Wilding, 2004; Weismer et al., 2000). Unfortunately, patients with detectable cognitive impairments are often excluded with only one known study concluding that cognitive deficits might impact findings in TBI (Y. T. Wang et al., 2004, 2005). As cognition likely plays a role in habitual speech timing, it may also impact modification of rate. For example, if habitual speech rate is reduced, but individuals are capable of increasing their rate, they may be compensating for motor or cognitive impairments by voluntarily slowing their speech rate. Thus, it is essential that we examine the ability to voluntarily manipulate rate if we are to accurately interpret the impact of findings for populations with co-occurring cognitive and motor deficits.

For individuals with dysarthria, findings on rate modification have yielded mixed results. In ALS, a population with marked reductions in speaking rate, patients can increase rate, although to a lesser degree than control participants in both habitual and fast rate conditions (Turner & Weismer, 1993; Weismer et al., 2000). The ability to increase rate when instructed to do so may suggest that individuals with ALS reduce rate as a compensatory strategy as faster habitual rate may not be sustainable due to fatigue inherent in ALS. Yet, other researchers found that individuals with ALS have limited ability to reduce rate but increase speech rate by decreasing pause time rather than decreasing articulation rate (Turner & Weismer, 1993). Given cognitive decline is less severe in ALS compared to other neurodegenerative conditions, it is likely that these individuals with ALS speak slowly due to motor speech abnormalities, but they may also use internal strategies to further reduce rate in an attempt to compensate for these motor changes.

It is less understood how cognitive impairment might impact modulation of speech rate or compensatory strategies in individuals with dysarthria. In neurodegenerative conditions that result in cognitive decline, researchers found that patients with dysarthria secondary to PD, patients with MCI, and neurotypical controls could increase and decrease articulation rate but to varying degrees (Lowit et al., 2006). Control participants demonstrated the greatest amount of change (significantly greater than MCI and PD) while the group with MCI had the least amount of change across conditions (Lowit et al., 2006). The performance of the group with PD is consistent with other findings that speakers with dysarthria can alter speech or articulation rate but to a lesser degree than controls and generally slower during each condition (Hammen & Yorkston, 1996; Tjaden & Wilding, 2011, 2004; Turner & Weismer, 1993). The fact that individuals with MCI (in the absence of dysarthria) had reduced ability to modify articulation rate suggests that cognitive dysfunction may influence performance (Lowit et al., 2006). Given individuals with HD or PD may present with co-occurring cognitive deficits, the reduced ability to alter rate may not be entirely due to the presence of dysarthria.

Studying patient's volitional control of speech rate also holds direct clinical importance to determine stimulability for rate control strategies to compensate for dysarthria. Reduced speaking rate is commonly used as a compensatory strategy to improve communicative effectiveness of patients with various motor speech disorders but this is relatively unexplored in populations with inherent motor and cognitive deficits. There is evidence that decreasing speech rate using pacing strategies results in improved intelligibility in at least some individuals with dysarthria (Van Nuffelen et al., 2009, 2010; K. M. Yorkston et al., 1990). It is possible that the lack of consensus for improved intelligibility across all patients could be a potential effect of differing methods to measure intelligibility. However, none of these studies quantified cognitive ability, which might also drive differences in volitional control of rate. The use of rate control strategies (i.e., pacing board) may be more difficult with significant cognitive dysfunction. For example, if reducing speech rate is a compensatory strategy, it is possible that impairments in self-monitoring, disinhibition, memory, or awareness of performance might lead to reduced ability to modulate one's speech rate to an optimal level to compensate for their motor impairment (reduced intelligibility).

Review of Basal Ganglia Disorders

As previously stated, studying the speech of individuals with degenerative neurological conditions may provide an opportunity to parse the relative contributions of motor function and cognitive function to changes in speech timing measures. In particular, studying individuals with basal ganglia disorders, such as Huntington's disease (HD) and Parkinson's disease (PD), may be beneficial, because both share a common site for primary neurodegeneration, and typically involve some degree of cognitive and motor impairment. Speech production, and particularly speech timing (speech rate, pause times) can be affected in similar ways.

This motor speech dysfunction is unsurprising given that the basal ganglia is a crucial region for motor functioning. The type of motor speech impairment will vary based on the influence of each disease on basal ganglia function with HD resulting in what we typically consider a hyperkinetic dysarthria and with PD resulting in a hypokinetic dysarthria. Interestingly, speech timing may vary tremendously across patients with HD or PD. Despite characteristically different motor speech presentations in HD and PD, perceptual and acoustic evidence exists describing rate characteristics as fast, variable, or slow in individuals with each disease with different dysarthria types. In fact, this variability may explain why some patients with HD and PD have been grouped together in a free classification study of speech perceptual features (Lansford et al., 2014).

In addition to the varied speech rate characteristics, both diagnoses may be accompanied by decline in cognitive skills. This cognitive decline is likely related to degeneration of frontostriatal pathways and subsequent inefficiency of this supportive cognitive network for individuals with HD (Dominguez et al., 2017; Watkins et al., 2000; Wolf et al., 2008) and PD(Lewis et al., 2003; Zgaljardic et al., 2003). In addition, patients with PD and mild cognitive dysfunction have been shown to have hippocampal degeneration (Weintraub et al., 2011). This may also impair select cognitive functions such as memory encoding and storage. It is possible that some of the heterogeneity reported in speaking rate of these groups is partially due to an integration of cognitive decline and motoric functioning. Below, detailed information is provided for each diagnosis of interest.

Huntington's disease. HD is a neurodegenerative disorder that is typically characterized by chorea, cognitive decline, and psychiatric changes (McClogan & Tabrizi, 2018). Although disease progression primarily involves degeneration of medium spiny neurons in the striatum of the basal ganglia, cerebellar atrophy and cerebral white matter degeneration have also been reported (Fennema-Notestine et al., 2004; Rodda, 1981). Basal ganglia damage is primarily associated with motor functioning but also leads to the disruption of multiple functional networks within the brain (e.g., frontostriatal networks supporting cognition). Dysarthric speech is a common clinical symptom presenting in 93% of individuals (Rusz et al., 2014) and referred to as 'hyperkinetic' in nature. The classic description of hyperkinetic dysarthria includes speech with variable rate, prolonged intervals, inappropriate silences, reduced pitch variability, irregular and imprecise articulation, phonatory deviations, and sudden forced inspiration or expiration (Darley et al., 1969; J. Duffy, 2013). However, recent research suggests that motor speech patterns in HD are more diverse than originally reported. Specifically, two related studies of dysarthria in patients with HD and mild to moderate dysarthria found distinct speaker groups that were differentiated, in part, based on speaking rate (Diehl et al., 2019; Kim et al., 2022). Groups were perceived to have abnormally slow, fast, and normal speaking rate(Diehl et al., 2019). These differences were based solely on perceptual ratings, as measured by the Mayo Clinic dysarthria rating scale (Darley et al., 1969). This variability in motor speech presentation may explain why the dysarthria profiles of individuals with HD are not always distinct from those of individuals with other neurological conditions (e.g., PD, cerebellar ataxia) based upon speech perceptual characteristics (Lansford et al., 2014).

As previously mentioned, HD influences the frontostriatal networks that support cognition, and, thus, most individuals with HD present with cognitive decline. In fact, cognitive decline, which is reflected in difficulty multi-tasking, decreased processing speed, and executive dysfunction, may begin up to ten years prior to clinical diagnosis in genetically confirmed HD (Papoutsi et al., 2014). This means that patients who are not yet experiencing obvious limb motor deficits may have detectable cognitive dysfunction. With disease progression, patients with HD often experience difficulty with new learning, delayed recall, abstraction, concentration (Zakzanis, 1998), attention (e.g., sustained, divided, alternating), cognitive flexibility (Ho et al., 2003; Pringsheim et al., 2012; Sprengelmeyer et al., 1995), immediate memory, lexical retrieval, processing speed, and with psychomotor tasks (e.g., Trails A, Stroop task, Symbol digit modalities)(Ho et al., 2003). Working memory (Lahr et al., 2018; Stout et al., 2011; You et al., 2014) dysfunction has also been reported due to the suspected role of the basal ganglia and decline in frontostriatal circuits to support effective functioning. Additionally, executive function impairments, or difficulty with skills such as flexibility, planning, organization, and self-monitoring have been reported (Ho et al., 2003; Holl et al., 2013; Lawrence et al., 1996). Individuals with HD have demonstrated impaired verbal fluency task performance (e.g., search, retrieval, word generation, self-monitoring) but typical performance on a risky decision-making task compared to neuro-typical adults (Holl et al., 2013). Similarly, individuals with early symptoms of HD had significant impairment in planning tasks but unimpaired performance on a decision-making task compared to controls (Watkins et al., 2000). These reports across the spectrum of disease severity suggest that subtle cognitive changes exist which might impact skills to support effective motor speech control.

One study attempted to reduce the heterogeneity of their cohort with HD by examining speech profiles of choreatic versus bradykinetic subgroups, with the idea that differences in motor presentation would be reflected in speech characteristics (Skodda et al., 2014). Overall, results indicated that patients with HD, overall, had reduced speech rate and increased pausing relative to controls. Those with the bradykinetic profile had reduced articulatory velocity, increased pause length, and more imprecise syllable repetition compared to the choreatic group. The bradykinetic group also tended to have lower cognitive scores (indicating greater severity) than the choreatic group (Skodda et al., 2014). Thus, both motor and cognitive changes may have contributed to the slower speech rate, although it is also possible that individuals in the bradykinetic group experienced greater disease severity at the time of the study. These deficits in speech timing of the bradykinetic profile are relatively consistent with Rusz and colleagues' report of reduced speech rate, fewer pauses, and prolonged intervals that increased the patients' speech to pause ratio (Rusz et al., 2014). The authors believe that motor and cognitive systems contributed to the changes in speech timing (Rusz et al., 2014), and reflect the widespread neurodegeneration which occurs in HD and the disruption of frontostriatal networks(Bohanna et al., 2011; Fennema-Notestine et al., 2004; Jech et al., 2007; Rodda, 1981). Only one study, previously mentioned, has specifically examined the influence of motor function and cognitive function on speech production in HD and found some positive correlations between measures related to habitual speech timing and cognitive ability as measured by the SDMT (Chan et al., 2022).

Parkinson's disease. PD is a progressive disorder that occurs in 1-2% of adults over 55 years in age with an average disease duration of 15 years (Jang et al., 2009). Symptoms of PD manifest due to a loss of neurons in the substantia nigra which leads to a reduction in motor signal (e.g., reduced dopamine) to the striatum. Overall movement becomes slowed and reduced in amplitude as a result. Specific limb motor abnormalities include resting tremor, rigidity, bradykinesia, reduced postural reflexes, flexed posture, and freezing (Hoehn & Yahr, 1967; Jankovic, 2008). Non-speech oral movement abnormalities are also reported with tremor observed in the jaw, lips, or tongue (Jankovic, 2008). Directly impacting speech, hypokinetic dysarthria presents in almost 90% of patients (Muller et al., 2001) with abnormalities in phonatory, prosodic, and articulatory features of speech production (e.g., monopitch, reduced stress, monoloudness, imprecise consonants, inappropriate silences, short rushes of speech, harsh or breathy voice, low pitch, variable rate, increased rate in segments, increased rate overall, and repeated phonemes) (Darley et al., 1969; J. R. Duffy, 2013). Consistent with kinematic evidence for limb, tongue, and jaw movements, as motor movements supporting speech become reduced in amplitude, the movement has a shorter duration (Munhall et al., 1985; Ostry et al., 1983; Ostry & Munhall, 1985) leading to changes such as possible perceived increased rate of speech(Darley et al., 1969; J. R. Duffy, 2013). However, discrepancies related to speaking rate are apparent in the literature for PD with some studies suggesting faster speech rate (Darley et al., 1969; Metter & Hanson, 1986; Netsell et al., 1975) and others reporting normal (Ludlow et al., 1987; Metter & Hanson, 1986; Skodda & Schlegel, 2008), or reduced (Ludlow et al., 1987; Metter & Hanson, 1986; Weismer et al., 2001) rate across patients. Further, ability to alter speech rate at the sentence or phrase level (i.e., from habitual to fast or slow) may be impaired in degree of change in PD compared to controls (Ludlow et al., 1987; Tjaden & Wilding, 2011). Others identified varied performance altering rate with and without external cues (Ackermann et al., 1997). Reduced voluntary control of speech musculature may be associated with the rate abnormalities in this population but limited evidence exists describing possible factors driving these within population differences. Some researchers suggest cognitive factors(Lowit et al., 2006) or pharmaceutical influences (De Letter et al., 2006) may be contributing to the heterogeneity of speech rate but additional research is needed to substantiate these claims.

Aside from motor dysfunction, patients with PD may also present with cognitive impairment as reduced dopamine in the striatum leads to degeneration and inefficiency of frontostriatal pathways. Typically, mild cognitive impairment may be evident early in the disease with more prominent deficits developing later. However, the report of cognitive dysfunction to warrant a dementia diagnosis in PD varies from 15% to 31% of patients (Aarsland et al., 2005; Hanagasi et al., 2017). However, longitudinal research suggests that 47% of patients with PD developed MCI in 2-6 years and progressed to dementia within 5 subsequent years(Pigott et al., 2015). Similar to HD, specific deficits are diverse but may include impaired learning and memory, processing speed, spatial working memory, divided attention (Cholerton et al., 2019), impulsivity (Canário et al., 2019), and disinhibition. Further, executive function, visuospatial skills, and memory with increased level of cognitive impairment associated with reduced life expectancy (Levy, Tang, et al., 2002). Researchers have suggested that processing speed may be particularly vulnerable in early PD due to inefficient dopaminergic pathways between the striatum and prefrontal cortex (Cholerton et al., 2019). Although these impairments may vary across patients, processing speed in particular appears to be particularly sensitive to discriminate between patients with PD and neurotypical controls. Therefore, as speculated with HD, it is possible that some of the heterogeneity in speech rate among individuals in the PD population stems from underlying cognitive impairment and warrants further exploration.

Purpose and Research Questions

Investigating the interaction of motor speech and cognitive symptoms is important to guide clinical services for patients with HD and PD. Both populations have great variability in reports of speech timing, and both experience motor and cognitive dysfunction as a result of basal ganglia degeneration. Early detection of these changes in speech production and the ability to reliably monitor disease progression is imperative to provide appropriate SLP services for these individuals. The relationship between cognition and motor functioning in speech production has not been fully described in existing literature, but it is possible that the aforementioned cognitive impairments characteristic of these disorders might interfere with typical motor speech processes. For example, impairments in self-monitoring, disinhibition, or awareness of performance might lead to reduced ability to modulate one's speech rate to an optimal level to compensate for their motor impairment (reduced intelligibility). Alternatively, people who have difficulty with lexical retrieval or reduced processing speed may have increased pausing to formulate their intended message; thus reducing overall speech rate. These explanations seem reasonable as extended pause durations are related to processing speed in mild motor speech disorders (Ho et al., 2003; Papoutsi et al., 2014) and might explain patients' need for additional time in conversation (Hartelius et al., 2010). In line with other literature of this interaction in degenerative disease, reduced processing speed, specifically, was the only cognitive skill suggested to relate to the reduced level of speech timing, thus far (Feenaughty et al., 2014; Rodgers et al., 2013). It is possible that the reduced processing speed in HD (Ho et al., 2003; Papoutsi et al., 2014) and PD may also impact speech timing, but further research is needed to determine whether alternative skills (i.e., other domains of cognition) are influential as well. To my knowledge, only one study included consideration of cognitive ability related to motor speech performance in HD with limited findings (Chan et al., 2022). The proposed study will investigate the interaction of cognitive and motor speech impairments related to speech timing in HD and PD. By gaining a better understanding of this interaction and how it might compare across this spectrum of hyperkinetic to hypokinetic basal ganglia dysfunction we might further our ability to develop appropriate patient centered services for these populations.

The following research questions will be addressed:

<u>Research Question 1:</u>

1a. How is habitual speech timing (e.g., articulation rate, speech rate, mean pause length) influenced by speech task (e.g., sentence reading, paragraph reading) and participant group (e.g., HD versus HCNC, PD versus PDNC)?

1b. Is there a relationship between habitual speech timing (e.g., articulation rate, speech rate, mean pause length) and performance on the SDMT within groups (e.g., HD, PD, All Control)?

<u>Hypothesis 1</u>: I hypothesize that speech timing is associated with motor and cognitive ability, and thus is impacted by neurological disorders impacting motor and cognitive functioning. Further, I hypothesize that habitual speech timing is impacted by the cognitive demands of a task and processing speed is an important cognitive construct that is predictive of performance on speech timing measures.

I predict that all groups will show variability in speech timing with decreased performance on tasks suspected of greater cognitive linguistic demand (i.e., paragraph-level reading) and that measures of speech timing will be more impaired in the neurological populations compared to control participants. Measures of speech timing with consideration for pausing behavior (i.e., speech rate, articulation rate) will likely be affected to the greatest extent for participants with HD due to the earlier onset of cognitive decline. I predict that articulation time of participants with HD and PD will be similar or reduced compared to neurotypical controls across all tasks. Reduced performance on processing speed will be shown to the greatest extent in HD and PD and lead to reduced speech rate and increased mean pause length on tasks of higher cognitive-linguistic demand (i.e., paragraph-level reading).

Contrary to my hypothesis, if groups do not vary in performance across tasks, this might indicate that the cognitive-linguistic demands of the selected tasks are more comparable than anticipated. If measures of speech timing that account for pausing behavior are not impacted to the greatest extent for participants with HD, it is possible that our participants with PD are more cognitively impaired than anticipated or that even subtle cognitive impairments impact pausing behavior. If reduced performance on processing speed is not associated with reduced speech rate or mean pause length, this might suggest that motor deficits impact task differences in speech timing greater than cognitive deficits or that a different underlying cognitive construct (i.e., memory, executive functioning) is important to support speech timing.

<u>Research Question 2:</u>

2a. How is ability to modify speech timing (e.g., change in articulation rate, change in speech rate, change in mean pause length) from habitual rate to fast or slow rate influenced by speech task (e.g., sentence or paragraph reading) and participant group (e.g., HD versus HDNC, PD versus PDNC)?

2b. Is there a relationship between change in speech timing measures (e.g., change in articulation rate, change in speech rate, change in mean pause length) from habitual rate to fast or slow rate and performance on the SDMT within groups (e.g., HD, PD, All Control)?

Hypothesis 2: I hypothesize that ability to modify speech timing is associated with motor and cognitive ability, and thus is impacted by neurological disorders impacting motor and cognitive functioning. Further, I hypothesize that modification of speech timing is impacted by the cognitive demands of a task and processing speed is an important cognitive construct that is predictive of the degree of change in speech timing.

I predict that participants with HD and PD will show ability to alter speaking rate among conditions but to a lesser degree than neurotypical controls. I also predict that participants with HD and PD will have greater difficulty manipulating rate on the passage reading task over the sentence reading task compared to neurotypical controls. Reduced processing speed will be associated with decreased ability to modify rate.

Alternative to my hypothesis, if participants with HD and PD do not differ in ability to modify rate compared to controls this suggests that cognitive and/or motor speech impairment do not impact ability to change rate within our cohort. If performance for participant groups does not differ between tasks, this suggests comparable demands for altering speech timing between short, sentence reading, and longer paragraph tasks. If reduced processing speed is not associated with decreased ability to modify rate, this would suggest that motor control alone drives performance or that a differing underlying cognitive construct is important for ability to modify rate.

CHAPTER II

METHODS

Participants

Participants included 27 individuals with Huntington's disease, 21 individuals with Parkinson's disease, and 37 matched, neurotypical control participants. A total of 21 of the neurotypical controls were assigned to the HD control group (HDNC) while 16 were assigned to the PD control group (PDNC). All participants were recruited from the Vanderbilt University Medical Center Huntington's Disease Center of Excellence and Parkinson's disease clinics as well as the greater Nashville region. Detailed information regarding participant inclusion/exclusion criteria is provided below.

Participants with HD and PD. All participants with HD and PD were diagnosed by a board-certified neurologist and those with HD also had record of genetic testing confirming the mutation responsible for HD. Participants were required to be native English speakers due to potential differences in speech timing across languages (Ben-David & Icht, 2017) and be a minimum of 18 years old at the time of recruitment. Participants with HD had perceivable dysarthria as indicated by a Unified Huntington's Disease Rating Scale (UHDRS) (Huntington Study Group, 1996) motor examination dysarthria rating greater than or equal to 1 (1 = "unclear, no need to repeat"). Participants with PD presented with perceivable dysarthria as indicated by a Unified Parkinson's Disease Rating Scale (UPDRS) (Goetz et al., 2008) motor examination speech rating greater than or equal to 1 (1= "slight: Loss of modulation, dictation, or volume, but still all words easy to understand"). Dysarthria was a required symptom for inclusion but all participants had to score within a range of 80% to 100% intelligible on the Sentence

Intelligibility Test (SIT) (K. M. Yorkston & Beukelman, 1996). The intelligibility range was specified to control for potential influences of speech severity when transcribing speech samples and in the interpretation of results (Feenaughty et al., 2013; Rodgers et al., 2013). These recordings were orthographically transcribed by three graduate speech-language pathology students, compared to the sentence key, and an average percent intelligibility was calculated. All participants passed a pure tone audiometric hearing screening with bilateral pure tone thresholds of at least 40 dB at 500 Hz and 1-4 KHz and self-report normal or corrected vision. To reduce the impact of overt language impairments on the comprehension or completion of study tasks and interpretation of results, all participants completed the Quick Aphasia Battery (QAB) (Wilson et al., 2018) with HD and PD participants achieving an overall score greater than 8.0/10.0 while ignoring dysarthric errors.

Exclusionary criteria for participants with HD and PD included (1) the presence of comorbid neurological disorders or sensory impairments that might interfere with study tasks, (2) a level of physical or neurological impairment that would invalidate cognitive and/or language testing, and (3) severe anxiety or depression requiring hospitalization in the past six months or resulting in inability to engage in study tasks.

Neurotypical control participants. Healthy neurotypical control participants were matched pair-wise to patients with HD and PD on age (+ or – 5 years), sex, handedness, and education (+ or – 2 years). Neurotypical control participants followed the same inclusionary and exclusionary criteria aside from those related to the diagnosis and symptoms of HD or PD. Control participants were required to score 8.9/10.0 or greater on the QAB for inclusion.

In addition, control participants were excluded by self-reported learning disabilities, psychiatric diagnoses, use of antipsychotics, and a depression score greater than 7 on the

Hospital Anxiety and Depression Scale (HADS) (Zigmond & Snaith, 1983). The HADS is a 14-item measure on which participants rate each item on a 3-point scale (0= no problem to 3= severe problem). The score requirement on the HADS serves to reduce the influence of significant anxiety or depression on participant performance as these symptoms may interfere with performance on speech production tasks (Cannizzaro et al., 2004; Yi et al., 2019). These variables would not be appropriate exclusionary criteria for patients with HD and PD due to the high prevalence of report or of use in the HD and PD populations (Bonelli & Hofmann, 2007; Gotham et al., 1986; Rosenblatt & Leroi, 2000; Zhang et al., 2011).

Demographic and Clinical Questionnaire

All participants with HD and PD and controls completed a screening and demographic questionnaire specific to the participant group (see Appendix A) at the start of the research session. This questionnaire was used to gather information related to study inclusion and, if applicable, disease status. The information was obtained through retrieval of patient medical records or self-report. Consideration of demographic variables are important as research suggests differences in speech timing related to normal aging (Amerman & Parnell, 1990; Ramig, 1983). In addition to information related to the inclusion/exclusion criteria previously described, disease status, education level, and other demographic information necessary for matching with neurotypical controls will be collected.

Patient medications (e.g., class, dosage, duration of use) used to treat disease symptoms are of particular interest due to evidence suggesting possible influences on the motor speech performance of some patients. While the influence of vesicular monoamine transporter-2 (VMAT-2) use has not been investigated as extensively, atypical antipsychotic use has been shown to impact limb motor and speech production (Caligiuri et al., 2009, 2010; Rusz et al., 2014) and dopamine agonists (i.e., carbidopa-levodopa) are suggested to impact speech production to varying degrees (De Letter et al., 2005; De Letter, Santens, De Bodt, et al., 2007; De Letter, Santens, Estercam, et al., 2007; Im et al., 2019; Louis, 2001; Rusz et al., 2016; Spencer et al., 2009). For all patients with HD and PD, use and dosage of VMAT-2 inhibitors, atypical antipsychotics, and dopamine agonists was documented. As these variables are part of the symptom presentation or treatment of HD and PD, excluding these patients would not be representative of the clinical populations.

Characterization of Participant Disease Severity

Participants with HD and PD completed disease specific measures to determine disease severity to better characterize participant groups. Disease severity in HD was measured using the UHDRS motor assessment dysarthria rating and total functional capacity scale (TFC) (Huntington Study Group, 1996). For patients with PD, disease severity was recorded using the UPDRS motor examination dysarthria rating and Hoehn and Yahr scale (Goetz et al., 2008; Hoehn & Yahr, 1967). A description of each measure is provided below.

UHDRS Motor Assessment dysarthria rating: The UHDRS motor assessment is a commonly used clinical tool to measure the severity of movement abnormalities in patients with HD. It is comprised of standardized ratings for symptoms of oculomotor dysfunction, dysarthria, chorea, dystonia, gait abnormalities, and postural instability (Huntington Study Group, 1996). A total motor score can be calculated by calculating the sum of the scores in the above areas. Lower scores indicate lower motor impairment while higher scores indicate more severe motor impairment. The UHDRS Motor Assessment includes a rating scale to evaluate severity of dysarthria and this subcomponent was utilized to determine participant inclusion.

UHDRS TFC. The TFC is used to determine the functional impact of disease symptoms in HD across five domains: (1) occupation, (2) finances, (3) domestic chores, (4) activities of daily living, and (5) care level (Huntington Study Group, 1996). The sum of the domain ratings is reported as the individual's Total Functional Capacity Score. A higher score indicates a greater level of impairment in functional ability.

UPDRS Part III- Motor Examination dysarthria rating. The UPDRS motor examination is a widely used clinical tool to measure the severity of movement abnormalities in patients with PD (Goetz et al., 2008). It is comprised of standardized ratings for speech, facial expression, rigidity, movement of limbs, gait, postural stability, and tremor. The measure includes a total of 33 items that are rated on a 5-point scale (0= "Normal", 1= "slight", 2= "Mild", 3= "Moderate", and 4= "Severe" level of impairment). An individual's total motor score is reported as the sum of assigned ratings for the 33 items. The rating for dysarthria severity is of particular interest to the present study and was used to determine study inclusion. However, the remaining items of the motor exam were not completed.

Hoehn and Yahr Scale. The Hohen and Yahr Scale (Hoehn & Yahr, 1967) is often administered with the UPDRS in order to characterize severity or stage of progression in PD. The stages range from 1 (least severe) to 5 (most severe). A stage is selected by observable motor symptoms and functional ability.

Cognitive Task

The Symbol Digit Modalities Test (SDMT) was completed by all participants to measure attention and processing speed as processing speed is of primary interest in the present study (Cholerton et al., 2019; Ho et al., 2003; Papoutsi et al., 2014). To complete the task, individuals used a predefined code to substitute numbers for as many randomly ordered geometric figures as possible within a 90-second time limit (A. Smith, 1968, 1973, 1982). The number of correct oral and written responses will be recorded. Higher scores on the SDMT suggests an increased level of processing speed and attention switching.

Experimental Speech Tasks

All speech tasks were recorded with a mouth-to-microphone distance of approximately 6 inches using an omnidirectional condenser microphone (Audiotechnica AT899) and digital recorder (Tascam DR40) with the sampling rate set to 44.1 kHz and the quantization level set to 16 bits. Detailed descriptions of these tasks are provided below.

Connected speech tasks. Connected speech tasks for the present research questions included reading aloud at the sentence level and the paragraph level. Other connected speech tasks were collected to be utilized for future research projects (i.e., picture sequence descriptions, and self-generated narratives). A series of connected speech tasks was proposed due to suggestions that cognitive-linguistic load varies across tasks and may differentially impact performance.

Participants read aloud a series of five sentences that were adapted for use in a prior study on rate modification (Lowit et al., 2006; K. Yorkston & Beukelman, 1981). Sentences were eight to nine words in length. Participants also completed a longer, paragraph-level reading commonly used in communication disorders literature and clinical practice; the phonetically balanced Rainbow Passage (Fairbanks, 1960). Both tasks were first completed at habitual rate and volume and presented in printed form in black font. To provide a model, the examiner first read the stimuli aloud once while participants read along and the participant read independently after (Rodgers et al., 2013). The participants' independent readings were used for analyses of speech timing.

Rate modification task. The rate modification task was used to determine participants' ability to modify their rate of speech and was completed by reading aloud at the sentence and the paragraph level. The same series of five sentences previously utilized in a similar study were used (Lowit et al., 2006) to evaluate ability to alter rate at the sentence level. The Rainbow Passage (Fairbanks, 1960) was used to evaluate performance modifying rate across an extended duration at the paragraph level (presumed higher cognitive demand). Participants were first instructed to read the sentence or paragraph at habitual rate. Following the first trial, participants read the same sentences or paragraph again in counter-balanced order for fast and slow conditions. Participants were instructed to read the sentence or paragraph stimulus aloud at twice their typical speaking rate for the fast condition and half as fast during the slow condition.

Procedures

Participants completed all tasks for this research study in one visit of approximately two hours in duration. The visit began with the consent/assent process followed by the demographic and clinical status interview. To reduce the duration of the visit, any clinical information that participants were unable to report (i.e., motor scores, genetic testing results, etc.) was retrieved from patient medical records. Next, all participants completed the cognitive task followed by the speech experimental tasks (approximately 30-35 minutes to complete each). Participants were offered the chance to take a ten-minute break following the cognitive tasks if desired.

Data Preprocessing and Transcription

Connected speech tasks. Audio recordings from connected speech tasks and the rate modification tasks were transcribed and coded by a trained graduate student and reviewed by a second student. Any discrepancies were reviewed jointly and resolved through discussion. Samples were coded for dysfluencies, fillers, and non-speech vocalizations. Discrepancies were resolved through discussion to obtain final syllable counts. Filled pauses, dysfluent words (i.e., syllable repetitions), and non-speech vocalizations did not contribute to the syllable count of the sample.

All samples underwent audio file preprocessing to optimize the output of MATLAB speech pause analysis program (Green et al., 2004). Pauses were defined as silent pauses greater than 200 milliseconds (Tjaden & Wilding, 2004), and filled pauses (e.g., non-lexical vocalizations) (Clark & Fox Tree, 2002; Goldman-Eisler, 1968). Therefore, all fillers and non-speech vocalizations were silenced during preprocessing of files. Dysfluencies were omitted from files by deleting the segment from the start to end of the dysfluent word.

Acoustic Analyses

Connected speech tasks. The following measures of speech timing used in previous research (Lowit et al., 2006; Rodgers et al., 2013; Tjaden & Wilding, 2011) were calculated for each connected speech task using output from the Speech Pause Analysis program (Green et al., 2004) in MATLAB:

Speech Rate: Speech rate in syllables per second was defined as the total number of syllables divided by the total sample duration (including articulation and pause time).

Articulation Rate: Articulation rate in syllables per second was defined as the total number of syllables divided by the total articulation time (removing pauses >200 ms and non-speech vocalizations) (Rodgers et al., 2013; Tjaden & Wilding, 2004).

Mean Pause Length: Mean pause length was the average length of all pausing occurrences within a participant's sample (Tjaden & Wilding, 2011).

Rate modification task. As described above, articulation and speech rate were calculated for trials of the sentence reading and paragraph reading at the habitual, fast, and slow conditions. Percent change in speech and articulation rate were calculated between habitual and fast as well as between habitual and slow conditions for each participant and each task (Lowit et al., 2006; Tjaden & Wilding, 2004). As a change score, the further the resulting value is from zero, positively or negatively, the greater the degree of change. An increase or decrease of the variable of interest is represented as a positive or negative value, respectively. Figure 1 provides the change score equations and an example of the bidirectional products. Each change score was calculated as the habitual rate minus the fast or slow rate for both tasks.

Figure 1. Rate Modification Equations and Example

Change Equations:

Change Score Habitual → Fast = Fast Speech Timing Measure – Habitual Speech Timing Measure

Change Score Habitual → Slow = Slow Speech Timing Measure – Habitual Speech Timing Measure

Example:

Articulation Rate Habitual = 4 syll/s
Articulation Rate Fast = 6 syll/s
Articulation Rate Slow = 2 syll/s

Habitual → Fast Articulation Rate = 6 – 4 = 2 syll/s
Habitual → Slow Articulation Rate = 2 – 4 = -2 syll/s

Mean Pause Length Habitual = 2 s
Mean Pause Length Fast = 1 s
Mean Pause Length Slow = 3 s

Habitual → Fast Mean Pause Length = 1 – 2 = -1 s
Habitual → Slow Mean Pause Length = 3 – 2 = 1 s

Figure 1 Legend. Speech Rate is anticipated to result similarly to articulation rate in direction. Participants will typically result in a positive value when speeding up rate and a negative value when reducing rate. Mean pause length presents with an inverse relationship. When participants are speeding up rate, mean pause length will typically be negative as the individual reduces pausing to complete the speech task faster. Similarly, mean pause length is anticipated to be positive when reducing rate as participants increase pausing behavior to slow down.

CHAPTER III

RESULTS

Relevant clinical and demographic information, including participants' standard scores on the written version of the SDMT were collected to characterize the groups of participants included in this study. Descriptive statistics for clinical and demographic characteristics by participant group are in Table 1. All participant groups presented with high intelligibility suggesting mild dysarthria for those with HD and PD. The HD group presented with the lowest standard score on the SDMT, indicating the greatest degree of cognitive impairment among groups. The groups with HD and PD both achieved lower cognitive scores on the SDMT compared to matched controls.

Matched group differences were examined for clinical and demographic descriptors of age, years of education, SDMT standard score, and percent intelligibility using independent t-tests. Participants in the HD and HDNC groups did not demonstrate a significant effect of age ($t[41.55] = 0.66$, $p = 0.511$) or education ($t[45.33] = -0.78$, $p = 0.437$). Participants with HD demonstrated significantly lower percent intelligibility ($t[27.37] = -5.57$, $p < 0.001$) and lower SDMT standard scores ($t[45.95] = -11.60$, $p<0.001$) compared to the HDNC group. Similarly, participants in the PD and PDNC groups did not demonstrate a significant effect of age ($t[32.32] = -0.19$, $p = 0.853$) or education ($t[34.76] = 0.67$, $p = 0.51$) but those in the PD group had significantly lower percent intelligibility ($t[24.42] = -2.78$, $p<0.05$) and SDMT standard score ($t[27.06] = -3.80$, $p<0.001$) compared to PDNC.

Table 1. Participant Clinical and Demographic Information

Group	HD	HDNC	PD	PDNC
Total Number	27	21	21	16
Mean Age (SD) in years	51.9 (14)	49.0 (15)	66.7 (8.38)	67.2 (8.44)
Sex (male)	14	9	14	9
Education in years (SD)	14.3 (2.64)	14.9 (2.31)	16.3 (2.69)	15.8 (2.21)
Mean % Intelligibility (SD)	94.2 (4.93)	99.5 (0.709)	98.0 (2.18)	99.4 (0.643)
Mean QAB Overall (SD)	9.15 (0.423)	9.91 (0.154)	9.60 (0.382)	9.87 (0.197)
Mean HADS-A (SD)	6.26 (4.58)	4.05 (2.25)	6.05 (3.97)	2.88 (2.92)
Mean HADS-D (SD)	5.30 (4.77)	1.43 (1.54)	5.76 (3.65)	1.88 (1.89)
Mean SDMT SS (SD)	57.6 (18.2)	111 (13.7)	87.2 (24.5)	109 (9.36)
Mean Disease duration (SD) in years	5.80 (4.29)	NA	8.79 (4.84)	NA
Mean TFC Score (SD)	7.22 (2.55)	NA	NA	NA
Mean UPDRS H&Y Rating	NA	NA	NA	2.57 (0.98)

Habitual Speech Timing

For the purposes of the current study, all models were fit in R using the lme4 package. P-values were obtained for the models using the lmerTest package. To investigate research question 1a, the influence of task and group on habitual speech timing performance was analyzed with linear mixed effects models that examined main effects of group and task and their interaction. Each model was constructed with the habitual speech timing measure as the dependent variable (e.g., habitual articulation rate, habitual speech rate, habitual mean pause length), and Group (HD/PD versus designated NC cohort) and task (sentence, paragraph) as fixed effects in addition to a random effect of participant. Full model results are presented in Appendix A along with applicable simple slopes and simple effects.

In general, the HD group presented with slower articulation and speech rates and a greater mean pause length across most conditions when compared to matched controls. Differences between the PD groups presented similarly, but with less prominent degrees of difference for certain task conditions. In other words, the PD group performed below or more similarly to their matched control group. Descriptive statistics for all speech timing variables of interest at habitual rate (speech rate, articulation rate, and mean pause length) are provided in Table 2 and Table 3 by participant group.

Table 2. Sentence Reading Task- Speech Timing

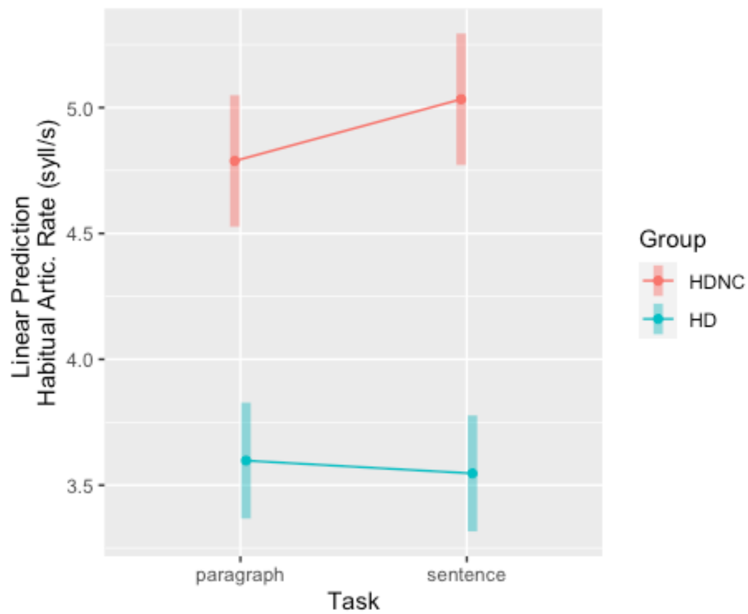
Speech Timing Measure	Rate	HD	HDNC	PD	PDNC
Mean Articulation Rate (SD)					
	Habitual	3.55 (0.69)	5.03 (0.48)	4.61 (0.66)	4.77 (0.36)
	Fast	4.38 (1.04)	6.53 (0.84)	6.10 (1.02)	6.31 (1.05)
	Slow	3.09 (0.57)	3.22 (0.69)	3.63 (0.72)	3.41 (0.86)
Mean Speech Rate (SD)					
	Habitual	3.32 (0.81)	5.01 (0.52)	4.52 (0.80)	4.76 (0.37)
	Fast	4.18 (1.17)	6.52 (0.84)	6.07 (1.06)	6.29 (1.06)
	Slow	2.71 (0.72)	2.97 (0.86)	3.45 (0.88)	3.16 (1.00)
Mean MPL (SD)					
	Habitual	0.24 (0.22)	0.02 (0.08)	0.11 (0.32)	0.01 (0.02)
	Fast	0.16 (0.20)	0.01 (0.02)	0.03 (0.08)	0.01 (0.02)
	Slow	0.36 (0.27)	0.18 (0.17)	0.14 (0.22)	0.23 (0.19)

Table 3. Paragraph Reading Task- Speech Timing

Speech Timing Measure	Rate	HD	HDNC	PD	PDNC
Mean Articulation Rate (SD)					
	Habitual	3.60 (0.62)	4.79 (0.55)	4.55 (0.57)	4.61 (0.50)
	Fast	4.18 (1.04)	6.07 (0.97)	5.79 (1.26)	6.02 (0.84)
	Slow	3.48 (0.69)	3.43 (0.62)	3.82 (0.67)	3.78 (0.75)
Mean Speech Rate (SD)					
	Habitual	2.62 (0.75)	4.17 (0.56)	3.74 (0.81)	4.04 (0.54)
	Fast	3.23 (1.26)	5.62 (1.08)	5.13 (1.49)	5.63 (0.88)
	Slow	2.38 (0.75)	2.77 (0.59)	2.96 (0.72)	3.06 (0.74)
Mean MPL (SD)					
	Habitual	0.73 (0.36)	0.48 (0.10)	0.57 (0.15)	0.49 (0.13)
	Fast	0.72 (0.45)	0.41 (0.12)	0.44 (0.13)	0.36 (0.08)
	Slow	0.80 (0.39)	0.58 (0.13)	0.62 (0.14)	0.58 (0.14)

Habitual articulation rate. The model of habitual articulation rate for HD and HDNC participants included a significant interaction of group and task ($b = -0.30$, $p = 0.009$; Figure 2). The HDNC group presented with a faster habitual articulation rate compared to those with HD on both the sentence and the paragraph tasks. Participants with HD demonstrated similar habitual articulation rate regardless of task while controls have a faster articulation rate on the sentence relative to the paragraph task.

Figure 2. HD & HDNC Habitual Articulation Rate Group by Task Interaction



The initial model for PD and PDNC habitual articulation rate yielded an interaction of group and task that was not significant ($p = 0.42$). The interaction term was removed from the model while all other fixed and random effects remained. There was no significant main effect of group ($p = 0.53$) or task ($p = 0.11$), suggesting comparable articulation rate between PD and PDNC groups and comparable performance on both tasks.

Habitual speech rate. For the initial model for HD and HDNC habitual speech rate, there was no significant interaction of group and task ($p = 0.32$) and the interaction term was removed. There was a significant main effect of group ($b = -1.62$, $p < 0.001$), indicating decreased habitual speech rate for participants with HD relative to matched controls and a significant main effect of task ($b = 0.76$, $p < 0.001$), indicating increased habitual speech rate for both groups in the sentence reading task relative to the paragraph reading task.

The initial model for PD and PDNC habitual speech rate also yielded an interaction of task and group that was not significant ($p = 0.67$). The interaction term was removed from the model while all other fixed and random effects remained. There was no significant main effect of group ($p = 0.21$), suggesting comparable speech rate for PD and PDNC participants. There was a significant main effect of task ($b = 0.75$, $p < 0.001$), indicating increased habitual speech rate for both groups in the sentence reading task relative to the paragraph reading task.

Habitual mean pause length. The interaction of group and task was not significant ($p = 0.56$) in the initial model for HD and HDNC habitual mean pause length. The interaction term was removed from the model while all other fixed and random effects remained. There was a significant main effect of group ($b = 0.24$, $p < 0.001$), indicating increased mean pause length for participants with HD relative to matched controls and a significant main effect of task ($b = -0.48$, $p < 0.001$), indicating decreased mean pause length in the sentence reading task relative to the paragraph reading task.

The initial model for PD and PDNC habitual mean pause length yielded an interaction of group and task that was not significant ($p = 0.73$). The interaction was removed from the model while all other fixed and random effects remained. The main effect of group was not significant ($p = 0.13$) while the main effect of task was significant ($b = -0.47$, $p < 0.001$), suggesting comparable mean pause length across groups with both exhibiting decreased mean pause length during the sentence reading task relative to the paragraph reading task.

Habitual Speech Timing and SDMT

To investigate research question 1b, the influence of cognition (e.g., SDMT standard score) and task on habitual speech timing performance was analyzed with mixed effects models for each individual group (HD, PD, all NC) following a similar structure to above. Each model was constructed with the habitual speech timing measure as the dependent variable (e.g., habitual articulation rate, habitual speech rate, habitual mean pause length), fixed effects of SDMT standard score and task, their interaction, and a random effect of participant. Full model results are presented in Appendix A.

Habitual articulation rate and SDMT. For the initial model examining SDMT and habitual articulation rate in HD, the interaction of SDMT and task was not significant ($p = 0.23$). The interaction was removed from the model while all other fixed and random effects remained. The main effect of SDMT score was significant ($b = 0.02$, $p = 0.005$), suggesting increased habitual articulation rate as SDMT performance increased. The main effect of task was not significant ($p = 0.47$), indicating no difference in habitual articulation rate across tasks for all participants.

The initial model for PD habitual articulation rate and SDMT score included an interaction of SDMT and task that was not significant and the interaction was removed from the model while all other fixed and random effects remained the same ($p = 0.58$). The main effect of SDMT score was significant ($b = 0.01$, $p = 0.01$), suggesting increased habitual articulation rate with increased SDMT performance. The main effect of task was not significant ($p = 0.36$), suggesting comparable habitual articulation rate for participants with PD across the sentence and paragraph reading tasks.

The initial model for HDNC and PDNC habitual articulation rate and SDMT score included an interaction of SDMT and task that was not significant ($p = 0.11$) and the interaction was removed from the model while all other fixed and random effects remained. The main effect of SDMT was not significant ($p = 0.56$), suggesting no relationship between SDMT score and habitual articulation rate for controls. The main effect of task was significant ($b = 0.21$, $p = 0.006$), suggesting increased habitual articulation rate in the sentence relative to the paragraph reading task for control participants.

Habitual speech rate and SDMT. The initial model for HD habitual speech rate and SDMT score included an interaction of SDMT and task that was not significant ($p = 0.78$), thus the interaction was removed from the model while other fixed and random effects remained. The main effects of SDMT score was significant ($b = 0.03$, $p<0.001$), suggesting increased habitual speech rate with increased SDMT score. The main effect of task was significant ($b = 0.71$, $p < 0.001$), suggesting increased habitual speech rate in the sentence reading task relative to the paragraph reading task for participants with HD.

The initial model for PD habitual speech rate and SDMT score included an interaction of SDMT and task that was not significant ($p = 0.11$), and the interaction was removed from the model leaving fixed and random effects in place. The main effect of SDMT was significant ($b = 0.02$, $p = 0.001$), suggesting increased habitual speech rate with increased SDMT score for participants with PD. The main effect of task was also significant ($b = 0.78$, $p < 0.001$), indicating increased habitual speech rate during the sentence reading task relative to the paragraph reading task for the PD group.

The initial model for HDNC and PDNC participants' habitual speech rate and SDMT score included an interaction of SDMT score and task that was not significant ($p = 0.11$) and the interaction was removed from the model leaving all other components intact. There was not a significant main effect of SDMT ($p =0.66$), indicating no relationship between SDMT score and habitual speech rate in control participants. There was a significant main effect of task ($b = 0.78$, $p < 0.001$), suggesting that control participants demonstrate increased habitual speech rate during the sentence compared to the paragraph reading task.

Habitual mean pause length and SDMT. The initial model for HD habitual mean pause length and SDMT score included an interaction of SDMT and task that was not significant ($p = 0.78$) and the interaction was removed from the model while all other fixed and random effects remained. The main effect of SDMT was significant ($b = -0.01$, $p = 0.01$) suggesting that habitual mean pause length decreases as participants' SDMT score increases, indicating greater cognitive functioning. The main effect of task was significant ($b = -0.5$, $p < 0.001$), indicating decreased habitual mean pause length during the sentence reading relative to the paragraph reading task.

The initial model for PD habitual mean pause length and SDMT score included an interaction of SDMT and task was not significant ($p = 0.15$) and the interaction was removed from the model leaving fixed and random effects in place. The main effect of SDMT was significant ($b = -0.01$, $p < 0.001$), indicating decreased habitual mean pause length as SDMT score increases. The main effect of task was significant ($b = -0.46$, $p < 0.001$), suggesting decreased habitual mean pause length in the sentence relative to the paragraph reading task.

The initial model for HDNC and PDNC habitual mean pause length and SDMT score included an interaction of SDMT and task was not significant ($p = 0.21$) and was removed from the model. The main effect of SDMT was not significant ($p = 0.628$), suggesting no relationship between habitual mean pause length and control participants' score on the SDMT. There was a significant main effect of task ($b = -0.47$, $p < 0.001$), suggesting decreased habitual mean pause length on the sentence relative to the paragraph reading task.

Rate Modification and Speech Timing

To investigate research question 2a, the influence of task and group on the degree of change for speech timing performance was analyzed with mixed effects models. All speech timing measures were calculated as change scores between rate conditions. Each model included the change score for the speech timing outcome variable, fixed effects of group and task, their interaction, and a random effect of participant. Full model results are presented in Appendix A along with applicable simple slopes and simple effects,

Descriptive statistics for group change scores, or the difference in speech timing performance between habitual, fast, and slow conditions are provided in Table 4 and Table 5. Visual representations of rate measures across conditions (Figures 3 and 4) indicate that all groups show some degree of difference in rate across speed conditions. In general, the HD group demonstrates lower change scores compared to other study groups. The PD group demonstrates fairly similar performance to controls when speeding up but achieved lower mean change scores when slowing down speech rate and articulation rate. While minimal group differences are apparent, a possible ceiling effect can be noted for the outcome variable of mean pause length; particularly on the sentence reading task.

Table 4. Rate Modification Change Scores- Sentence Reading Task

Speech Timing Measure	Change Condition	HD	HDNC	PD	PDNC
Articulation Rate					
	Habitual → Fast	0.83 (0.50)	1.5 (0.69)	1.49 (0.67)	1.54 (0.84)
	Habitual → Slow	-0.46 (0.67)	-1.81 (0.86)	-0.98 (0.62)	-1.36 (0.90)
Speech Rate					
	Habitual → Fast	0.86 (0.54)	1.51 (0.70)	1.55 (0.66)	1.54 (0.85)
	Habitual → Slow	-0.60 (0.74)	-2.03 (1.00)	-1.07 (0.76)	-1.60 (1.05)
MPL					
	Habitual → Fast	-0.08 (0.15)	-0.02 (0.07)	-0.08 (0.27)	-0.00 (0.03)
	Habitual → Slow	0.12 (0.20)	0.16 (0.18)	0.04 (0.35)	0.22 (0.19)

Table 5. Rate Modification Change Scores- Paragraph Reading Task

Speech Timing Measure	Change Condition	HD	HDNC	PD	PDNC
Articulation Rate					
	Habitual → Fast	0.59 (0.52)	1.28 (0.66)	1.24 (0.80)	1.42 (0.73)
	Habitual → Slow	-0.12 (0.42)	-1.36 (0.71)	-0.73 (0.77)	-0.83 (0.57)
Speech Rate					
	Habitual → Fast	0.62 (0.65)	1.46 (0.72)	1.39 (0.82)	1.59 (0.68)
	Habitual → Slow	-0.23 (0.38)	-1.40 (0.73)	-0.77 (0.83)	-0.98 (0.59)
MPL					
	Habitual → Fast	-0.02 (0.15)	-0.07 (0.11)	-0.12 (0.11)	-0.13 (0.11)
	Habitual → Slow	0.07 (0.14)	0.10 (0.11)	0.06 (0.12)	0.09 (0.15)

Figure 3. Sentence-Level Speech Timing Across Rate Conditions

A.

B.

C.

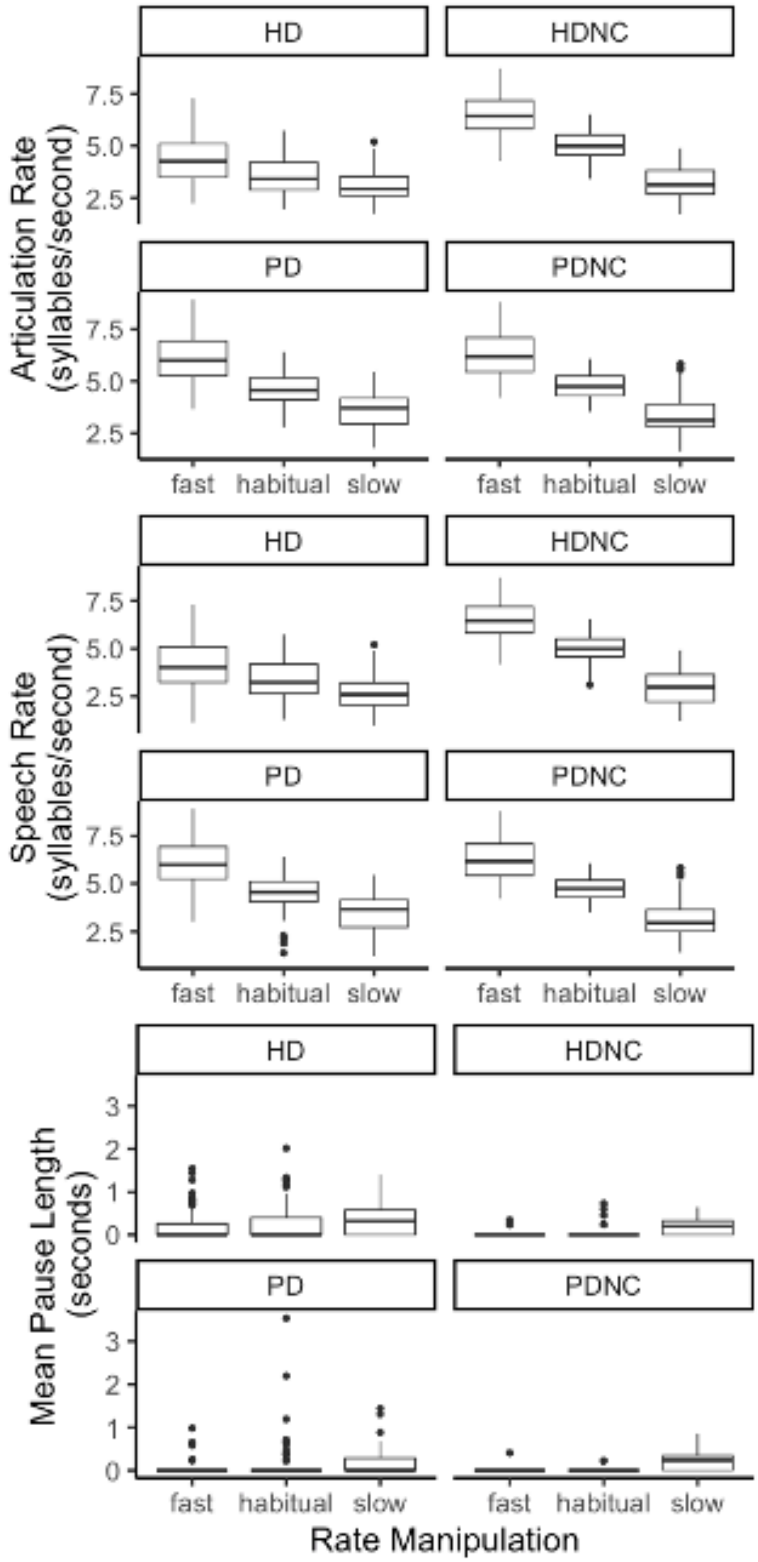
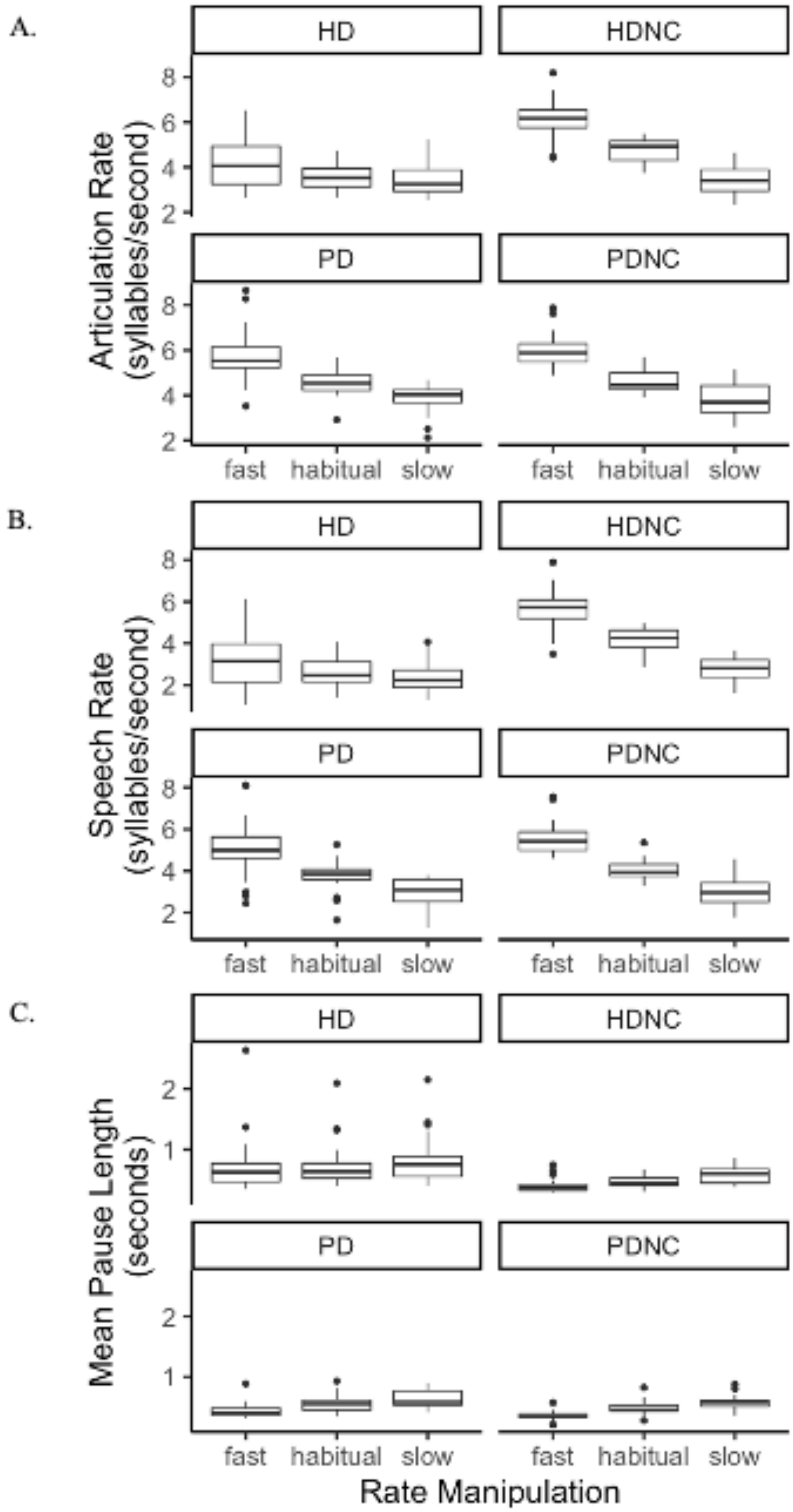


Figure 4. Paragraph-Level Speech Timing Across Rate Conditions



Habitual to fast articulation rate change. The interaction in the initial model for HD and HDNC articulation rate change from the habitual to fast condition was not significant ($p = 0.85$) and was removed from the model. A significant main effect of group ($b = -0.68$, $p < 0.001$) was identified, indicating that participants with HD demonstrate a reduced ability to increase articulation rate compared to HDNCs. There was a significant main effect of task ($b = 0.23$, $p = 0.002$), suggesting that, across groups, participants demonstrated a greater degree of articulation rate change from habitual to fast conditions on the sentence reading task relative to the paragraph reading task.

The initial model for PD articulation rate change from the habitual to fast condition included an interaction that was not significant ($p = 0.581$) and was removed. The main effects of group ($p = 0.623$) and task ($p = 0.095$) were not significant, suggesting comparable change in articulation rate when speeding up across both groups and tasks.

Habitual to slow articulation rate change. The initial model for HD and HDNC articulation rate change from the habitual to slow condition revealed an interaction of group and task that was not significant ($p = 0.45$) and was removed from the model. The main effect of group was significant ($b = 1.3$, $p < 0.001$), indicating that the HD group was not able to slow articulation rate as much as the HDNC group. The main effect of task was also significant ($b = -0.39$, $p < 0.001$), suggesting that across participants, the ability to slow down articulation rate is greater on the sentence compared to the paragraph reading task.

The initial mode for PD and PDNC articulation rate change from the habitual to slow condition revealed a group by task interaction that was not significant ($p = 0.124$). The interaction was removed from the model. The main effect of group was group was not significant ($p = 0.293$), suggesting comparable change in articulation rate between groups. The main effect of task was significant ($b = -0.371$, $p < 0.001$), indicating a decrease (i.e., further from zero) in articulation change on the sentence relative to the paragraph task. Therefore, the degree of change in articulation rate when slowing down is greater on the sentence relative to the paragraph reading.

Habitual to fast speech rate change. The interaction of group and task for the initial model of HD and HDNC speech rate change from the habitual to fast condition was not significant ($p = 0.32$). The interaction was removed from the model leaving all other fixed and random effects in place. The main effect of group was significant ($b = -0.75$, $p < 0.001$), suggesting the HD group was not able to increase speech rate as much as the HDNC group. The main effect of task was not significant ($p = 0.08$), indicating a similar degree of speech rate change to increase rate for both groups across tasks.

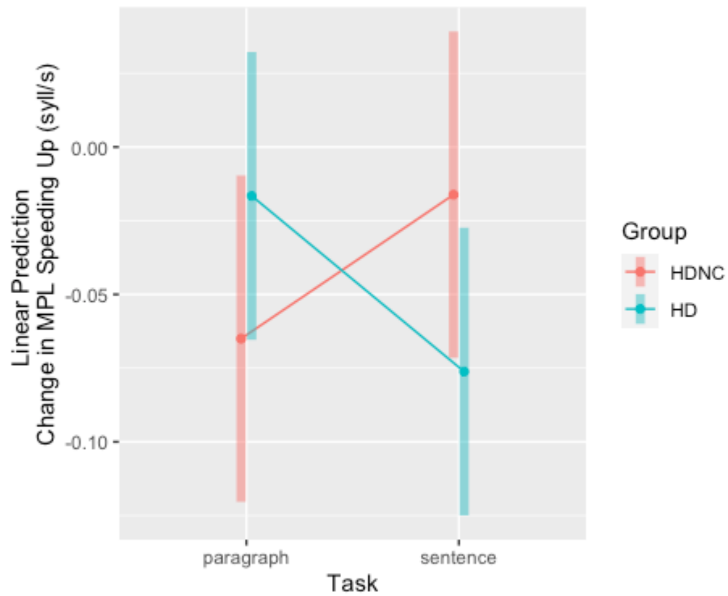
The initial model for PD and PDNC speech rate change from the habitual to fast condition revealed an interaction of group and task that was not significant ($p = 0.374$). The interaction was removed. The main effects of group ($p = 0.668$) and task ($p = 0.579$) were also not significant, suggesting comparable change in speech rate when speeding up across both groups and tasks.

Habitual to slow speech rate change. In the initial model for HD and HDNC speech rate change from the habitual to slow conditions, the interaction of group and task was not significant ($p = 0.14$) and was removed. All other fixed and random effects remained. The main effect of group was significant ($b = 1.30$, $p < 0.001$), indicating that the HD group was not able to slow speech rate as much as the HDNC group. The main effect of task was significant ($b = -0.48$, $p < 0.001$), indicating a greater degree of reduced speech rate during the sentence compared to the paragraph reading.

In the initial model for PD and PDNC speech rate change from the habitual to slow conditions, the interaction was not significant ($p = 0.109$) and was removed. The main effect of group was not significant ($p = 0.151$), suggesting comparable change in speech rate across groups when slowing down. There was a significant main effect of task ($b = -0.43$, $p<0.001$), indicating that participants with PD and matched controls reduced speech rate to a greater degree on the sentence relative to the paragraph reading task.

Habitual to fast mean pause length change. The initial model for HD and HDNC mean pause length change from the habitual to fast conditions included fixed effects of group and task, their interaction, and a random effect of participant. Due to concerns for model overfitting (e.g., singularity), the model was reduced in complexity by removing the random effect of participant and leaving all other model components intact. Model output was identical to the initial version which is reported here. The interaction of group and task was significant ($b = -0.11$, $p = 0.042$) (Figure 5). Simple effects were found to be nonsignificant, however, the groups differed in the degree of change based upon task. Participants with HD demonstrated a greater reduction in mean pause length when speeding up on the sentence compared to the paragraph task. Those in the HDNC group exhibited the opposite relationship with a greater reduction in mean pause length on the paragraph compared to the sentence task.

Figure 5. HD and HDNC Mean Pause Length- Speed Up Group by Task Interaction



The interaction of group and task for the initial mode for PD and PDNC mean pause length change from the habitual to fast conditions was not significant (p = 0.192). The interaction was removed from the model. The main effect of group was not significant (p = 0.422), suggesting that the PD and PDNC groups demonstrated similar change to mean pause length when increasing rate. The main effect of task was significant (b = 0.08, p = 0.018), suggesting that the change in mean pause length is increased across participants on the sentence relative to the paragraph task.

Habitual to slow mean pause length change. The initial model for HD and HDNC mean pause length change from the habitual to slow conditions produced an interaction of group and task that was not significant (p = 0.99). The main effects of group (p = 0.36) and task (p = 0.08) were not significant; suggesting comparable change in mean pause length when reducing rate across both groups and tasks.

The initial model for PD and PDNC mean pause length change from the habitual to slow condition included an interaction of group and task that was not significant (p = 0.085) and the interaction was removed from the model. The main effects of group ($p = 0.084$) and task ($p = 0.291$) were not significant, suggesting comparable change in mean pause length when reducing rate across both groups and tasks.

Rate Modification and SDMT

To investigate research question 2b, the influence of cognition (e.g., SDMT standard score) and task on the change speech timing performance was analyzed with mixed effects models for each individual group (HD, PD, all NC) following a similar structure to above. Each model was constructed with the speech timing change score as the dependent variable (e.g., change in articulation rate, speech rate, mean pause length), fixed effects of SDMT standard score and task, their interaction, and a random effect of participant. Full model results are presented in Appendix A along with applicable simple slopes and simple effects,

Habitual to fast articulation rate change and SDMT. In the initial model examining the change in articulation rate between habitual and fast conditions for the HD group, the interaction of SDMT standard score and task was not significant ($p = 0.540$) and was removed from the model. The main effect of SDMT was not significant ($p = 0.053$), indicating no relationship between SDMT score and the change in articulation rate when speeding up for participants with HD. The main effect of task was significant ($b = 0.243$, $p= 0.003$), indicating a greater increase in articulation rate on the sentence relative to the paragraph task.

For participants with PD, the initial model examining the change in articulation rate between habitual and fast conditions included an interaction of SDMT and task that was not significant ($p = 0.343$) and was removed from the model. The main effects of SDMT ($p = 0.249$) and task ($p = 0.106$) were also not significant, indicating no relationship between SDMT standard score or across tasks and change in articulation rate when increasing rate for participants with PD.

For the HDNC and PDNC participants, the initial model for change in articulation rate between the habitual and fast conditions included an interaction of SDMT and task that was not significant ($p = 0.815$) and was removed from the mode. The main effect of SDMT was significant ($b = 0.02$, $p = 0.040$), indicating that the control participants have an increase in the change score for articulation rate relative to an increase in SDMT score when speeding up. In other words, individuals who perform better on cognitive testing are able to manipulate articulation rate to a greater degree to speed up. The main effect of task was not significant ($p = 0.108$), suggesting that participants in the control groups alter articulation rate to a comparable degree across tasks when increasing their rate.

Habitual to slow articulation rate change and SDMT. In the model examining participants with HD's change in articulation rate between the habitual and slow conditions, the interaction of SDMT and task was significant ($b = -0.01$, $p = 0.00352$, Figure 6). A higher score on the SDMT, indicating a higher level of cognitive functioning, was associated with a greater degree of change in articulation rate when slowing down on both speech tasks. However, the degree of change in rate is greatest for the sentence task relative to the paragraph reading task. A lower score on the SDMT, indicating reduced cognitive functioning, is associated with a smaller decrease in articulation rate when slowing down regardless of task. In fact, articulation rate is observed to increase to some degree when prompted to slow down in a subset of cases with low cognitive scores (Figure 7).

Figure 6. HD Change in Articulation Rate-Slow Down SDMT by Task Interaction

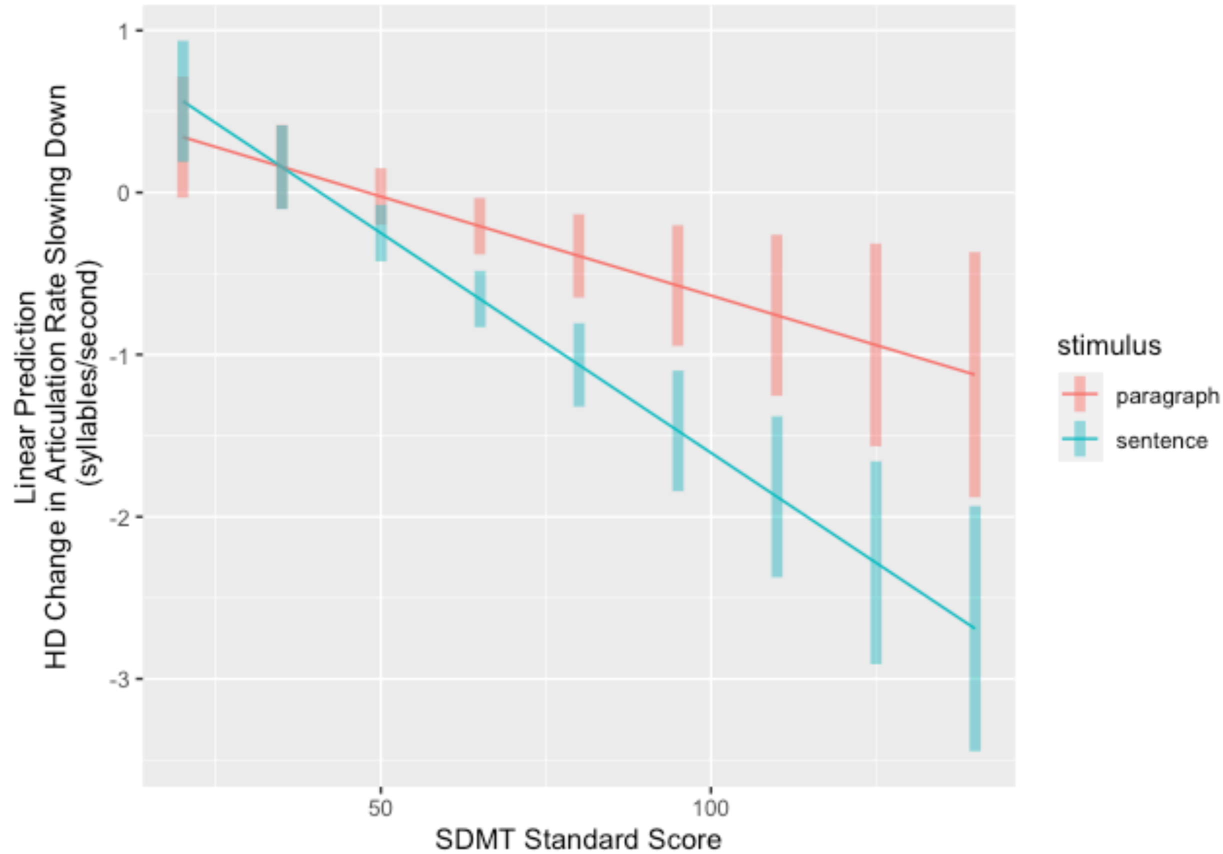
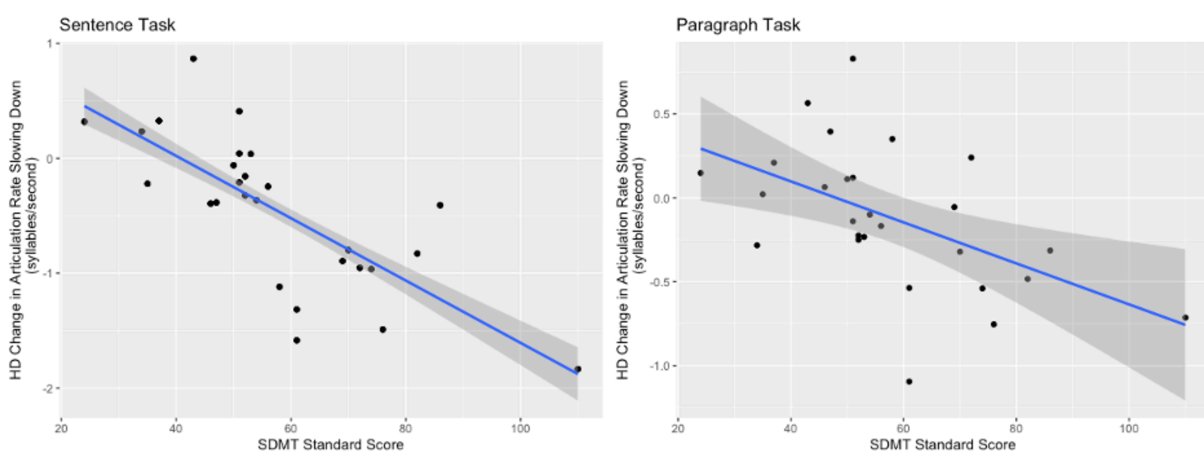


Figure 7. HD Participants' SDMT Scores by Change in Slow Down Articulation Rate



For participants with PD, the initial model examining the change in articulation rate between habitual and slow conditions included an interaction of SDMT and task that was not significant ($p = 0.113$) and was removed from the model. The main effect of SDMT was not significant ($p = 0.126$) indicating no relationship between participants with PD's score on the SDMT and ability to change articulation rate when decreasing rate. The main effect of task was significant ($b = -0.25$, $p = 0.025$), suggesting a greater degree of change in articulation rate when slowing down on the sentence compared to the paragraph reading task for participants with PD.

For the HDNC and PDNC participants, the initial model for change in articulation rate between the habitual and slow conditions revealed an interaction of SDMT and task that was not significant ($p = 0.308$) and was removed from the model. The main effect of SDMT was not significant ($p = 0.915$), indicating no relationship between score on the SDMT and ability to alter articulation rate when slowing down for participants in the control groups. There was a main effect of task ($b = -0.48$, $p < 0.001$), suggesting that participants in the control groups decrease or change their articulation rate to a greater degree when slowing down on the sentence compared to the paragraph reading task.

Habitual to fast speech rate change and SDMT. In the initial model for participants with HD's change in speech rate between habitual and fast conditions, the interaction of SDMT and task was not significant ($p = 0.340$) and was removed from the model. The main effects of SDMT ($p = 0.056$) and task ($p = 0.053$) were also not significant, suggesting no relationship between SDMT standard score or task and change in speech rate when speeding up for participants with HD.

For participants with PD, the initial model examining the change in speech rate between the habitual and fast conditions revealed an interaction of SDMT and task that was not significant ($p = 0.277$) and was removed from the model. The main effects of SDMT ($p = 0.470$) and task ($p = 0.350$) were also not significant, suggesting no relationship between SDMT standard score or task and participants with PDs ability to alter speech rate when increasing rate.

For participants in the HDNC and PDNC groups, the initial model examining the change in speech rate between the habitual and fast conditions included an interaction of SDMT and task that was not significant ($p = 0.794$) and was removed from the model. The main effect of SDMT was significant ($b = 0.02$, $p = 0.037$), indicating that as SDMT score increases, reflecting higher cognitive functioning, participants' degree of change in speech rate will increase when speeding up. The main effect of task was not significant ($p = 0.939$), suggesting no difference in degree of change in speech rate when speeding up.

Habitual to slow speech rate change and SDMT. In the model examining the change in speech rate between habitual and slow conditions for the HD group, the interaction of SDMT and task was significant ($b = -0.02$, $p = 0.0004$, Figure 8). While both tasks demonstrate some degree of change in speech rate with increased SDMT score, the sentence reading task exhibits the greatest degree of change relative to cognitive performance. Therefore, in the HD group, a higher score on the SDMT, or higher cognitive ability, is associated with a greater reduction in speech rate; particularly on the sentence reading task. A low score on the SDMT, indicating greater cognitive impairment, is associated with reduced ability to slow down speech rate and in some cases, participants demonstrate an increase in speech rate. Individual data points are shown in Figure 9.

Figure 8. HD Change in Speech Rate-Slow Down SDMT by Task Interaction

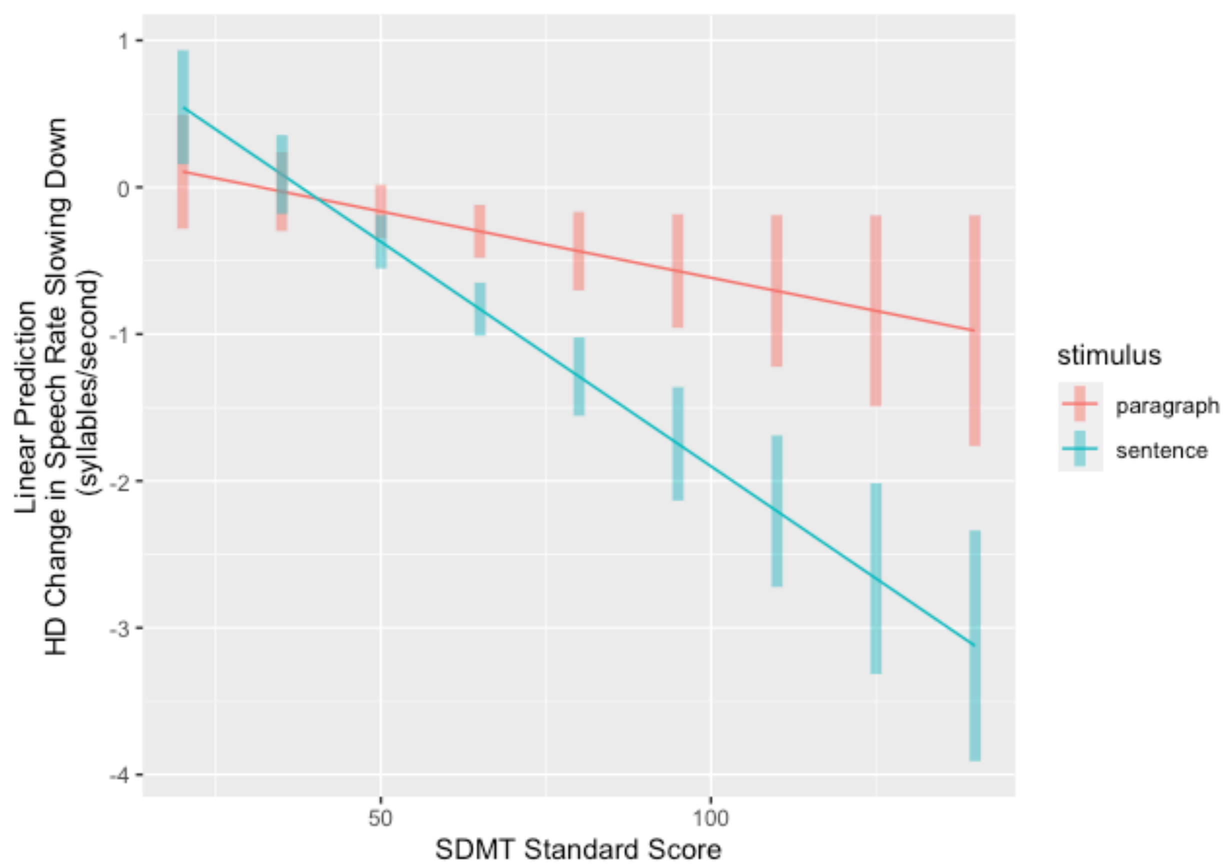
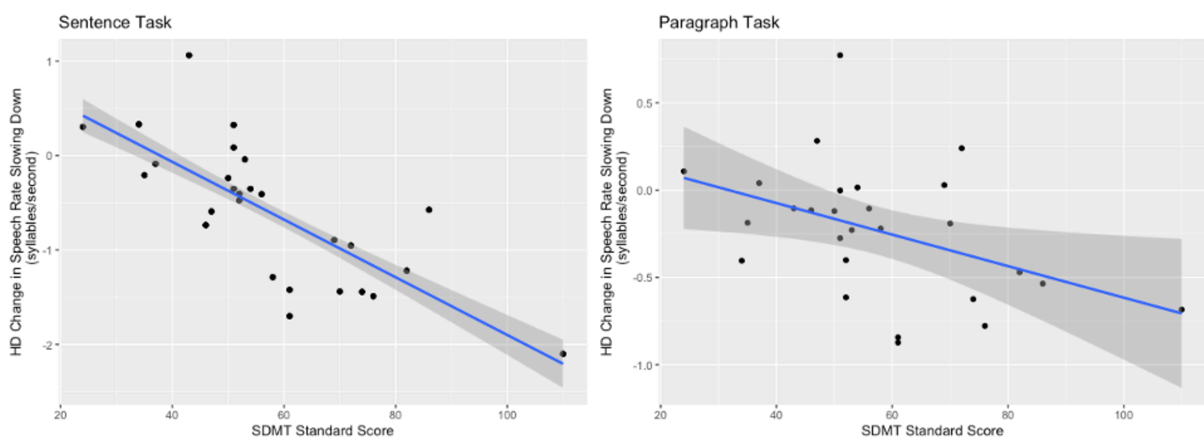


Figure 9. HD Participants' SDMT Scores by Change in Slow Down Speech Rate



For the PD group, the initial model examining the change in speech rate between habitual and slow conditions included an interaction of SDMT and task that was not significant (p =

0.122) and was removed from the model. The main effect of SDMT was not significant ($p = 0.091$), indicating no relationship between SDMT score and ability to change speech rate when reducing rate. The main effect of task was significant ($b = -0.29$, $p = 0.025$), indicating that participants with PD have a greater degree of change or reduction in speech rate when slowing down on the sentence compared to the paragraph reading task.

For the HDNC and PDNC groups, the initial model examining the change in speech rate between habitual and slow conditions included an interaction of SDMT and task that was not significant ($p = 0.326$) and was removed from the model. The main effect of SDMT was not significant ($p = 0.977$), indicating no relationship between SDMT performance and ability to alter speech rate when slowing down for control participants. The main effect of task was significant ($b = -0.62$, $p < 0.001$), suggesting that control participants demonstrate a greater ability to alter and reduce speech rate when slowing down on the sentence reading task.

Habitual to fast mean pause length change and SDMT. In the initial model examining the change in mean pause length between habitual and fast conditions for participants with HD, the interaction of SDMT and task was not significant ($p = 0.288$) and was removed from the model. Due to concerns for model overfitting (e.g., singularity), the model was reduced in complexity by removing the random effect of participant and leaving all other model components intact. Model output was identical to the initial version which is reported here. The main effects of SDMT ($p = 0.807$) and task ($p = 0.155$) were both not significant, suggesting no relationship between SDMT standard score or task and participants' ability to modify mean pause length when increasing rate.

For participants with PD, the model examining the change in mean pause length between habitual and fast conditions revealed an interaction of SDMT and task that was significant (b =

0.004, p = 0.0467, Figure 10), indicating relatively consistent predicted mean pause length across SDMT standard scores on the paragraph. However, a higher SDMT standard score was associated with a smaller reduction of mean pause length on the sentence reading task and a lower SDMT score, or greater cognitive impairment, was associated with a greater degree of reduction on this task. Individual data points are shown in Figure 11.

Figure 10. PD Change in Mean Pause Length-Speed Up SDMT by Task Interaction

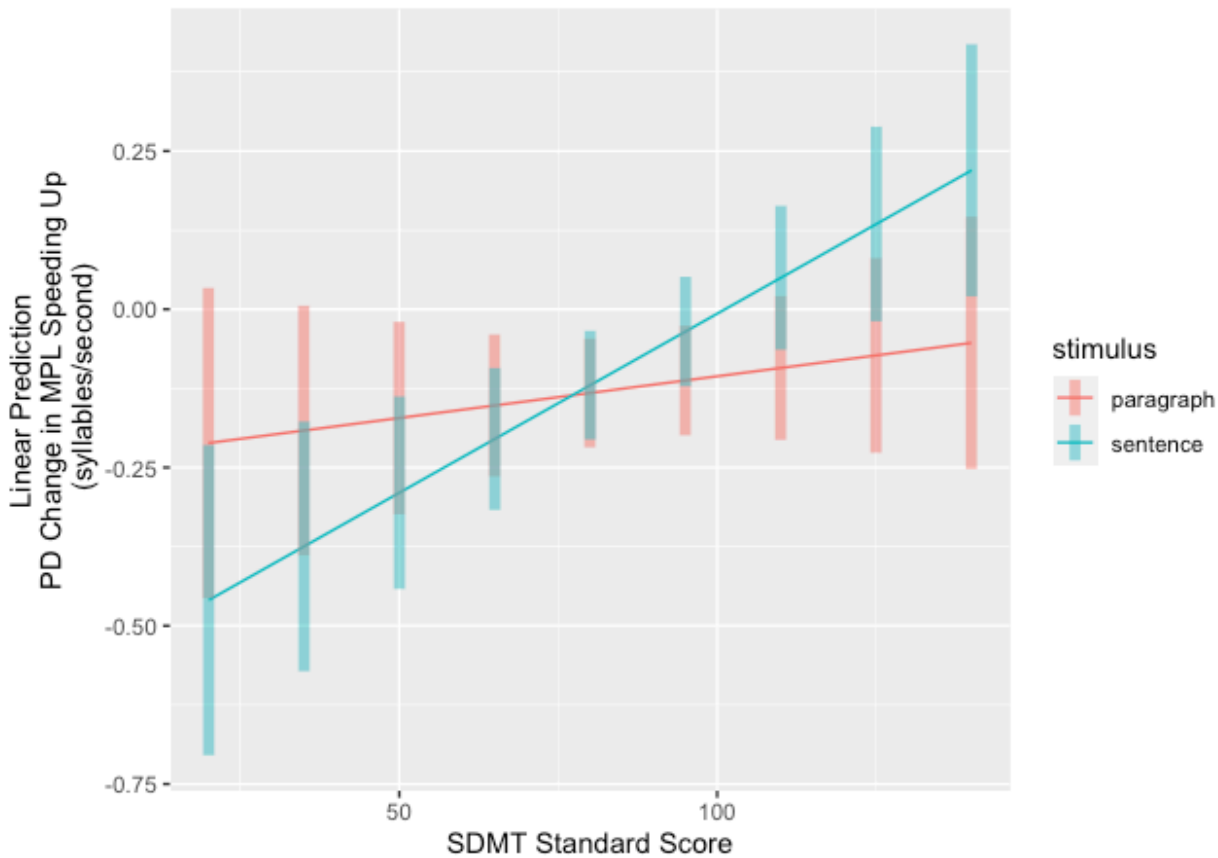
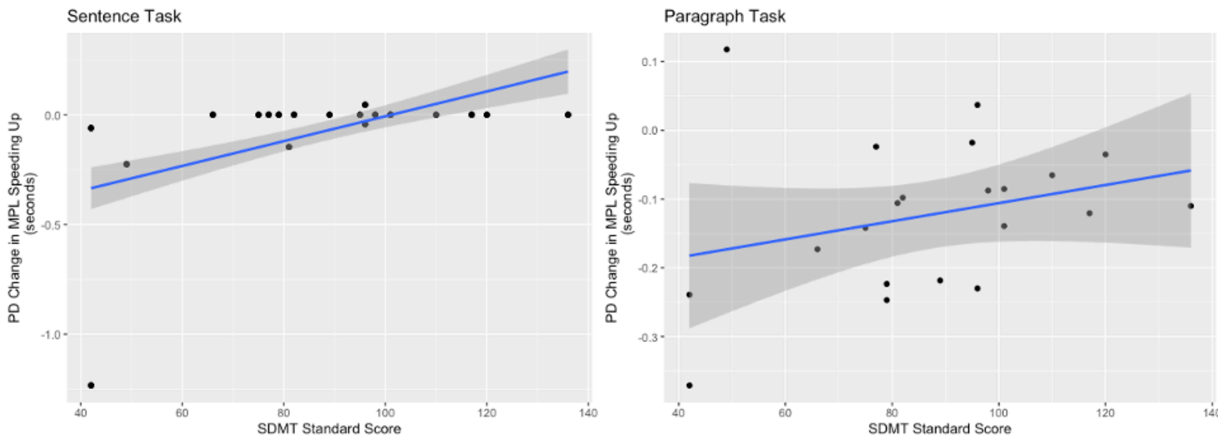


Figure 11. PD Participants' SDMT Scores by Change in Speed Up MPL



The SDMT by task interaction of mean pause length when speeding up for the HDNC and PDNC group was not significant (p = 0.859). Due to concerns for model overfitting (e.g., singularity), the model was reduced in complexity by removing the random effect of participant and leaving all other model components intact. Model output was identical to the initial version which is reported here. The interaction was removed from the model. The main effect of SDMT was not significant, suggesting that control participants' ability to change mean pause length when speeding up is not related to SDMT performance. The main effect of task was significant (b = 0.0840653, p < 0.001) with control participants presenting with reduced ability to change mean pause length when speeding up.

Habitual to slow mean pause length change and SDMT. In the initial model examining the change in mean pause length between habitual and slow conditions for participants with HD, the interaction of SDMT and task was significant (b = 0.005, p = 0.029, Figure 12). This indicates participants with HD who present with higher cognitive ability have a smaller degree of change in mean pause length when slowing down on the paragraph reading task, However, the participants with HD are changing mean pause length more in order to slow down on the sentence reading task. Individual data points are shown in Figure 13.

Figure 12. HD Change in Mean Pause Length-Slow Down SDMT by Task Interaction

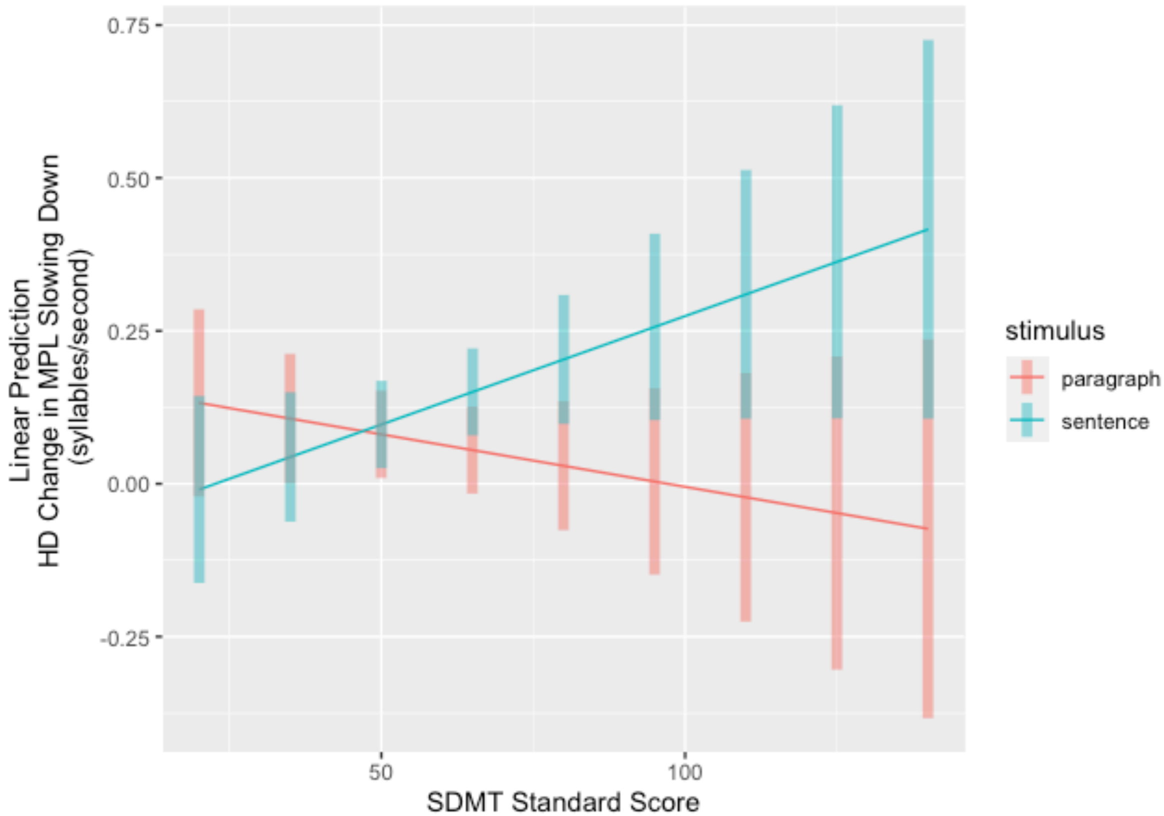
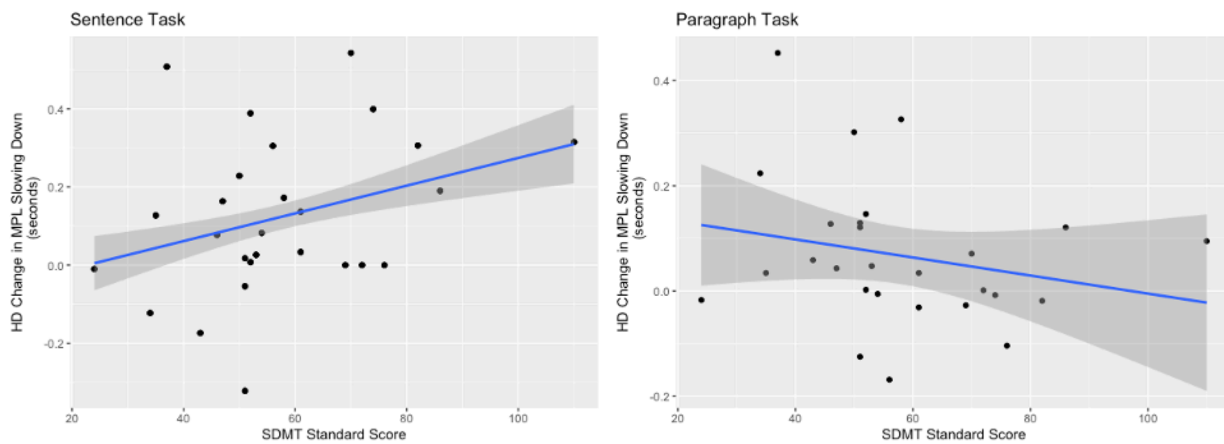


Figure 13. HD Participants' SDMT Scores by Change in Slow Down MPL



For participants with PD, the initial model examining the change in mean pause length between habitual and slow conditions included an interaction of SDMT and task that was not significant ($p = 0.511$) and was removed from the model. The main effects of SDMT ($p = 0.193$) and task ($p = 0.792$) were also not significant, indicating no relationship between SDMT standard score or task and ability to alter mean pause length when reducing rate for participants with PD.

For participants in the HDNC and PDNC groups, the initial model examining the change in mean pause length between habitual and slow conditions included an interaction of SDMT and task that was not significant ($p = 0.070$) and was removed from the model. The main effect of SDMT was not significant ($p = 0.512$), indicating no relationship between performance on the SDMT and ability to alter mean pause length when decreasing rate. The main effect of task was significant ($b = 0.09$, $p = 0.006$), indicating that control participants demonstrate a greater ability to alter mean pause length when reducing rate on the sentence reading task relative to the paragraph reading task.

CHAPTER IV

DISCUSSION

Many neurogenic communication disorders result in observable changes to motor speech functioning and cognitive ability. Yet, our understanding of how changes in these two domains (i.e., motor speech and cognitive) interact and how they relate to speech timing and responsiveness to strategy use (i.e., manipulating rate) has been limited. Although it is common to consider neurogenic communication disorders within a specific domain (i.e., either motor, cognitive, or language), this leaves a substantial lack of knowledge to support clinical practice in populations with dual motor and cognitive impairment as all individuals, including healthy adults, utilize some combination of motor speech and cognitive abilities in order to communicate both effectively and efficiently. We must be able to precisely and accurately move our articulators as well as meet the cognitive demands of the speech task (e.g., reading aloud, conversing). Further, when we attempt to alter our rate as when using speech therapy techniques to, for example, reduce rate, we need to be able to implement a strategy (i.e., recall the strategy and maintain it) throughout task completion.

The goal of this current project was to improve our understanding of the influence of motor (i.e., dysarthria) and cognitive abilities (e.g., processing speed) on habitual speech timing, and the ability to modify rate in both individuals with neurogenic communication disorders at risk for cognitive and motor decline and healthy adults. It is reasonable to assume that impairment in cognition may differentially impact individuals' performance across motor speech assessment tasks. Further, cognitive deficits may contribute to individual's immediate responsiveness to commonly employed intervention strategies (i.e., ability to volitionally alter rate). An improved understanding of the role of cognition in participant task performance and their ability to respond to rate modification will provide speech-language pathologists with a better understanding of how dual motor and cognitive impairments may influence treatment recommendations and treatment response. The implications of the current study's findings may lead to an improved understanding of the interaction of motor speech functioning and cognition in speech production and the differences in speech timing across tasks of cognitive-linguistic demand in both disordered and neurotypical groups. Additional information of task-dependent performance will lead to a better understanding for the selection and interpretation of motor speech evaluations.

Habitual Speech Timing Across Groups and Tasks

Research Question 1a

> **How is habitual speech timing (e.g., articulation rate, speech rate, mean pause length) influenced by speech task (e.g., sentence reading, paragraph reading) and participant group (e.g., HD versus HCNC, PD versus PDNC)?**

Consistent with predictions for research question 1a, participants with HD differed significantly from controls in both articulation rate (i.e., reduced articulation rate relative to controls) and in pause-related measures (i.e., reduced speech rate, increased mean pause length relative to controls). The reduced articulation rate for individuals with HD was observed across all speech tasks and likely reflects the impact of the individuals' motor deficit on speech production regardless of task complexity. These findings of generally reduced articulation rate in HD are consistent with previous acoustic analyses with findings of reduced articulation rate within the population due to impaired motor control on both paragraph and monologue tasks (Chan et al., 2022; Rusz et al., 2014). Our findings expand upon this previous work to indicate that sentence-level stimuli may also be sensitive to effects of motor deficits in HD. However, it is important to note that participants with HD also had notably slower speech rate and increased mean pause lengths compared to HDNCs. This difference in pausing behavior for the HD group, paired with the high level of intelligibility in the group, suggests that cognitive ability may be at least contributing in some degree to participant performance beyond that of articulation ability alone.

One possible explanation of slowed articulation rate, speech rate and increased pause lengths is that individuals with HD anticipate the task demands will result in motoric difficulty, and independently employ some degree of increased pausing and slowed articulation as a form of compensatory strategy for their reduced habitual motor control when reading aloud. Similar findings of reduced speaking rate to compensate for decreased articulation control have been reported in aging adults (Mefferd & Corder, 2014) and ALS (Turner & Weismer, 1993; Weismer et al., 2000). As the HD group can increase rate to some degree (Tables 2 and 3), we know they are not speaking at maximum motor capacity habitually. Alternatively, and likely, the combined increased pause duration and decreased habitual speech rate may reflect the changes in cognitive function experienced by individuals with HD compared to controls. As suggested by Feenaughty and colleagues (2013), the longer pauses may be reflective of reduced processing speed as well. Given the group's higher degree of processing speed deficit as the HD group presents with the lowest SDMT scores among study groups, and the general increased cognitive dysfunction associated with HD from early in disease progression (Papoutsi et al., 2014), an association with processing speed ability would be unsurprising. Although the current study includes only reading tasks, these findings are consistent with previous literature that has reported associations between pausing behavior, cognitive ability, and the cognitive complexity of a task during forms of spontaneous speech (Rochester, 1971; Walker, 1988b), and increased pausing behavior during habitual speech tasks in other neurogenic disorders experiencing cognitive deficits (Y. T. Wang et al., 2005).

As hypothesized, participants with PD performed more similarly on speech timing measures to matched controls despite presenting with a perceivable dysarthria. Consistent with previous work comparing sentence and paragraph level reading tasks in this population, articulation rate was comparable to controls (Lowit et al., 2006). In the current study, we extend these findings and show a similarity in performance between the PD group and PDNC group for speech rate and pause length, as well. The PD group also presented with a higher mean SDMT standard score, indicating less processing speed impairment and a high intelligibility compared to the HD group. The lack of significant findings for habitual speech timing differences between PD and PDNC may reflect the increased intelligibility and processing speed ability in the PD group compared to the degree of impairment seen in the HD group. It may be that the participants with PD presented with less cognitive and/or motor dysfunction to impact ultimate performance. Thus, the potential effects of cognitive decline on speech timing measures was not observed. Based upon these group comparison differences between HD versus HDNC and PD versus PDNC, clinicians might anticipate a greater deviation from typical rate performance in a population such as HD which typically presents with a greater degree of cognitive impairment beyond dysarthria compared to that of PD and may warrant additional supports (i.e., external aids) during intervention.

Findings related to task differences for habitual articulation rate are in partial agreement with study predictions. Task differences were not well anticipated for articulation rate. The observed faster habitual articulation for HDNC on the sentence versus paragraph task is consistent with previous speech kinematic research suggesting that healthy, young adults demonstrate reduced motor control on tasks of higher cognitive-linguistic complexity (Dromey & Bates, 2005; Dromey & Benson, 2003). Therefore, it’s possible that healthy adults without neurological diagnoses may vary in articulation rate depending on the complexity of the given task. Alternatively, the finding of HD and HDNC’s increased articulation rate on sentence reading and decreased rate on the paragraph reading may also be consistent with previous reports of possible formal styles of speaking when reading paragraph-level material aloud for some individuals (Feenaughty et al., 2013). Although, the previous work found a slower rate at the paragraph level compared to a spontaneous narrative in a population with dual motor and cognitive impairment (Feenaughty et al., 2013), perhaps when taking on a more ‘storytelling’ role on a less familiar task like the paragraph reading, some speakers are reducing rate or increasing aspects such as pausing for story effect and emphasis. However, this task difference was not present among the PD and PDNC groups, consistent with predictions. This lack of consistency, at least across the control groups, may require further investigation for other possible contributing factors (i.e., age differences). For most groups, it appears that the motor demands of the task to drive articulation rate may be comparable.

For measures accounting for pausing behavior (e.g., speech rate, mean pause length), both participants with HD, PD, and their respective matched controls (HDNC and PDNC, respectively) demonstrated increased speech rate and decreased pausing on the sentence reading task compared to the paragraph reading task. It is possible that the reduction in pausing and faster speech rate on the sentence task is indicative of the task's lower cognitive complexity in comparison to the paragraph reading. The brief, sentence reading task represents presumed lower cognitive demand. The longer, passage reading is thought to recruit additional cognitive resources for an increased duration of time. This suggests that while articulation rate may not change as much across sentence and paragraph reading tasks, pausing behavior may be more sensitive to task differences at the habitual rate, leading to increased pause lengths and decreased speech rate on the more complex paragraph reading task.

Research Question 1b

Is there a relationship between habitual speech timing (e.g., articulation rate, speech rate, mean pause length) and performance on the SDMT within groups (e.g., HD, PD, All Control)?

Consistent with predictions for research question 1b, participants with HD and PD demonstrated an association between SDMT performance (i.e., processing speed ability) and all habitual speech timing measures (i.e., articulation rate, speech rate, mean pause length). It was predicted that participants with superior processing speed performance would have faster articulation and speech rate and reduced mean pause length. The data revealed just this, in the HD and PD groups, as processing speed declined, speech rate and articulation rate were slower and mean pause length increased. These findings expand upon previous reports of the association between SDMT performance and a measure similar to articulation rate on a paragraph reading task with participants with early HD (Chan et al., 2022). Processing speed may not play an isolated role in speech rate and pause length, associated with cognition, but also in articulation or motor control (i.e., articulation rate). The present study further supports that processing speed may also impact measures of speech timing beyond articulation rate (i.e., speech rate, pause length) and the less complex, sentence reading level in HD and also in PD despite differing underlying neuropathology. Patients with HD who have earlier, or greater levels of reduced processing speed may present with habitual rate that is dramatically reduced at baseline while their motor speech system and intelligibility remain fairly intact.

Although their overall degree of cognitive impairment was not as severe as the HD group in the present study, the PD group was found to have similar associations with greater processing speed ability associated with increased articulation rate, increased speech rate, and decreased mean pause length. Those with PD and a less dramatic deficit in processing speed may still present with slower rate and increased pausing when compared to cognitively intact patients. Therefore, processing speed is an essential component of efficient speech production and insults to processing speed may negatively impact efficient communication in these degenerative populations beyond the influence of motoric functioning alone. These findings confirm predictions and previous studies associating cognitive decline with decreased speech and articulation rate and increased pausing behavior (Chan et al., 2022; Rochester, 1971; Rodgers et al., 2013; Walker, 1988b). It's also possible that some of the observed variations of rate within dysarthric populations (Diehl et al., 2019; Kim et al., 2022) is linked to differential cognitive ability, including processing speed, among patients. Perhaps when speakers were identified as differentially faster or slower in comparison to one another (Diehl et al., 2019; Kim et al., 2022), they differed in underlying cognitive functioning. The current study expands this work to suggest that some degree of rate variability may be driven by the specific construct of processing speed. Speech therapists must consider both motor and cognitive abilities of patients when evaluating patients with motor speech disorders' habitual abilities, particularly when these patients present with diagnoses at risk for reduced processing speed.

In contrast with predictions for research question 1b, the only group to present with no association between measures of speech timing and processing speed was the combined control sample. Given the high SDMT performance of the control participants, there may not be enough variability in the combined control sample's SDMT scores to reveal an association with habitual speech timing measures. It is possible that there could be an unknown point at which decline in processing speed begins to impact habitual speech timing, and the control sample is performing above this "cutoff" point. As we see associations between SDMT performance and speech timing measures in HD and PD, It may be that the point of SDMT impact on speech timing is lower in individuals with simultaneous motor deficits, explaining the lack of association for controls.

Also differing from predictions, no interactions between SDMT performance and speech task were observed, suggesting no differential impact of processing speed ability on measures of speech timing between sentence reading and paragraph reading. Although the tasks differ in duration (i.e., sentence reading is shorter duration than paragraph reading), it may be that these tasks involve similar underlying skills such as decoding and self-monitoring. Thus, processing speed ability may have impacted performance similarly on each task. Future research may need to include tasks with more distinct task differences in processing speed, or other cognitive skill, requirements to determine possible differences in task cognitive load.

Of note, we do find a common theme of main effects of task wherein participants present with increased speech rate and decreased pause length on the sentence compared to the paragraph reading. There are two possible explanations for these findings and both relate to task differences, including physiological and cognitive requirements for each. First, with regard to physiological requirements, the sentence reading task is brief and participants do not need to pause as frequently to breathe or transition between phrases. In comparison, the paragraph reading task requires participants to scan between lines, maintain speech for a longer duration, and involves more opportunities for breathing and natural pausing behavior between phrases. Possible that ceiling impacts influence opportunities for pausing during the sentence task, given the low requirement to breathe or transition during that task in particular. Alternatively, another cognitive construct may be more important than processing speed in habitual speech timing. For example, other cognitive skills in the domains of memory, attention, or executive functioning may be able to differentiate speech timing behavior in the control cohort.

Ability to Modify Rate Across Groups and Tasks

Research Question 2a

> **How is ability to modify speech timing (e.g., change in articulation rate, change in speech rate, change in mean pause length) from habitual rate to fast or slow rate influenced by speech task (e.g., sentence or paragraph reading) and participant group (e.g., HD versus HDNC, PD versus PDNC)?**

Consistent with predictions for research question 2a, all groups demonstrate ability to alter rate to some degree. The group with HD presented with the most restricted ability to modify rate volitionally in comparison to other study groups, as evident through descriptive statistics of mean change scores across measures of speech timing (Tables 4 and 5). These findings are consistent with previous reports of significant correlations between cognition and ability to modify rate in a study including older adults with mild cognitive impairment, individuals with PD, and healthy controls (Lowit et al., 2006). The reduced ability of the HD group to modify rate across speech timing measures associated with pausing, rather than articulation rate alone, may similarly be associated with the group's increased degree of cognitive deficit.

In contrast with predictions for research question 2a, the group with PD did not differ significantly in ability to increase or decrease rate when compared to matched controls. The participants with PD demonstrated fairly comparable change scores relative to controls and no significant group comparisons for rate modification were identified for articulation rate, speech rate, or mean pause length. This might suggest that the degree of cognitive or motor deficit in the PD group was not significant enough to impact modification of speech timing for the control sample. Although individuals with PD are reported to be at risk for a range of cognitive disorders ranging in severity from mild cognitive impairment to dementia, the occurrence of mild cognitive disorders is reported in more than 50% of cases across disease progression (Sollinger et al., 2010). The PD population is six times more likely to develop overt dementia over time with advanced age and motor dysfunction (Aarsland et al., 2001; Levy, Schupf, et al., 2002), supporting the likelihood of profound changes in cognition in later disease stages. It is possible that additional differences in speech timing and rate manipulation may manifest further in disease progression given the overall mild disease status of the PD cohort. To better understand this issue in PD, future research should recruit a larger range of dysarthria and cognitive impairment in the PD cohort.

Furthermore, similar to the findings during the habitual rate trials, across participant groups, differences in ability to modify rate were observed between tasks. That is, participants were able to modify articulation rate and mean pause length to a greater degree on sentence reading in comparison to paragraph reading. This finding was also observed for speech rate in the slow speaking rate condition, but not in the fast speaking rate condition. As with habitual rate, these differences are important to note as both tasks are commonly used to evaluate speech production in neurogenic communication disorders. Clinicians should use an array of tasks such as sentence and paragraph reading to understand a patients' true rate manipulation ability when probing for possible intervention strategies (i.e., reducing rate to increase intelligibility). Only administering a paragraph task may limit understanding of the patient's ability to volitionally slow down, for example. It may be that these observed task differences are driven by the differing nature of the tasks' physiological demands (i.e., need to breathe/pause to sustain speech on paragraph), a differing level of cognitive complexity between tasks (i.e., increased time duration, scanning between lines on the paragraph), or some combination of both. The finding that there are no task-related differences in the ability to speed up speech rate is interesting. This might mean that in some way, as in research question one, the differences in the reading task demands are very similar. Alternatively, participants could already be speaking at or near capacity on these reading level tasks. By including tasks with less familiarity or longer, spontaneous narratives, we may see more variation in participant performance. Future studies including a larger array of tasks that recruit different underlying skillsets must be done to better understand this finding. However, it is unknown why this finding is unique to the speeding up condition. It may be that speakers are not manipulating pausing and articulation to the same ratios as in other speech timing measures when speeding up, as both factor into speech rate change.

Differing from above task differences is that of mean pause length. The PD and PDNC groups demonstrate a greater ability to speed up rate by reducing mean pause length on the sentence compared to the paragraph reading. Further, the HD and HDNC groups demonstrate an inverse relationship with task and mean pause length when attempting to increase rate. Those with HD change or reduce mean pause length more when speeding up on the sentence compared to the paragraph. Those in the HDNC group are able to reduce mean pause length more when attempting to increase rate on the paragraph compared to the sentence task. It is possible the HDNC participants are simply speaking at or near capacity on the sentence reading task, with limited opportunity to demonstrate pausing behavior at baseline but utilize pausing to a greater degree with increased natural occurrences during the paragraph task. In other words, the HDNC group has more opportunity to reduce or alter pausing behavior on paragraph-level stimuli. People with HD may be having more trouble manipulating rate during the paragraph task due to increased cognitive load. Anecdotally, patients with HD were observed to have difficulty scanning between lines and may have struggled to maintain a strategy, such as slowing down, on the longer, paragraph task. When slowing down, it appears that mean pause length does not present with any group or task differences. As previously discussed, the limited variability in participant performance on this measure and potential ceiling effects may have impacted findings.

Research Question 2b

Is there a relationship between change in speech timing measures (e.g., change in articulation rate, change in speech rate, change in mean pause length) from habitual rate to fast or slow rate and performance on the SDMT within groups (e.g., HD, PD, All Control)?

In partial agreement with predictions for research question 2b, we find mixed results related to the importance of processing speed in supporting the ability to manipulate rate. In the fast rate condition, among the neurotypical control groups, the degree of increase in articulation rate and speech rate was associated with increased SDMT score. Thus, individuals who demonstrated better processing speed on the SDMT were able to increase articulation rate and speech rate to a greater degree than individuals with worse processing speed performance. In contrast, neither the HD or PD groups demonstrated a relationship between SDMT performance and ability to increase articulation or speech rate. The significant association in the control group may indicate that a higher level of processing speed could actually play some role in motor planning for exceeding habitual articulation rate beyond that of motor control alone in healthy adults as well as influence pausing behavior. Existing research supports the important role of processing speed, among other cognitive abilities, to limb-motor planning in the context of age-related motor decline (Stöckel et al., 2017). Future research should investigate the age difference between processing speed and motor ability across the age span of the HDNC and PDNC groups to better understand how these limb-motor findings translate to motor speech planning. As mean pause length was not associated with controls' SDMT when speeding up, it may be that pausing is less frequent, rather than of shorter durations, to drive rate change or participants rely more upon motor manipulation. However, as previously discussed, mean pause length interpretation may be limited in this study due to potential ceiling effects.

In the slow rate condition, the HD group was the only group to demonstrate a relationship between articulation rate and speech rate reduction and processing speed, as measured by the SDMT. Increased processing speed was associated with an increased ability to reduce rate, and this difference was greatest on the sentence task versus the paragraph task. Therefore, patients presenting with reduced processing speed in clinic may have the most difficulty responding to rate reduction strategies to improve intelligibility. Further work must be done to determine how to optimize intervention (i.e., increased frequency, duration changes, external aids) to better support effective rate change when cognition is impaired. Interestingly, some participants with severely reduced processing speed increased, rather than decreased, speech rate when prompted to slow down. These findings are consistent with previous reports of reduced manipulation of rate in populations with cognitive impairment (Lowit et al., 2006) but add support for the specific construct of processing speed across the change of multiple speech timing measures in HD. Paired with the association of higher cognitive ability and reduced mean pause length when reducing rate in HD, there is strong evidence for an influence of cognition on participant performance. Given the great degree of processing speed deficit in this group, this provides evidence to support the importance of the cognitive construct of processing speed and its predictive ability for change in speech timing when impaired. Strong relationships between processing speed and rate control were not as evident in the PD and neurotypical control groups, aside from when controls increased rate. As discussed related to group and task differences for rate modification, this lack of association may be a result of overall reduced severity and variability of cognitive and motor performance within these groups.

Limitations and Future Directions

This project provides an exploratory look at the interaction of motor and cognitive contributions to speech production within the HD, PD, and healthy adult populations. It is part of a larger goal to develop clinical guidelines on the influence of multiple cognitive domains on speech timing across tasks with additional variation in cognitive-linguistic demands. For this project, I have investigated a subset of commonly used speech production tasks and participant performance on one cognitive skill, processing speed, relative to speech timing. Future research should expand upon task-related differences in speech timing performance, ability to manipulate rate with intervention, and the potential impact of additional cognitive constructs relative to speech timing and rate modification.

Additional research to improve our understanding of task-related differences is warranted given the limitation of similar reading tasks within the present study. Additional connected speech tasks beyond reading aloud (i.e., cartoon descriptions, spontaneous narratives, etc.) may require additional demands of processing speed, or simply different underlying skills for efficient completion (i.e., attention, memory). As the current study is part of a larger data set, incorporating findings from additional collected tasks into future analyses is imperative to expand our understanding of their potential influence on habitual speech timing as well as in rate modification across a larger span of stimuli. A long-term goal is to provide clinicians with guidance on interpretation of commonly used motor speech assessment and treatment tasks when administered to patients with motor and cognitive disorders.

While we present interesting findings related to clinical populations' ability to volitionally alter speaking rate, these findings must be interpreted with caution relative to intervention success. The rate modification tasks in the present study served as probing tasks of baseline ability to respond to verbal directions to alter rate. No additional training was provided. It is important to note that participants may respond differently to rate manipulation with additional intervention and modeling. Future research should determine whether patients with co-occurring motor and cognitive deficits respond differently to various methods of instruction and support relative to intervention (i.e., written/visual supports, external aids, modeling, frequency and dosage of intervention).

The SDMT, used in the current study, is often used as a measurement of processing speed and attention ability, is shown to be associated with speech timing research (Chan et al., 2022; Rodgers et al., 2013). However, it is plausible that other cognitive domains may differentially impact patient performance on different connected speech tasks or differentially impact performance on habitual rate versus ability to modify rate. For example, the present study found stronger associations between habitual measures of speech timing and processing speed compared to ability to modify rate and processing speed. It may be that rate modification recruits more cognitive support from other domains, such as working memory, that weren't considered in the present analyses. The inclusion of testing related to other cognitive subsystems such as memory, attention, and executive functions may be valuable to better understand how a patient's unique constellation of cognitive and motor speech deficits impacts speech production and ability and stimulability for rate modification. By expanding our understanding of additional cognitive domains relative to speech timing, researchers can develop improved guidelines for clinicians to capitalize on intact abilities and accommodate for those hindering efficient and effective communication simultaneously.

APPENDIX A

RESEARCH QUESTION 1-PART 1:
HABITUAL RATE DIFFERENCES BETWEEN PARTICIPANT GROUPS AND TASKS
HUNTINGTON'S DISEASE AND MATCHED CONTROLS
Tables of results for model investigating habitual articulation rate (outcome variable) predicted by Group (HD v. HDNC) and Stimulus (sentences v. paragraphs) with a random effect of participant.

Articulation Rate – Habitual Condition Model (HD):

articulation_rate_habitual ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.28614	0.5349
Residual		0.07058	0.2657

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	4.78817	0.13033	55.98515	36.738	< 2e-16 ***
Group	-1.19059	0.17378	55.98515	-6.851	6.1e-09 ***
Stimulus	0.24516	0.08198	45.99818	2.990	0.00447 **
Group*Stimulus	-0.29607	0.10931	45.99818	-2.708	0.00946 **

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

Predicted Values:

Group	stimulus	emmean	SE	df	lower.CL	upper.CL
HDNC	paragraph	4.79	0.130	56	4.53	5.05
HD	paragraph	3.60	0.115	56	3.37	3.83
HDNC	sentence	5.03	0.130	56	4.77	5.29
HD	sentence	3.55	0.115	56	3.32	3.78

Degrees-of-freedom method: kenward-roger
Confidence level used: 0.95

Simple Effects:
stimulus = paragraph:

contrast	estimate	SE	df	t.ratio	p.value
HD - HDNC	-1.19	0.174	56	-6.851	<.0001

stimulus = sentence:

contrast	estimate	SE	df	t.ratio	p.value
HD - HDNC	-1.49	0.174	56	-8.555	<.0001

Table of results for models investigating habitual speech rate (outcome variable) predicted by Group (HD v. HDNC) and Stimulus (sentences v. paragraphs) with a random effect of participant.

Speech Rate – Habitual Condition Initial Model (HD):

speech_rate_habitual ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.37340	0.6111
Residual		0.09417	0.3069

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	4.1697	0.1492	56.1742	27.945	< 2e-16 ***
Group	-1.5538	0.1989	56.1742	-7.810	1.56e-10 ***
Stimulus	0.8360	0.0947	46.0000	8.827	1.84e-11 ***
Group*Stimulus	-0.1279	0.1263	46.0000	-1.013	0.316

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

Speech Rate – Habitual Condition Model (HD):

speech_rate_habitual ~ Group + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.37338	0.611
Residual		0.09422	0.307

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	4.20572	0.14493	50.50125	29.019	< 2e-16 ***
Group	-1.61774	0.18867	46.00000	-8.574	4.27e-11 ***
Stimulus	0.76405	0.06266	47.00000	12.194	3.65e-16 ***

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

Table of results for models investigating habitual mean pause length (outcome variable) predicted by Group (HD v. HDNC) and Stimulus (sentences v. paragraphs) with a random effect of participant.

Mean Pause Length – Habitual Condition Initial Model (HD):

mean_pause_length_habitual ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.02451	0.1565
Residual		0.02955	0.1719

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.47627	0.05074	76.31628	9.387	2.34e-14 ***
Group	0.25799	0.06765	76.31628	3.814	0.000276 ***
Stimulus	-0.45458	0.05305	46.00000	-8.568	4.36e-11 ***
Group*Stimulus	-0.04111	0.07074	46.00000	-0.581	0.563943

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

Mean Pause Length – Habitual Condition Initial Model (HD):

mean_pause_length_habitual ~ Group + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.02472	0.1572
Residual		0.02914	0.1707

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	0.48784	0.04663	60.57687	10.462	3.35e-15 ***
Group	0.23744	0.05767	46.00000	4.117	0.000158 ***
Stimulus	-0.47770	0.03484	47.00000	-13.710	< 2e-16 ***

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

PARKINSON’S DISEASE AND MATCHED CONTROLS

Tables of results for model investigating habitual articulation rate (outcome variable) predicted by Group (PD v. PDNC) and Stimulus (sentences v. paragraphs) with a random effect of participant.

Articulation Rate – Habitual Condition Initial Model (PD):

articulation_rate_habitual ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.22793	0.4774
Residual		0.07302	0.2702

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	4.60805	0.13715	44.48435	33.599	<2e-16 ***
Group	-0.05574	0.18205	44.48435	-0.306	0.761
Stimulus	0.16003	0.09554	35.00000	1.675	0.103
Group*Stimulus	-0.10373	0.12682	35.00000	-0.818	0.419

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

Articulation Rate – Habitual Condition Model (PD):

articulation_rate_habitual ~ Group + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.22826	0.4778
Residual		0.07235	0.2690

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	4.63749	0.13231	39.13045	35.051	<2e-16 ***
Group	-0.10760	0.17065	35.00000	-0.631	0.532
Stimulus	0.10116	0.06254	36.00000	1.618	0.114

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

Tables of results for model investigating <u>habitual speech rate</u> (outcome variable) predicted by Group <u>(PD v. PDNC)</u> and Stimulus <u>(sentences v. paragraphs)</u> with a <u>random effect of participant</u>.

<u>Speech Rate – Habitual Condition Initial Model (PD):</u>

speech_rate_habitual ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.3592	0.5993
Residual		0.1043	0.3229

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	4.04113	0.17020	43.73099	23.744	< 2e-16 ***
Group	-0.30307	0.22591	43.73099	-1.342	0.187
Stimulus	0.71700	0.11416	35.00000	6.281	3.3e-07 ***
Group*Stimulus	0.06549	0.15153	35.00000	0.432	0.668

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

<u>Speech Rate – Habitual Condition Model (PD):</u>

speech_rate_habitual ~ Group + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.3604	0.6003
Residual		0.1019	0.3192

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	4.02255	0.16458	38.74189	24.44	< 2e-16 ***
Group	-0.27033	0.21283	35.00000	-1.27	0.212
Stimulus	0.75417	0.07422	36.00000	10.16	4.04e-12 ***

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

Tables of results for model investigating habitual mean pause length (outcome variable) predicted by Group (PD v. PDNC) and Stimulus (sentences v. paragraphs) with a random effect of participant.

Mean Pause Length – Habitual Condition Initial Model (PD):

mean_pause_length_habitual ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.01923	0.1387
Residual		0.01889	0.1374

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.48983	0.04881	55.79859	10.036	4.18e-14 ***
Group	0.07672	0.06478	55.79859	1.184	0.241
Stimulus	-0.48433	0.04859	35.00000	-9.968	9.21e-12 ***
Group*Stimulus	0.02277	0.06449	35.00000	0.353	0.726

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

Mean Pause Length – Habitual Condition Model (PD):

mean_pause_length_habitual ~ Group + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.01946	0.1395
Residual		0.01843	0.1357

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.48337	0.04518	44.56637	10.699	6.78e-14 ***
Group	0.08811	0.05619	35.00000	1.568	0.126
Stimulus	-0.47141	0.03156	36.00000	-14.937	< 2e-16 ***

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

RESEARCH QUESTION 1-PART 2:
INFLUENCE OF COGNITIVE SCORE (SDMT STANDARD SCORE) ON HABITUAL RATE BY GROUP

HUNTINGTON'S DISEASE

Tables of results for models investigating habitual articulation rate (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Articulation rate by SDMT– Habitual Condition Initial Model (HD):

articulation_rate_habitual ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.26411	0.5139
Residual		0.06256	0.2501

Number of obs: 54, groups: participant, 27

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	2.681871	0.370849	30.236040	7.232	4.54e-08 ***
SDMT_W_SS	0.015900	0.006149	30.236040	2.586	0.0148 *
Stimulus	-0.319103	0.229513	25.000001	-1.390	0.1767
SDMT_W_SS*Stimulus	0.004657	0.003806	25.000001	1.224	0.2325

Stimulus coded: paragraph = 0, sentence = 1

Articulation rate by SDMT– Habitual Condition Model (HD):

articulation_rate_habitual ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.26351	0.5133
Residual		0.06376	0.2525

Number of obs: 54, groups: participant, 27

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	2.547774	0.354317	25.474748	7.191	1.39e-07 ***
SDMT_W_SS	0.018228	0.005848	24.999999	3.117	0.00455 **
Stimulus	-0.050909	0.068722	26.000001	-0.741	0.46546

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating habitual speech rate (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Speech Rate by SDMT– Habitual Condition Initial Model (HD):

speech_rate_habitual ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2846	0.5334
Residual		0.1112	0.3335

Number of obs: 54, groups: participant, 27

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.166408	0.408196	32.960515	2.857	0.007343 **
SDMT_W_SS	0.025169	0.006769	32.960515	3.718	0.000743 ***
Stimulus	0.627278	0.306009	25.000000	2.050	0.051005 .
SDMT_W_SS*Stimulus	0.001403	0.005074	25.000000	0.277	0.784392

Stimulus coded: paragraph = 0, sentence = 1

Speech Rate by SDMT– Habitual Condition Model (HD):

speech_rate_habitual ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2865	0.5353
Residual		0.1073	0.3275

Number of obs: 54, groups: participant, 27

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.125998	0.381051	25.693540	2.955	0.006612 **
SDMT_W_SS	0.025871	0.006275	24.999999	4.123	0.000361 ***
Stimulus	0.708099	0.089136	26.000000	7.944	2.02e-08 ***

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating habitual mean pause length (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Mean Pause Length by SDMT– Habitual Condition Initial Model (HD):

mean_pause_length_habitual ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.02794	0.1671
Residual		0.04957	0.2227

Number of obs: 54, groups: participant, 27

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.1471596	0.1806461	44.2513434	6.350	1.01e-07 ***
SDMT_W_SS	-0.0071692	0.0029955	44.2513434	-2.393	0.0210 *
Stimulus	-0.5517059	0.2043092	25.0000003	-2.700	0.0122 *
SDMT_W_SS*Stimulus	0.0009726	0.0033879	25.0000003	0.287	0.7764

Stimulus coded: paragraph = 0, sentence = 1

Mean Pause Length by SDMT– Habitual Condition Model (HD):

mean_pause_length_habitual ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.02881	0.1697
Residual		0.04783	0.2187

Number of obs: 54, groups: participant, 27

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.119151	0.151931	26.993414	7.366	6.36e-08 ***
SDMT_W_SS	-0.006683	0.002471	24.999999	-2.705	0.0121 *
Stimulus	-0.495689	0.059520	26.000000	-8.328	8.26e-09 ***

Stimulus coded: paragraph = 0, sentence = 1

PARKINSON'S DISEASE

Tables of results for models investigating habitual articulation rate (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Articulation rate by SDMT– Habitual Condition Initial Model (PD):

articulation_rate_habitual ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.25581	0.5058
Residual		0.03944	0.1986

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	3.359822	0.447944	21.705938	7.501	1.84e-07 ***
SDMT_W_SS	0.013677	0.004954	21.705938	2.761	0.0115 *
Stimulus	0.180842	0.231537	19.000001	0.781	0.4444
SDMT_W_SS*Stimulus	-0.001428	0.002561	19.000001	-0.558	0.5835

Stimulus coded: paragraph = 0, sentence = 1

Articulation rate by SDMT– Habitual Condition Model (PD):

articulation_rate_habitual ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.25649	0.5065
Residual		0.03808	0.1951

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	3.422091	0.433772	19.184028	7.889	1.93e-07 ***
SDMT_W_SS	0.012963	0.004786	18.999998	2.708	0.0139 *
Stimulus	0.056302	0.060225	20.000001	0.935	0.3610

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating habitual speech rate (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Speech Rate by SDMT– Habitual Condition Initial Model (PD):

speech_rate_habitual ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.32152	0.5670
Residual		0.07994	0.2827

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.644898	0.522335	23.151051	3.149	0.004468 **
SDMT_W_SS	0.024007	0.005777	23.151051	4.156	0.000378 ***
Stimulus	1.312665	0.329634	19.000000	3.982	0.000798 ***
SDMT_W_SS*Stimulus	-0.006081	0.003646	19.000000	-1.668	0.111739

Stimulus coded: paragraph = 0, sentence = 1

Speech Rate by SDMT– Habitual Condition Model (PD):

speech_rate_habitual ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.31796	0.5639
Residual		0.08707	0.2951

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.909986	0.497737	19.320695	3.837	0.00108 **
SDMT_W_SS	0.020966	0.005482	19.000000	3.825	0.00114 **
stimulus	0.782490	0.091060	20.000000	8.593	3.79e-08 ***

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating habitual mean pause length (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Mean Pause Length by SDMT– Habitual Condition Initial Model (PD):

mean_pause_length_habitual ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.01446	0.1203
Residual		0.02535	0.1592

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.951093	0.164490	33.571309	5.782	1.73e-06 ***
SDMT_W_SS	-0.004410	0.001819	33.571309	-2.424	0.0209 *
Stimulus	-0.193832	0.185632	19.000000	-1.044	0.3095
SDMT_W_SS*Stimulus	-0.003071	0.002053	19.000000	-1.496	0.1512

Stimulus coded: paragraph = 0, sentence = 1

Mean Pause Length by SDMT– Habitual Condition Model (PD):

mean_pause_length_habitual ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.01368	0.1169
Residual		0.02692	0.1641

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.084956	0.138141	20.320353	7.854	1.39e-07 ***
SDMT_W_SS	-0.005946	0.001502	19.000000	-3.959	0.000842 ***
Stimulus	-0.461559	0.050635	20.000000	-9.115	1.47e-08 ***

Stimulus coded: paragraph = 0, sentence = 1

COMBINED CONTROL SAMPLE (NC = HDNC + PDNC)

Tables of results for models investigating habitual articulation rate (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Articulation Rate by SDMT– Habitual Condition Initial Model (NC):

articulation_rate_habitual ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.15217	0.3901
Residual		0.09066	0.3011

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	4.844534	0.767790	50.262051	6.310	7.07e-08 ***
SDMT_W_SS	-0.001217	0.006922	50.262051	-0.176	0.861
Stimulus	-0.870921	0.663454	35.000000	-1.313	0.198
SDMT_W_SS*Stimulus	0.009785	0.005982	35.000000	1.636	0.111

Stimulus coded: paragraph = 0, sentence = 1

Articulation Rate by SDMT– Habitual Condition Model (NC):

articulation_rate_habitual ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.15006	0.3874
Residual		0.09488	0.3080

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	4.304901	0.693355	35.187199	6.209	4.01e-07 ***
SDMT_W_SS	0.003675	0.006243	34.999999	0.589	0.55982
Stimulus	0.208345	0.071615	36.000000	2.909	0.00617 **

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating habitual speech rate (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Speech Rate by SDMT– Habitual Condition Initial Model (NC):

speech_rate_habitual ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.16980	0.4121
Residual		0.09323	0.3053

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	4.340134	0.799087	49.409603	5.431	1.7e-06 ***
SDMT_W_SS	-0.002049	0.007204	49.409603	-0.284	0.777
Stimulus	-0.315003	0.672805	35.000000	-0.468	0.643
SDMT_W_SS*Stimulus	0.009969	0.006066	35.000000	1.643	0.109

Stimulus coded: paragraph = 0, sentence = 1

Speech Rate by SDMT– Habitual Condition Model (NC):

speech_rate_habitual ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.16760	0.4094
Residual		0.09764	0.3125

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	3.790367	0.725736	35.175800	5.223	8.07e-06 ***
SDMT_W_SS	0.002935	0.006535	34.999996	0.449	0.656
Stimulus	0.784529	0.072648	36.000002	10.799	7.66e-13 ***

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating mean pause length (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Mean Pause Length by SDMT– Habitual Condition Initial Model (NC):

mean_pause_length_habitual ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.001391	0.0373
Residual		0.006626	0.0814

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.647360	0.139508	67.953707	4.640	1.64e-05 ***
SDMT_W_SS	-0.001498	0.001258	67.953707	-1.191	0.237801
Stimulus	-0.693966	0.179360	34.999993	-3.869	0.000455 ***
SDMT_W_SS*Stimulus	0.002054	0.001617	34.999993	1.270	0.212451

Stimulus coded: paragraph = 0, sentence = 1

Mean Pause Length by SDMT– Habitual Condition Model (NC):

mean_pause_length_habitual ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.001335	0.03654
Residual		0.006739	0.08209

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.5340994	0.1072890	35.5582174	4.978	1.65e-05 ***
SDMT_W_SS	-0.0004711	0.0009635	34.9999999	-0.489	0.628
Stimulus	-0.4674442	0.0190855	36.0000000	-24.492	< 2e-16 ***

Stimulus coded: paragraph = 0, sentence = 1

RESEARCH QUESTION 2-PART 1:
CHANGE IN SPEECH TIMING BETWEEN HABITUAL, FAST, AND SLOW CONDITIONS

Tables of results for the change in articulation rate from habitual to fast (outcome variable) predicted by Group (HD v. HDNC) and Stimulus (sentences v. paragraphs) with a random effect of participant.

Articulation Rate – Fast Change Condition Initial Model (HD):

speed_up_artic_rate ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2254	0.4748
Residual		0.1189	0.3449

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.28325	0.12805	64.40180	10.021	9.05e-15 ***
Group	-0.69596	0.17073	64.40180	-4.076	0.000128 ***
Stimulus	0.21565	0.10642	46.00180	2.026	0.048554 *
Group*Stimulus	0.02738	0.14190	46.00180	0.193	0.847863

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

Articulation Rate – Fast Change Condition Model (HD):

speed_up_artic_rate ~ Group + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2266	0.4761
Residual		0.1165	0.3413

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.27555	0.12157	54.17328	10.492	1.17e-14 ***
Group	-0.68227	0.15529	46.00000	-4.393	6.51e-05 ***
Stimulus	0.23105	0.06967	47.00000	3.316	0.00176 **

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

Tables of results for the change in articulation rate from habitual to slow (outcome variable) predicted by Group (HD v. HDNC) and Stimulus (sentences v. paragraphs) with a random effect of participant.

Articulation Rate – Slow Change Condition Initial Model (HD):

slow_down_artic_rate ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.3303	0.5747
Residual		0.1154	0.3397

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-1.3629	0.1457	59.3834	-9.356	2.76e-13 ***
Group	1.2458	0.1942	59.3834	6.414	2.57e-08 ***
Stimulus	-0.4455	0.1048	46.0000	-4.250	0.000103 ***
Group*Stimulus	0.1063	0.1398	46.0000	0.761	0.450816

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

Articulation Rate – Slow Change Condition Model (HD):

slow_down_artic_rate ~ Group + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.3308	0.5751
Residual		0.1143	0.3381

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-1.39278	0.14023	51.91104	-9.932	1.34e-13 ***
Group	1.29898	0.18122	46.00000	7.168	5.11e-09 ***
Stimulus	-0.38568	0.06902	47.00000	-5.588	1.12e-06 ***

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

Tables of results for the change in speech rate from habitual to fast (outcome variable) predicted by Group (HD v. HDNC) and Stimulus (sentences v. paragraphs) with a random effect of participant.

Speech Rate – Fast Change Condition Initial Model (HD):

speed_up_speech_rate ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2352	0.4849
Residual		0.1870	0.4325

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.45515	0.14179	70.21493	10.263	1.30e-15 ***
Group	-0.83661	0.18905	70.21493	-4.425	3.45e-05 ***
Stimulus	0.05844	0.13346	46.00000	0.438	0.664
Group*Stimulus	0.17943	0.17794	46.00000	1.008	0.319

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

Speech Rate – Fast Change Condition Model (HD):

speed_up_speech_rate ~ Group + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2351	0.4849
Residual		0.1871	0.4325

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.40468	0.13266	57.29938	10.588	4.16e-15 ***
Group	-0.74689	0.16680	46.00000	-4.478	4.95e-05 ***
Stimulus	0.15937	0.08829	47.00000	1.805	0.0775

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

Tables of results for the change in speech rate from habitual to slow (outcome variable) predicted by Group (HD v. HDNC) and Stimulus (sentences v. paragraphs) with a random effect of participant.

Speech Rate – Slow Change Condition Initial Model (HD):
slow_down_speech_rate ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.3563	0.5969
Residual		0.1716	0.4142

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-1.4015	0.1586	63.2038	-8.839	1.20e-12 ***
Group	1.1684	0.2114	63.2038	5.527	6.60e-07 ***
Stimulus	-0.6260	0.1278	46.0000	-4.897	1.24e-05 ***
Group*Stimulus	0.2549	0.1704	46.0000	1.496	0.142

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

Speech Rate – Slow Change Condition Model (HD):
slow_down_speech_rate ~ Group + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.3541	0.5950
Residual		0.1761	0.4196

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-1.47316	0.15129	53.96392	-9.737	1.75e-13 ***
Group	1.29589	0.19347	46.00000	6.698	2.59e-08 ***
Stimulus	-0.48257	0.08566	47.00000	-5.634	9.61e-07 ***

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

Tables of results for the change in mean pause length from habitual to fast (outcome variable) predicted by Group (HD v. HDNC) and Stimulus (sentences v. paragraphs) with a random effect of participant.

Mean Pause Length – Fast Change Condition Initial Model (HD):
speed_up_MPL ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.0000	0.0000
Residual		0.0163	0.1277

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.06500	0.02786	92.000	-2.333	0.0218 *
GroupHD	0.04842	0.03715	92.000	1.303	0.1957
Stimulus	0.04885	0.03941	92.000	1.240	0.2182
Group*Stimulus	-0.10845	0.05254	92.000	-2.064	0.0418 *

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

Predicted Values:

Group	stimulus	emmean	SE	df	lower.CL	upper.CL
HDNC	paragraph	-0.0650	0.0279	92	-0.1203	-0.00966
HD	paragraph	-0.0166	0.0246	92	-0.0654	0.03222
HDNC	sentence	-0.0162	0.0279	92	-0.0715	0.03919
HD	sentence	-0.0762	0.0246	92	-0.1250	-0.02738

Degrees-of-freedom method: kenward-roger
Confidence level used: 0.95

Simple Effects:
stimulus = paragraph:

contrast	estimate	SE	df	t.ratio	p-value
HD - HDNC	0.0484	0.0372	92	1.303	0.1957

stimulus = sentence:

contrast	estimate	SE	df	t.ratio	p-value
HD - HDNC	-0.0600	0.0372	92	-1.616	0.1095

Degrees-of-freedom method: kenward-roger

Tables of results for the change in mean pause length from habitual to slow (outcome variable) predicted by Group (HD v. HDNC) and Stimulus (sentences v. paragraphs) with a random effect of participant.

Mean Pause Length – Slow Change Condition Initial Model (HD):

slow_down_MPL ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.001168	0.03417
Residual		0.025190	0.15871

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.098600	0.035428	91.819742	2.783	0.00654 **
Group	-0.030793	0.047237	91.819742	-0.652	0.51610
Stimulus	0.057252	0.048980	45.999999	1.169	0.24848
Group*Stimulus	-0.001192	0.065307	45.999999	-0.018	0.98551

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

Mean Pause Length – Slow Change Condition Model (HD):

slow_down_MPL ~ Group + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.001436	0.03789
Residual		0.024654	0.15702

Number of obs: 96, groups: participant, 48

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.09894	0.03020	77.47162	3.276	0.00158 **
Group	-0.03139	0.03413	45.99996	-0.920	0.36258
Stimulus	0.05658	0.03205	46.99993	1.765	0.08400

Group coded: HDNC = 0, HD = 1
Stimulus coded: paragraph = 0, sentence = 1

PARKINSON'S DISEASE

Tables of results for the change in articulation rate from habitual to fast (outcome variable) predicted by Group (PD v. PDNC) and Stimulus (sentences v. paragraphs) with a random effect of participant.

Articulation Rate – Fast Change Condition Initial Model (PD):

speed_up_artic_rate ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.3258	0.5708
Residual		0.2490	0.4990

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.4161	0.1895	52.9771	7.471	7.89e-10 ***
Group	-0.1754	0.2516	52.9771	-0.697	0.489
Stimulus	0.1234	0.1764	35.0000	0.699	0.489
Group*Stimulus	0.1303	0.2342	35.0000	0.556	0.581

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

Articulation Rate – Fast Change Condition Model (PD):

speed_up_artic_rate ~ Group + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.3282	0.5729
Residual		0.2442	0.4942

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.3791	0.1773	43.1124	7.777	9.66e-10 ***
Group	-0.1102	0.2227	35.0000	-0.495	0.6236
Stimulus	0.1973	0.1149	36.0000	1.717	0.0945

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

Tables of results for the <u>change in articulation rate from habitual to slow</u> (outcome variable) predicted by Group (<u>PD v. PDNC</u>) and Stimulus (<u>sentences v. paragraphs</u>) with a <u>random effect of participant</u>.

<u>Articulation Rate – Slow Change Condition Initial Model (PD):</u>

slow_down_artic_rate ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.3735	0.6112
Residual		0.1491	0.3862

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.82574	0.18074	46.33495	-4.569	3.64e-05 ***
Group	0.09442	0.23991	46.33495	0.394	0.695713
Stimulus	-0.53372	0.13654	35.00000	-3.909	0.000406 ***
Group*Stimulus	0.28538	0.18123	35.00000	1.575	0.124329

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

<u>Articulation Rate – Slow Change Condition Model (PD):</u>

slow_down_artic_rate ~ Group + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.3705	0.6087
Residual		0.1553	0.3940

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.90673	0.17350	40.22134	-5.226	5.67e-06 ***
Group	0.23711	0.22213	35.00000	1.067	0.293094
Stimulus	-0.37174	0.09161	36.00000	-4.058	0.000255 ***

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

Tables of results for the <u>change in speech rate from habitual to fast</u> (outcome variable) predicted by Group (<u>PD v. PDNC</u>) and Stimulus (<u>sentences v. paragraphs</u>) with a <u>random effect of participant</u>.

<u>Speech Rate – Fast Change Condition Initial Model (PD):</u>

speed_up_speech_rate ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2958	0.5438
Residual		0.2790	0.5282

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.59359	0.18953	55.34553	8.408	1.81e-11 ***
Group	-0.20623	0.25158	55.34553	-0.820	0.416
Stimulus	-0.05804	0.18675	35.00000	-0.311	0.758
Group*Stimulus	0.22312	0.24789	35.00000	0.900	0.374

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

<u>Speech Rate – Fast Change Condition Model (PD):</u>

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2965	0.5445
Residual		0.2775	0.5268

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.53027	0.17594	44.49373	8.698	3.74e-11 ***
Group	-0.09467	0.21893	35.00000	-0.432	0.668
Stimulus	0.06860	0.12248	36.00000	0.560	0.579

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

Tables of results for the change in speech rate from habitual to slow (outcome variable) predicted by Group (PD v. PDNC) and Stimulus (sentences v. paragraphs) with a random effect of participant.

Speech Rate – Slow Change Condition Initial Model (PD):

slow_down_speech_rate ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.4939	0.7028
Residual		0.1769	0.4206

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	-0.9838	0.2048	45.3914	-4.805	1.73e-05 ***
Group	0.2095	0.2718	45.3914	0.771	0.444799
Stimulus	-0.6166	0.1487	35.0000	-4.147	0.000204 ***
Group*Stimulus	0.3243	0.1974	35.0000	1.643	0.109379

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

Speech Rate – Slow Change Condition Model (PD):

slow_down_speech_rate ~ Group + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.4897	0.6998
Residual		0.1852	0.4304

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-1.0758	0.1972	39.7967	-5.454	2.8e-06 ***
Group	0.3716	0.2532	35.0000	1.468	0.151166
Stimulus	-0.4326	0.1001	36.0000	-4.323	0.000116 ***

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

Tables of results for the change in mean pause length from habitual to fast (outcome variable) predicted by Group (PD v. PDNC) and Stimulus (sentences v. paragraphs) with a random effect of participant.

Mean Pause Length – Fast Change Condition Initial Model (PD):

speed_up_MPL ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.007667	0.08756
Residual		0.019341	0.13907

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.130692	0.041085	64.779709	-3.181	0.00225 **
Group	0.007917	0.054536	64.779709	0.145	0.88502
Stimulus	0.130285	0.049170	35.000000	2.650	0.01201 *
Group*Stimulus	-0.086819	0.065266	35.000000	-1.330	0.19205

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

Mean Pause Length – Fast Change Condition Model (PD):

speed_up_MPL ~ Group + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.00746	0.08637
Residual		0.01975	0.14055

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.10605	0.03675	51.33999	-2.886	0.0057 **
Group	-0.03549	0.04369	35.00000	-0.812	0.4221
Stimulus	0.08101	0.03268	36.00000	2.479	0.0180 *

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

Tables of results for the change in mean pause length from habitual to slow (outcome variable) predicted by Group (PD v. PDNC) and Stimulus (sentences v. paragraphs) with a random effect of participant.

Mean Pause Length – Slow Change Condition Initial Model (PD):

slow_down_MPL ~ Group * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.01787	0.1337
Residual		0.03418	0.1849

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.08884	0.05704	62.61814	1.558	0.1244
Group	-0.03353	0.07571	62.61814	-0.443	0.6594
Stimulus	0.13451	0.06537	35.00000	2.058	0.0471 *
Group*Stimulus	-0.15361	0.08676	35.00000	-1.770	0.0854

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

Mean Pause Length – Slow Change Condition Model (PD):

slow_down_MPL ~ Group + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.01686	0.1298
Residual		0.03621	0.1903

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.13243	0.05172	49.99195	2.561	0.0135 *
Group	-0.11033	0.06205	35.00000	-1.778	0.0841 .
Stimulus	0.04733	0.04424	36.00000	1.070	0.2918

Group coded: PDNC = 0, PD = 1
Stimulus coded: paragraph = 0, sentence = 1

RESEARCH QUESTION 2-PART 2:
INFLUENCE OF COGNITIVE SCORE (SDMT STANDARD SCORE) ON CHANGE IN SPEECH TIMING OUTCOME VARIABLES BY GROUP

HUNTINGTON'S DISEASE

Tables of results for models investigating the change in articulation rate from habitual to fast conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Articulation rate by SDMT– Fast Change Condition Initial Model (HD):

speed_up_artic_rate ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.16076	0.4010
Residual		0.07553	0.2748

Number of obs: 54, groups: participant, 27

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.047665	0.315405	34.178811	-0.151	0.8808
SDMT_W_SS	0.011025	0.005230	34.178811	2.108	0.0424 *
Stimulus	0.392588	0.252180	25.000000	1.557	0.1321
SDMT_W_SS*Stimulus	-0.002597	0.004182	25.000000	-0.621	0.5402

Stimulus coded: paragraph = 0, sentence = 1

Articulation rate by SDMT– Fast Change Condition Model (HD):

speed_up_artic_rate ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.16166	0.4021
Residual		0.07374	0.2716

Number of obs: 54, groups: participant, 27

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.027116	0.291457	25.816983	0.093	0.92659
SDMT_W_SS	0.009726	0.004794	25.000000	2.029	0.05324 .
Stimulus	0.243026	0.073908	26.000000	3.288	0.00289 **

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating the change in articulation rate from habitual to slow conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Articulation rate by SDMT– Slow Change Condition Model (HD):

slow_down_artic_rate ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.07807	0.2794
Residual		0.09232	0.3038

Number of obs: 54, groups: participant, 27

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.586411	0.267832	41.324922	2.189	0.03426 *
SDMT_W_SS	-0.012215	0.004441	41.324922	-2.750	0.00880 **
Stimulus	0.518845	0.278810	25.000000	1.861	0.07455
SDMT_W_SS*Stimulus	-0.014898	0.004623	25.000000	-3.222	0.00352 **

Simple Slopes:
emtrends(HD_only_slow_artic, ~ stimulus, var = "SDMT_W_SS")

stimulus	SDMT_W_SS.trend	SE	df	lower.CL	upper.CL
paragraph	-0.0122	0.00444	41.3	-0.0212	-0.00325
sentence	-0.0271	0.00444	41.3	-0.0361	-0.01815

Degrees-of-freedom method: kenward-roger
Confidence level used: 0.95

Simple Effects:
SDMT_W_SS = 25:

contrast	estimate	SE	df	t.ratio	p-value
paragraph - sentence	-0.146	0.1719	25	-0.852	0.4025

SDMT_W_SS = 75:

contrast	estimate	SE	df	t.ratio	p.value
paragraph - sentence	0.599	0.1154	25	5.187	<.0001

SDMT_W_SS = 125:

contrast	estimate	SE	df	t.ratio	p.value
paragraph - sentence	1.343	0.3224	25	4.167	0.0003

Degrees-of-freedom method: kenward-roger

Tables of results for models investigating the change in speech rate from habitual to fast conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Speech Rate by SDMT– Fast Change Condition Initial Model (HD):

speed_up_speech_rate ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.1453	0.3812
Residual		0.1864	0.4318

Number of obs: 54, groups: participant, 27

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	-0.173494	0.373725	41.949107	-0.464	0.6449
SDMT_W_SS	0.013752	0.006197	41.949107	2.219	0.0319 *
Stimulus	0.606000	0.396188	25.000000	1.530	0.1387
SDMT_W_SS*Stimulus	-0.006392	0.006570	25.000000	-0.973	0.3399

Stimulus coded: paragraph = 0, sentence = 1

Speech Rate by SDMT– Fast Change Condition Model (HD):

speed_up_speech_rate ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.1455	0.3815
Residual		0.1860	0.4313

Number of obs: 54, groups: participant, 27

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.010572	0.322295	26.714379	0.033	0.9741
SDMT_W_SS	0.010556	0.005255	25.000000	2.009	0.0555
Stimulus	0.237869	0.117390	26.000000	2.026	0.0531

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating the change in speech rate from habitual to slow conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Speech Rate by SDMT– Slow Change Condition Model (HD):

slow_down_speech_rate ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.06399	0.2530
Residual		0.12064	0.3473

Number of obs: 54, groups: participant, 27

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.286735	0.278799	44.638296	1.028	0.309272
SDMT_W_SS	-0.009025	0.004623	44.638296	-1.952	0.057206
Stimulus	0.869419	0.318716	25.000000	2.728	0.011491 *
SDMT_W_SS*Stimulus	-0.021538	0.005285	25.000000	-4.075	0.000408 ***

Stimulus coded: paragraph = 0, sentence = 1

Simple slopes:
emtrends(HD_only_slow_speech, ~ stimulus, var = "SDMT_W_SS")

Stimulus	SDMT_W_SS.trend	SE	df	lower.CL	upper.CL
paragraph	-0.00903	0.00462	44.6	-0.0183	0.000288
sentence	-0.03056	0.00462	44.6	-0.0399	-0.021250

Degrees-of-freedom method: kenward-roger
Confidence level used: 0.95

Simple effects:
SDMT_W_SS = 25:

contrast	estimate	SE	df	t.ratio	p-value
paragraph - sentence	-0.331	0.196	25	-1.684	0.1046

SDMT_W_SS = 75:

contrast	estimate	SE	df	t.ratio	p-value
paragraph - sentence	0.746	0.132	25	5.655	<.0001

SDMT_W_SS = 125:

contrast	estimate	SE	df	t.ratio	p-value
paragraph - sentence	1.823	0.369	25	4.946	<.0001

Degrees-of-freedom method: kenward-roger

Tables of results for models investigating the change in mean pause length from habitual to fast conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Mean Pause Length by SDMT– Fast Change Condition Initial Model (HD):

speed_up_MPL ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.00000	0.0000
Residual		0.02296	0.1515

Number of obs: 54, groups: participant, 27

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.0384459	0.0983153	50.00	0.391	0.697
SDMT_W_SS	-0.0009555	0.0016303	50.00	-0.586	0.560
Stimulus	-0.2023194	0.1390388	50.00	-1.455	0.152
SDMT_W_SS*Stimulus	0.0024781	0.0023055	50.00	1.075	0.288

Stimulus coded: paragraph = 0, sentence = 1

Mean Pause Length by SDMT– Fast Change Condition Initial Model (HD):

speed_up_MPL ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.00000	0.0000
Residual		0.02303	0.1518

Number of obs: 54, groups: participant, 27

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.0329134	0.0726232	51.00	-0.453	0.652
SDMT_W_SS	0.0002835	0.0011545	51.00	0.246	0.807
Stimulus	-0.0596006	0.0413020	51.00	-1.443	0.155

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating the change in mean pause length from habitual to slow conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Mean Pause Length by SDMT– Slow Change Condition Model (HD):

slow_down_MPL ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.006604	0.08126
Residual		0.022182	0.14894

Number of obs: 54, groups: participant, 27

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	0.166637	0.110086	47.500009	1.514	0.1367
SDMT_W_SS	-0.001716	0.001825	47.500009	-0.940	0.3519
Stimulus	-0.246981	0.136665	25.000000	-1.807	0.0828
SDMT_W_SS*Stimulus	0.005262	0.002266	25.000000	2.322	0.0287 *

Stimulus coded: paragraph = 0, sentence = 1

Simple slopes:
emtrends(HD_only_slow_down_MPL, ~ stimulus, var = "SDMT_W_SS")

stimulus	SDMT_W_SS.trend	SE	df	lower.CL	upper.CL
paragraph	-0.00172	0.00183	47.5	-0.005387	0.00196
sentence	0.00355	0.00183	47.5	-0.000126	0.00722

Degrees-of-freedom method: kenward-roger
Confidence level used: 0.95

Simple Effects:
SDMT_W_SS = 25:

contrast	estimate	SE	df	t.ratio	p-value
paragraph - sentence	0.1154	0.0843	25	1.370	0.1828

SDMT_W_SS = 75:

contrast	estimate	SE	df	t.ratio	p-value
paragraph - sentence	-0.1477	0.0566	25	-2.610	0.0151

SDMT_W_SS = 125:

contrast	estimate	SE	df	t.ratio	p-value
paragraph - sentence	-0.4107	0.1580	25	-2.599	0.0155

Degrees-of-freedom method: kenward-roger

PARKINSON'S DISEASE

Tables of results for models investigating the change in articulation rate from habitual to fast conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Articulation rate by SDMT– Fast Change Condition Initial Model (PD):

speed_up_artic_rate ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2989	0.5467
Residual		0.2371	0.4869

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.363302	0.603502	28.986500	0.602	0.552
SDMT_W_SS	0.010063	0.006675	28.986500	1.508	0.142
Stimulus	0.786248	0.567656	19.000000	1.385	0.182
SDMT_W_SS*Stimulus	-0.006108	0.006278	19.000000	-0.973	0.343

Stimulus coded: paragraph = 0, sentence = 1

Articulation rate by SDMT– Fast Change Condition Model (PD):

speed_up_artic_rate ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2992	0.5470
Residual		0.2364	0.4863

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.629599	0.537853	19.754264	1.171	0.256
SDMT_W_SS	0.007009	0.005891	18.999999	1.190	0.249
Stimulus	0.253654	0.150062	20.000000	1.690	0.106

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating the change in articulation rate from habitual to slow conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Articulation rate by SDMT– Slow Change Condition Initial Model (PD):

slow_down_artic_rate ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.3513	0.5927
Residual		0.1018	0.3190

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.373399	0.554904	23.730912	0.673	0.5075
SDMT_W_SS	-0.012670	0.006137	23.730912	-2.064	0.0501 .
Stimulus	-0.844758	0.371888	19.000000	-2.272	0.0349 *
SDMT_W_SS*Stimulus	0.006840	0.004113	19.000000	1.663	0.1127

Stimulus coded: paragraph = 0, sentence = 1

Articulation rate by SDMT– Slow Change Condition Model (PD):

slow_down_artic_rate ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.3468	0.5889
Residual		0.1107	0.3328

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.075186	0.525338	19.366592	0.143	0.8877
SDMT_W_SS	-0.009250	0.005782	19.000000	-1.600	0.1262
Stimulus	-0.248333	0.102695	20.000000	-2.418	0.0253 *

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating the change in speech rate from habitual to fast conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Speech Rate by SDMT– Fast Change Condition Initial Model (PD):

speed_up_speech_rate ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2571	0.5071
Residual		0.3090	0.5559

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.661285	0.620285	31.501319	1.066	0.294
SDMT_W_SS	0.008327	0.006860	31.501319	1.214	0.234
Stimulus	0.864350	0.648071	19.000000	1.334	0.198
SDMT_W_SS*Stimulus	-0.008020	0.007168	19.000000	-1.119	0.277

Stimulus coded: paragraph = 0, sentence = 1

Speech Rate by SDMT– Fast Change Condition Model (PD):

speed_up_speech_rate ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2552	0.5052
Residual		0.3129	0.5594

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	1.010918	0.535915	20.011944	1.886	0.0738 .
SDMT_W_SS	0.004317	0.005850	19.000000	0.738	0.4695
Stimulus	0.165082	0.172626	20.000000	0.956	0.3503

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating the change in speech rate from habitual to slow conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Speech Rate by SDMT– Slow Change Condition Initial Model (PD):

slow_down_speech_rate ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.4268	0.6533
Residual		0.1422	0.3771

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.567074	0.621870	24.318780	0.912	0.3708
SDMT_W_SS	-0.015384	0.006878	24.318780	-2.237	0.0347 *
Stimulus	-0.979573	0.439683	19.000000	-2.228	0.0382 *
SDMT_W_SS*Stimulus	0.007882	0.004863	19.000000	1.621	0.1215

Stimulus coded: paragraph = 0, sentence = 1

Speech Rate by SDMT– Slow Change Condition Model (PD):

slow_down_speech_rate ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.4210	0.6489
Residual		0.1538	0.3922

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.223463	0.584854	19.411290	0.382	0.7065
SDMT_W_SS	-0.011443	0.006434	19.000000	-1.779	0.0913 .
Stimulus	-0.292353	0.121029	20.000000	-2.416	0.0254 *

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating the change in mean pause length from habitual to fast conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Mean Pause Length by SDMT– Fast Change Condition Initial Model (PD):

speed_up_MPL ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.009424	0.09708
Residual		0.025032	0.15822

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	-0.237696	0.153024	35.355306	-1.553	0.1293
SDMT_W_SS	0.001318	0.001692	35.355306	0.779	0.4413
Stimulus	-0.334972	0.184455	19.000000	-1.816	0.0852
SDMT_W_SS*Stimulus	0.004340	0.002040	19.000000	2.128	0.0467 *

Stimulus coded: paragraph = 0, sentence = 1

Simple Slopes:
emtrends(PD_only_speed_up_MPL, ~ stimulus, var = "SDMT_W_SS")

stimulus	SDMT_W_SS.trend	SE	df	lower.CL	upper.CL
paragraph	0.00132	0.00169	35.4	-0.00212	0.00475
sentence	0.00566	0.00169	35.4	0.00222	0.00909

Degrees-of-freedom method: kenward-roger
Confidence level used: 0.95

Simple Effects:
SDMT_W_SS = 25:

contrast	estimate	SE	df	t.ratio	p.value
paragraph - sentence	0.22646	0.1359	19	1.666	0.1121

SDMT_W_SS = 75:

contrast	estimate	SE	df	t.ratio	p.value
paragraph - sentence	0.00944	0.0548	19	0.172	0.8650

SDMT_W_SS = 125:

contrast	estimate	SE	df	t.ratio	p.value
paragraph - sentence	-0.20757	0.0913	19	-2.274	0.0348

Degrees-of-freedom method: kenward-roger

Tables of results for models investigating the change in mean pause length from habitual to slow conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Mean Pause Length by SDMT– Slow Change Condition Initial Model (PD):

slow_down_MPL ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.01266	0.1125
Residual		0.05531	0.2352

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.071387	0.214923	36.726026	-0.332	0.742
SDMT_W_SS	0.001453	0.002377	36.726026	0.611	0.545
Stimulus	-0.196177	0.274186	19.000000	-0.715	0.483
SDMT_W_SS*Stimulus	0.002031	0.003032	19.000000	0.670	0.511

Stimulus coded: paragraph = 0, sentence = 1

Mean Pause Length by SDMT– Slow Change Condition Model (PD):

slow_down_MPL ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.01342	0.1159
Residual		0.05379	0.2319

Number of obs: 42, groups: participant, 21

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.159928	0.169347	20.774576	-0.944	0.356
SDMT_W_SS	0.002469	0.001831	19.000000	1.348	0.193
Stimulus	-0.019095	0.071571	20.000000	-0.267	0.792

Stimulus coded: paragraph = 0, sentence = 1

NEUROTYPICAL CONTROLS (NC = HDNC + PDNC)

Tables of results for models investigating the change in articulation rate from habitual to fast conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Articulation Rate by SDMT– Fast Change Condition Initial Model (NC):

speed_up_artic_rate ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2620	0.5119
Residual		0.2162	0.4649

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.546522	1.077420	53.834834	-0.507	0.6141
SDMT_W_SS	0.017110	0.009714	53.834834	1.761	0.0838
Stimulus	-0.064409	1.024431	35.000000	-0.063	0.9502
SDMT_W_SS*Stimulus	0.002177	0.009236	35.000000	0.236	0.8150

Stimulus coded: paragraph = 0, sentence = 1

Articulation Rate by SDMT– Fast Change Condition Model (NC):

speed_up_artic_rate ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2649	0.5147
Residual		0.2105	0.4588

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.666597	0.949376	35.221610	-0.702	0.4872
SDMT_W_SS	0.018199	0.008546	35.000000	2.130	0.0403 *
Stimulus	0.175742	0.106665	36.000000	1.648	0.1081

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating the change in articulation rate from habitual to slow conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Articulation Rate by SDMT– Slow Change Condition Initial Model (NC):

slow_down_artic_rate ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.5185	0.7201
Residual		0.1409	0.3753

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-1.428119	1.265151	43.252974	-1.129	0.265
SDMT_W_SS	0.002697	0.011406	43.252974	0.236	0.814
Stimulus	0.366867	0.826958	35.000001	0.444	0.660
SDMT_W_SS*Stimulus	-0.007711	0.007456	35.000001	-1.034	0.308

Stimulus coded: paragraph = 0, sentence = 1

Articulation Rate by SDMT– Slow Change Condition Model (NC):

slow_down_artic_rate ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.5183	0.7200
Residual		0.1411	0.3757

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-1.002869	1.196474	35.093378	-0.838	0.408
SDMT_W_SS	-0.001158	0.010780	35.000000	-0.107	0.915
Stimulus	-0.483632	0.087340	36.000001	-5.537	2.89e-06 ***

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating the change in speech rate from habitual to fast conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Speech Rate by SDMT– Fast Change Condition Initial Model (NC):

speed_up_speech_rate ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2844	0.5333
Residual		0.2092	0.4573

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.446756	1.094574	52.551904	-0.408	0.6848
SDMT_W_SS	0.017786	0.009868	52.551904	1.802	0.0772
Stimulus	-0.255563	1.007711	35.000000	-0.254	0.8013
SDMT_W_SS*Stimulus	0.002390	0.009085	35.000000	0.263	0.7940

Stimulus coded: paragraph = 0, sentence = 1

Speech Rate by SDMT– Fast Change Condition Model (NC):

speed_up_speech_rate ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.2871	0.5358
Residual		0.2037	0.4514

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.578572	0.973126	35.204123	-0.595	0.5559
SDMT_W_SS	0.018981	0.008761	35.000000	2.167	0.0372 *
Stimulus	0.008069	0.104944	36.000001	0.077	0.9391

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating the change in speech rate from habitual to slow conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Speech Rate by SDMT– Slow Change Condition Initial Model (NC):

slow_down_speech_rate ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.6257	0.7910
Residual		0.1664	0.4079

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-1.627753	1.386693	43.102601	-1.174	0.247
SDMT_W_SS	0.003689	0.012502	43.102601	0.295	0.769
Stimulus	0.269016	0.898772	35.000000	0.299	0.766
SDMT_W_SS*Stimulus	-0.008078	0.008103	35.000000	-0.997	0.326

Stimulus coded: paragraph = 0, sentence = 1

Speech Rate by SDMT– Slow Change Condition Model (NC):

slow_down_speech_rate ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.6257	0.7910
Residual		0.1663	0.4079

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-1.1822830	1.3127142	35.0914351	-0.901	0.374
SDMT_W_SS	-0.0003495	0.0118274	34.9999996	-0.030	0.977
Stimulus	-0.6219235	0.0948247	36.0000003	-6.559	1.25e-07 ***

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating the change in mean pause length from habitual to fast conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Mean Pause Length by SDMT– Fast Change Condition Initial Model (NC):

speed_up_MPL ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.000000	0.0000
Residual		0.007621	0.0873

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	0.0152903	0.1360215	70.0000000	0.112	0.911
SDMT_W_SS	-0.0009855	0.0012263	70.0000000	-0.804	0.424
Stimulus	0.0500532	0.1923635	70.0000000	0.260	0.795
SDMT_W_SS*Stimulus	0.0003084	0.0017343	70.0000000	0.178	0.859

Stimulus coded: paragraph = 0, sentence = 1

Mean Pause Length by SDMT– Fast Change Condition Model (NC):

speed_up_MPL ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.000000	0.0000
Residual		0.007517	0.0867

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.0017158	0.0960539	71.0000000	-0.018	0.986
SDMT_W_SS	-0.0008313	0.0008612	71.0000000	-0.965	0.338
Stimulus	0.0840653	0.0201581	71.0000000	4.170	8.48e-05 ***

Stimulus coded: paragraph = 0, sentence = 1

Tables of results for models investigating the change in mean pause length from habitual to slow conditions (outcome variable) predicted by SDMT Standard Score and Stimulus (sentences v. paragraphs) with a random effect of participant.

Mean Pause Length by SDMT– Slow Change Condition Initial Model (NC):

slow_down_MPL ~ SDMT_W_SS * stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.008027	0.08959
Residual		0.016422	0.12815

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.299410	0.243623	63.189202	-1.229	0.2236
SDMT_W_SS	0.003570	0.002196	63.189202	1.625	0.1090
Stimulus	0.616342	0.282371	35.000000	2.183	0.0359 *
SDMT_W_SS*Stimulus	-0.004766	0.002546	35.000000	-1.872	0.0696

Stimulus coded: paragraph = 0, sentence = 1

Mean Pause Length by SDMT– Slow Change Condition Model (NC):

slow_down_MPL ~ SDMT_W_SS + stimulus + (1 | participant)

Random effects:

Groups	Name	Variance	Std.Dev.
participant	(Intercept)	0.007455	0.08634
Residual		0.017565	0.13253

Number of obs: 74, groups: participant, 37

Fixed effects:

	Estimate	Std. Error	df	t value	p-value
(Intercept)	-0.036570	0.199139	35.421527	-0.184	0.85534
SDMT_W_SS	0.001187	0.001790	35.000000	0.663	0.51152
Stimulus	0.090663	0.030813	36.000000	2.942	0.00567 **

Stimulus coded: paragraph = 0, sentence = 1

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