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THE ROLE OF PROCEDURAL LEARNING IN STUTTERING: IMPLICATIONS FROM VISUOMOTOR TRACKING PERFORMANCE

by

Victoria Tumanova

An Abstract

Of a thesis submitted in partial fulfillment
of the requirements for the Doctor of
Philosophy degree in Speech and Hearing Science
in the Graduate College of
The University of Iowa

December 2010

Thesis Supervisor: Professor Patricia M. Zebrowski

ABSTRACT

This research study examined motor control and procedural learning abilities in the oral and manual motor systems of adults who stutter, using people with Parkinson's disease, and age-matched controls as comparison groups. Participants in this study were asked to track a moving target on a computer screen with their jaw and with their dominant hand. Specifically, we compared their tracking accuracy for predictable and unpredictable signals. Procedural learning (defined as increased accuracy over time) was assessed by examining changes in tracking accuracy within a single tracking trial and between consecutive tracking trials of the same predictable condition.

There were two main findings in this study related to tracking accuracy and procedural learning in people who stutter (PWS) and age-matched controls (CPWS). First, our analyses revealed that there was no significant difference between PWS and CPWS in the accuracy of tracking of either predictable or unpredictable conditions for either the hand or the jaw, although a trend was observed in which PWS performed more poorly in both for decreased accuracy. Second, both PWS and CPWS showed evidence of procedural learning to the same extent.

There were two main findings in this study related to tracking accuracy and procedural learning in people who have Parkinson's disease (PPD) and age-matched controls (CPPD). First, tracking accuracy analyses revealed that PPD performed significantly more poorly than CPPD during jaw tracking of predictable conditions, but they were not significantly different from CPPD in jaw tracking of unpredictable conditions. During hand tracking PPD differed significantly from CPPD in tracking of both predictable and unpredictable conditions for their less accurate performance. Second, there was no significant difference between the two groups in the extent of procedural learning during jaw tracking. However, during hand tracking the PPD group

improved less with time than the CPPD, suggesting that the PPD group had reduced procedural learning ability in the manual motor domain.

Lastly, age was found to be an important factor determining tracking accuracy in our participants. Younger participants (PWS and CPWS) in the age range of 18-40 years had significantly better accuracy of jaw and hand tracking than the older individuals (PPD and CPPD) in the age range of 57-79 years.

Abstract Approved: _____
Thesis Supervisor

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Title and Department

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Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

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PH.D. THESIS

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This is to certify that the Ph.D. thesis of

Victoria Tumanova

has been approved by the Examining Committee for the thesis requirement for the Doctor of Philosophy degree in Speech and Hearing Science at the December 2010 graduation.

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Ergun Uc

To my parents Olga Tumanova and Valeriy Tumanov

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INTRODUCTION

Tying one's shoes or knowing which piano keys to strike to play Beethoven's Moonlight sonata – both rely heavily on the phenomenon of procedural learning and its end result, procedural memory. Defined as a long term memory for the execution of both cognitive and motor skills, procedural memory is crucial to automaticity in the production of motor, speech and language sequences. Of particular importance is the notion that procedural memories can be acquired without formal instruction and are not easily verbalized; they are learned and automatically retrieved and utilized. In this way, procedural memory can be contrasted with declarative memory, which requires conscious awareness for skill acquisition.

Disturbances or disruptions in procedural memory have been implicated in movement disorders such as Parkinson's disease, Huntington's disease and Tourette's syndrome (Jankovic, 2001, 2008; Walker, 2007). In the motor domain, these people have difficulty initiating movement and are slow in movement execution (complex movements are especially affected), they also show increased dependence on external sensory cues for movement execution (Abbruzzese, Pelosin, & Marchese, 2008; Pascual-Leone et al., 1993) and have little benefit from long-term practice of motor tasks (Agostino et al., 2004). Various tests of cognitive procedural learning like solving a puzzle and mirror-reading show impairment in these populations as well (Saint-Cyr, Taylor, & Lang, 1988). They are less efficient at learning the rules underlying the task at hand (Mentis et al, 2003; Muslimovic et al., 2007), and require more repetitions of a new task before they can acquire a new skill, and have difficulty performing novel problem-solving tasks unless provided with explicit instructions (Taylor, Saint-Cyr, & Lang, 1986).

Over the last decade, procedural memory has also been implicated in both language and speech production. The highly automatized nature of speech makes it intuitive to suggest that procedural memory governs the phonetic sequences of speech

and their associated motor processes. The sequential nature of language categorization (e.g. word class, phonological and grammatical knowledge) and sequence learning also supports the importance of procedural memory for language (Dell, Warker, Whalen, 2008; Tomblin, Mainela-Arnold, & Zhang, 2007; Ullman, 2001; 2004).

Investigators interested in procedural memory have understandably sought to indentify its neural underpinnings. The cerebellum and basal ganglia circuits were identified as being involved in procedural memory (Hikosaka, Nakamura, Sakai et al. 2002; Saint-Cyr, 2003). Based on studies of motor impairments found in patients with basal ganglia dysfunction, neurophysiological studies and lesion experiments in animals it has been proposed that cortico-striatal (cortico-basal ganglia-thalamo-cortical circuit) and cortico-cerebellar (cortico-cerebellar-thalamo-cortical circuit) systems contribute differently to motor sequence learning and automatization. Whereas the cerebellum together with related cortical regions maybe associated with a continuous matching of the action and the consequence (e.g. feedback mode) (Brown et al. 2005; Doyon, Penhune and Ungerleider, 2003; Gabrieli, 1998), the basal ganglia mediate performance of learned behaviors and are involved in open-loop control (e.g. feedforward mode) (Hikosaka, Nakamura, Sakai et al. 2002; Doya 1999; 2000; Gabrieli, 1995).

The hypothesis that procedural learning is crucial for language acquisition (Ullman, 2001; 2004), provoked several studies of artificial language learning in populations with language impairment and basal ganglia dysfunction. De Diego-Balaguer et al. (2008) reported that patients at different stages of Huntington's disease showed impaired performance in the artificial language learning test involving learning of words and grammar. Tomblin et al. (2007) observed decreased learning during a serial reaction time task (which required no overt use of language) in a group of adolescents diagnosed with SLI based on their poor grammatical and language learning abilities. Plante, Gomez, and Gerken (2002) showed that college students diagnosed with SLI were not able to learn a novel artificial grammar from pure exposure to that grammar, which the authors

interpreted as an evidence of procedural learning impairment. Apart from SLI, people with other developmental language learning disabilities like dyslexia and autism show impairments on tasks defined as requiring procedural learning (Nicolson and Fawcett, 2007). This new evidence of importance of procedural learning in development of speech and language lead us to examine this construct in stuttering.

Stuttering is a developmental speech disorder in which the speaker has disruptions in the flow of speech primarily through involuntary interruptions such as sound or syllable repetitions or audible and inaudible prolongations (also known as "blocks"). Numerous researchers have attempted to describe the status of both speech and non-speech motor systems in people who stutter (PWS) as a way to understand the etiology of these speech disfluencies. For example, studies using the spatiotemporal index, a measure of speech motor stability that indicates the degree to which the pattern of movement is consistent on repeated productions of the utterance, showed that fluent speech of PWS is characterized by decreased motor stability, especially in the context of longer and more complex utterances (Kleinow & Smith, 2000); fluent speech of PWS also was shown to have equal variability at habitual and non-habitual (fast or slow) speaking rates compared to the speech of people who do not stutter, who exhibit less variability at their habitual speaking rate (Smith & Kleinow, 2000). Another line of inquiry has revealed that compared to people who do not stutter, PWS show slower and more variable timing and sequencing abilities in non-speech movement of jaw and lips (Caruso, 1991; Loucks & De Nil, 2006; Max, Caruso, and Gracco, 2003). The same has been observed for movement of fingers (Max, Caruso, and Gracco, 2003; Zelaznik et al., 1997; Smits-Bandstra, De Nil, & Rochon, 2006) and hands during a clapping task (Olander, Smith and Zelaznik, 2010).

The idea that stuttering behavior may result from aberrant motor control mechanisms, especially in the timing of motor commands to muscles is not new (Zimmermann, Smith, & Hanley, 1981). Recently it has been brought in research focus

again. It has been proposed that the core dysfunction in stuttering may be an impaired ability of the basal ganglia to produce timing cues for initiation of speech segments (Alm, 2004). Having conducted a thorough review of evidence from various behavioral, imaging, neuropsychological and neuro-pharmacological studies of stuttering, Alm concluded that there is a strong indication that stuttering etiology may lie in basal ganglia dysfunction. This possibility suggests several avenues for further research, one of them being inquiry into the status of procedural learning abilities of PWS.

Based on the research evidence of the importance of procedural memory for both motor and cognitive functions, and, in particular, for speech and language, we hypothesize that it may be disrupted in people who stutter. This disruption may be the underlying cause of increased variability, longer latencies and other manifestations of general problems with coordination of speech and non-speech movements in people who stutter. In the present investigation we reviewed research evidence that procedural memory may be the underlying mechanism responsible for coordination of speech articulation leading to a hypothesis that it may be less robust in people who stutter.

This study used a non-speech jaw tracking task, and a comparable hand tracking task, to examine procedural memory in the oral and manual systems of adult PWS. We compared the tracking performance of this group to that of a group of people with Parkinson's disease (PPD), a movement disorder with (1) known deficits in procedural memory abilities, and (2) lesion(s) in the basal ganglia (Jankovic, 2008), as well as two groups of age-matched control participants, one was age-matched to PWS (CPWS) and the other to PPD (CPPD). To this end, we adapted a visuomotor tracking paradigm that has been long employed in studying motor procedural memory in movement disorders research. Participants in this study were asked to track a moving target on a computer screen with their jaw and with their dominant hand. Specifically, we compared their tracking of (1) a simple repetitive movement, (2) a complex periodic movement and (3) a complex aperiodic movement that cannot be learned or predicted by the participant.

Procedural learning ability was assessed by comparing participants' performance over subsequent tracking trials of the same condition. The extent of learning and overall accuracy during tracking was compared between people who stutter, people with Parkinson's disease and normally fluent people. To our knowledge this is the first study to examine motor procedural memory in the speech and manual systems of people who stutter and compare it to that of people who have Parkinson's disease. The results of this study will add to a growing body of literature examining the role of procedural memory in communication disorders.

CHAPTER I: REVIEW OF LITERATURE

The following literature review consists of several sections. The first section contains a discussion of what defines procedural memory and what methods exist for its assessment. The second section provides a review of the literature on neural mechanisms involved in procedural memory. The third section presents recent research on the importance of procedural memory for speech and language with the particular implications it may have for stuttering and its proposed etiology. The last section provides a statement of the problem.

Procedural Memory and its Assessment

Procedural memory is a form of a long term non-declarative memory for motor and cognitive skills and procedures. Acquisition of such skills is manifested by increased accuracy or speed of performance as a result of repeated exposure to a specific procedure, often without conscious recollection of the prior learning episode or the rules underlying the task (Cohen and Squire, 1980). Procedural memory is essential for effortless execution of complex sequential movements (speaking, walking, typing, playing instruments), it is also important for calibrating smoothness and accuracy of simple movements (Abbruzzese, Pelosin, & Marchese, 2008). It is however equally important for non-motor tasks such as learning categories, prototype abstraction, and statistical learning (Ashby, Ell, & Waldron 2003; Perruchet & Pacton, 2006; Reber, Stark, & Squire, 1998; Squire & Knowlton, 1995). Procedural memory can be very durable. It is generally contrasted with declarative memory, which involves the acquisition of facts and events accompanied by conscious awareness of the learned information. Actions guided by procedural memory can occur without the need for conscious control or attention.

The first solid evidence of dissociation between declarative and procedural memory was provided by Milner (1962) who demonstrated that a severely amnesic patient, H.M. could learn a mirror drawing skill, a procedure that required novel hand-eye

coordination, in the absence of any recollection of having practiced the task before (Milner, Corkin, & Teuber, 1968).

Commonly used methods to assess procedural memory in adults involve performing perceptual-motor and pattern-analyzing tasks. Mirror reading, mirror tracing, rotor pursuit, visuomotor tracking and serial reaction time tasks are examples of experimental tasks employed to assess procedural memory and motor skill learning.

During mirror reading tasks subjects are presented with mirror-reversed text to read. The text contains words of different length and complexity (usually infrequent longer words) and non-words. Subjects are asked to press a response key as quickly as possible if the item they have just read is a real word (Poldrack, & Gabrieli, 2001). The measure of learning in the task is accuracy at responding to real words and speed of response. Mirror tracing is a similar paradigm where the participant learns a new hand-eye coordination skill. During this task people are asked to copy a drawing by looking at the mirror, once they figure out how to copy one image in the mirror, they have little difficulty doing it the second time.

Another frequently employed experimental paradigm has been the serial reaction time task (SRTT; Nissen & Bullemer, 1987). The SRTT is a choice reaction time task, in which participants are required to respond as quickly as possible to the presentation of a visual stimulus appearing at one of several different spatial locations. Unknown to the participants, the location of the stimulus follows a repeating sequence. An important argument for the use of the SRTT as a measure of procedural learning is that the performance does not seem to depend on explicit memory processes since patients with impaired declarative memory, such as Alzheimer's disease (Knopman & Nissen, 1987), typically show improvement on the task, although they are unaware of the sequential nature of the stimuli.

Rotor pursuit and visuomotor tracking paradigms have also been commonly used. During the rotor pursuit task the subject is asked to follow a moving object on a rotating

device that has a place for a stylus. The task is to keep the stylus attached to the rotating surface as long as possible. The learning is assessed by the subject's time on and off target. Difficulty level is manipulated by the speed of the disk's rotation. The task in visuomotor tracking paradigms usually involves manual tracking a moving object presented on a computer screen. This paradigm has been used in human and animal research subjects (Bowen, 1968). It is easily adapted to address specific research questions related to motor procedural memory and was selected as a method of choice for the present investigation because it allows for assessment of motor control and procedural learning in speech system without the added demands of language.

Much of what we know about procedural memory was discovered using the above mentioned paradigms in patients with amnesia. Studies in this and several other clinical populations revealed that the two memory systems, declarative and procedural, are dissociable and presumably rely on distinct neural circuits (Squire, 1992).

Neural Substrates of Procedural Memory

In last twenty years much was discovered about the anatomy and physiology of the mechanisms involved in procedural memory. The cerebellum and basal ganglia circuits were identified as being involved in procedural memory acquisition tasks. It has long been appreciated that diseases primarily affecting the basal ganglia such as Parkinson's disease (PD), Huntington's disease (HD) and Tourette's syndrome (TS) lead to profound motor disorders and impaired procedural learning ability (Jankovic 2001; 2007; Walker, 2008).

Serial reaction time, mirror reading, and rotor pursuit task have often been used to show impaired skill learning in people with basal ganglia disorders (Gabrieli, 1995). PD and HD patients have shown an impaired procedural learning ability on rotor pursuit (Harrington et al., 1990; Heindel et al., 1989) and serial reaction time tasks (Ferrano,

Balota, & Connor, 1993; Knopman & Nissen, 1991). TS patients have also shown a mild but significant deficit on rotor pursuit task (Stebbins et al., 1995).

However, it has been shown that PD patients are able to successfully use visual and proprioceptive feedback to control reaching (Flowers, 1976; Flash et al., 1992; Ghilardi et al., 2000) and tracking movements (Bloxham, Mindel, & Frith, 1984; Day, Dick, & Marsden, 1984; Liu et al., 1999). In a study designed to elucidate the contribution of the basal ganglia-thalamo-cortical network to the process allowing correction of the ongoing motor command, Desmurget et al.(2004) showed that Parkinson's disease patients, who present with a severe dysfunction of the whole basal ganglia network, were easily able to correct their ongoing arm trajectory when small subliminal target jumps were generated during gaze shift (a paradigm that mimics the nature of the slight automatic corrections that occur in normal movements directed at stationary targets). The authors concluded that feedback control of movement may not be crucially dependent on the basal ganglia network. However, studies of motor abilities of people with PD show that the feedback control system may be the only one available for motor control, resulting is slow purposeful movements (Sheridan, Flowers, & Hurrell, 1987).

Anatomical and animal lesion studies allow more specific insight into the basal ganglia's contribution to sequence learning and procedural memory. These studies have shown that basal ganglia play a crucial role in coordination of multiple movements, performance of learned motor sequences and learning of new motor sequences (Hikosaka, Nakamura, Sakai et al. 2002; Saint-Cyr, 2003). The general neurological model of the basal ganglia function states that the direct and indirect pathways in the basal ganglia control the initiation, switching, modulation and termination of actions (Saint-Cyr, 2003). In particular to motor skill learning, Saint-Cyr (2003) suggested that basal ganglia are critical for finding the "ballpark", or recognizing and selecting appropriate pre-existing movement control patterns while inhibiting irrelevant ones in

early stages of learning. Studies that compared motor and non-motor sequence learning in HD patients showed participants were impaired on motor sequence learning that requires execution of smooth series of movements (like the rotor pursuit task) but not on the mirror tracing or non-motor skill learning, thus suggesting that the basal ganglia are particularly responsible for skill learning that depends on perceptual-motor sequencing (Sanes, Dimitrov, & Hallett, 1990). It should be noted that research studies in the past 20 years established that the basal ganglia are connected to the cerebral cortex via multiple discrete circuits or "loops" that may support sequencing functions in different domains (motor, cognitive and linguistic) (Alexander, DeLong, & Strick, 1986; Gabrieli, 1995). These cortico-basal ganglia-thalamo-cortical circuits are critical for the acquisition and retention of skilled motor behaviors. However, another brain circuit is of equally great importance for the acquisition and retention of skilled motor behaviors. That circuit is the cortico-cerebellar-thalamo-cortical circuit. The contribution of that circuit to motor learning is reviewed in the following paragraph.

Based on studies of motor impairments found in patients with basal ganglia dysfunction, neurophysiological studies and lesion experiments in animals it has been proposed that cortico-striatal (cortico-basal ganglia-thalamo-cortical circuit) and cortico-cerebellar (cortico-cerebellar-thalamo-cortical circuit) systems contribute differently to motor sequence learning and automatization. Whereas the cerebellum together with related cortical regions maybe associated with a continuous matching of the action and the consequence (e.g. feedback mode) (Brown et al. 2005; Doyon, Penhune and Ungerleider, 2003; Gabrieli et al., 1996), the basal ganglia mediate performance of learned behaviors and are involved in open-loop control (e.g. feedforward mode) (Hikosaka, Nakamura, Sakai et al. 2002; Doya 1999; 2000; Gabrieli, 1995). Restating this finding, we can say that whereas the basal ganglia are more responsible for feedforward controlled movements, the cerebellum mediates feedback controlled

movements. Both of those control modes are essential for speech movement coordination.

Feedback and Feedforward Control in Speech

Analysis of speech movement coordination suggests that there are predictive, sensorimotor commands sent by the nervous system to functional units involved in speech articulation (Abbs, Gracco, & Cole, 1984). The intended nervous system outputs for complex speech gestures were shown to be mainly achieved through a feedforward (open-loop) control mechanism. The feedforward theory, also referred to as the open loop theory, claims that elements that constitute a particular speech utterance are preprogrammed by a set of instructions rather like a computer program (Abbs, Gracco, & Cole, 1984). The program is then executed by the speech musculature without reliance on feedback concerning the movements actually performed. One weakness of the feedforward control is that it places an outstanding computational load on the speaker's control mechanism and substantial learning is required before these signals can be used reliably. Thus, the process of motor learning would be engaged in building up the predictive mechanisms, determining the necessary sensorimotor pathways, and calibrating the intermovement control mechanism. This process may rely on procedural learning and memory system.

Another control mechanism involved in movement execution is called the feedback control. During the feedback control of movements, signals from speech muscles return information to the controller (the nervous system) that regulates the movement as it is being completed. An important limitation of feedback control is that the delays in most feedback channels are too long to allow effective control of a motor sequence (Kent, 1997) and it has no mechanism for producing adaptive movements in remote and non-biomechanically linked articulators (Kelso, Tuller, Vatikiotis-Bateson et al., 1984).

It is logic to hypothesize that speech motor control system may use both ways of control. Feedback information may play an important role in motor learning (setting up the "program" for articulators.). This may explain why it takes so much time in the beginning to learn a new skill that becomes automatic after some time. The feedforward control may play an important role in controlling learned movements and adjusting upcoming control actions.

The Role of Procedural Memory in Speech and Language

It is well established that procedural memory is important for learning of sequences of motor and non-motor actions. Speech is a highly learned and automatized motor behavior, thus it is intuitive to suggest that speech motor control and articulation process may involve procedural memory. Children learn to produce speech implicitly, which means that they learn it simply by doing and they do not have intent to learn it or the awareness of their knowledge. The possibility that procedural memory plays an important role in language acquisition is also reinforced by the inherent characteristics of the language system. Language is sequential in nature and requires categorization processes to create syntactic knowledge such as classes of words (nouns, adjectives, verbs etc.), and grammatical knowledge. Research outside the language domain has shown that both sequence learning and categorization abilities rely on procedural memory system (Koechlin et al., 2002; Smith and McDowall, 2006; Ashby et al., 2007). More evidence for the significance of procedural memory in rule-based learning comes from recent studies of language acquisition and language disorders.

Recent theoretical and empirical studies of language have put forth a hypothesis that procedural learning may be crucial not only for the pure motor aspects of speech but also for "higher levels" of language such as phonological (rhyming and phonological awareness) and grammatical knowledge (Ullman, 2001; 2004; Tomblin, Mainela-Arnold, & Zhang, 2007; Dell, Warker, & Whalen, 2008). Ullman (2004) applied the procedural

and declarative categorization to language skills, proposing that the declarative memory system underlies the 'mental lexicon', subserving the acquisition, representation and use of words. The procedural memory system, on the other hand, underlies the 'mental grammar' that subserves learning of new rule-based procedures that govern the regularities of language (like phonological and grammatical rules), in addition to the learning of new skills and habits.

In a series of experiments Dell, Warker and Whalen (2008) demonstrated that artificial phonotactic constraints are implicitly learned by the participants in their studies. This learning was shown to be independent of people's awareness and intentions but very robust. The authors took their results to suggest that procedural memory may be a powerful mechanism by which action sequences, both linguistic and non-linguistic, are learned. Knowledge of one's native language phonology or acquisition of foreign language phonology is one of the domains where procedural memory is at work.

In an earlier study, Saffran, Aslin and Newport (1996) showed that segmentation of words from fluent speech can be accomplished by 8-month-old infants based solely on the statistical relationships between neighboring speech sounds. Infants in their study were able to extract information about word boundaries exclusively from statistical regularities that distinguished sound sequences within words from the ones occurring between word boundaries (familiarization speech stream, used in the study, contained no pauses, intonational patterns, or any other cues that, in normal speech, supplement the sequential statistics inherent in the structure of words). Moreover, acquisition of rules for this segmentation process was established from only 2 minutes of exposure to the sound stream.

Using the paradigm similar to the ones employed in Saffran, Aslin and Newport (1996), Pena et al. (2002) in a series of experiments demonstrated that after a short familiarization to a continuous speech stream, adult listeners were able to segment it using the statistics of the input, and they were able to extract the structural regularities

(morpho-syntactic structures) included in the stream and generalize to a new speech stream when an additional cue of short pauses at word boundaries was added in the input. The authors suggested that listeners employ different computational algorithms for segmentation of words of a language and segmentation of grammatical structures. More evidence for the role of procedural memory in language acquisition comes from studies of clinical populations with abnormal basal ganglia function.

De Diego-Balaguer et al. (2008) reported that patients at different stages of Huntington's disease and pre-symptomatic gene carriers showed impaired performance in the artificial language learning test. When presented with a simplified artificial language where words and rules could be extracted, early stage Huntington's disease patients demonstrated a greater impairment in rule learning than in word learning compared to age- and education-matched controls. Huntington's disease patients at later stages were impaired both on word and rule learning. While gene-carriers are spared in their overall performance, when they learned a set of abstract artificial language rules they were then impaired in the transfer of those rules to similar artificial language structures.

Recent studies of children and adolescents with specific language impairment (SLI) also lend support to the importance of procedural memory for language. Tomblin, Mainela-Arnold and Zhang (2007) observed decreased learning during a serial reaction time task (which required no overt use of language) in a group of adolescents who were diagnosed with SLI in kindergarten based on their poor grammatical abilities and a history of poor language learning. Another recent study of people with SLI showed similar results: college students diagnosed with SLI were not able to learn a novel artificial grammar from pure exposure to that grammar (Plante, Gomez, & Gerken, 2002) compared to participants without specific language impairment.

In summary, studies of both adults which typically involve visuomotor learning or artificial grammar learning and infants which typically employ statistical learning paradigms (e.g. tracking regularities in a speech-like input) converge on the importance

of procedural memory for learning of motor and non-motor (e.g. linguistic) sequences and rules.

Procedural Memory in People Who Stutter: Feedback and Feedforward Control

Evidence that procedural memory may be less robust in people who stutter comes from different sources, including studies of phonological abilities and sequence learning abilities, especially when the system is taxed with some additional task demands. Findings from recent studies show that phonological abilities of PWS may not be as strong as the ones of normally fluent people. Both adults (Ludlow, Siren, & Zikira, 1997) and children who stutter (Hakim & Ratner, 2004) have demonstrated diminished ability to learn phonological sequences relative to fluent controls. Using a cognitive linguistic dual task, in which participants planned and produced sentences using noun pairs while simultaneously making either category or rhyming decisions on different noun pairs, De Nil and Bosshardt (2001) found that PWS showed a significant impairment of rhyming and decision-making. PWS did not differ from people who do not stutter on the number of words used for sentence formulation, however, their sentences tended to contain fewer syllables and were less grammatically complex. These results were taken to suggest that PWS had less automatized processing of speech and language tasks as compared to people who do not stutter. Smits-Bandstra and De Nil (2007) demonstrated that PWS improve less with practice on a speech sequencing task (syllable sequencing task reaction time). These results, in light of Dell, Warker and Whalen (2008)'s hypothesis of the role of procedural memory in phonology, may be taken to suggest that procedural memory may be impaired in people who stutter. It should be noted, however, that learning of a sequence of syllables or nonsense words taps into phonological memory and, thus, has limited relevance to the motor aspect of speech production (see Bajaj, 2007), which may

be an important risk factor for stuttering development, and may be governed by a separate neurological substrate.

Studies of motor sequence learning in PWS, similar to the studies of phonological sequence learning, show that PWS do not perform as well as people who do not stutter. Webster (1986) evaluated the ability of PWS and people who do not stutter to learn 4-element finger tapping sequences and found that PWS did not show improved accuracy after practice on sequences with no repeated elements compared to people who do not stutter. Jones et al. (2002) used visuomotor tracking with a steering wheel to test how well PWS and people who do not stutter perform on random and sine wave tracking, they did not find a significant difference in tracking abilities of PWS and people who do not stutter in their study, however, they found that PWS had slower reaction times than people who do not stutter on the ballistic movement task (arm movement). Smits-Bandstra and De Nil (2007) using a finger-tap sequence learning task demonstrated that PWS improved less over practice than people who do not stutter and demonstrated difficulty in transitioning to increasingly automatized performance compared to the controls.

Two visuomotor tracking studies of children who stutter provided more evidence for less automatized performance of sequences of movements of PWS. To test the ability of children who stutter to coordinate articulator movements involved in speech production, Howell, Sackin and Rustin (1995) asked a group of 6 children who stutter (with a mean age of 9 years) and 6 age-matched children who do not stutter to track the movement of a simple sine wave (with a frequency of 3Hz) using their lower lip and the jaw. The results indicated that children who stutter did not perform as well as children who do not stutter in both lower lip and jaw tracking, producing much larger errors than the children who do not stutter.

Another study that employed a similar methodology was carried out by Zebrowski, Moon and Robin (1997). They tested the ability of 4 boys with

developmental stuttering (with a mean age of 12 years) and 4 age-matched normally fluent children to track the simple and complex (unpredictable) sine waves with their lower lip and jaw. Their results corroborated the results of Howell, Sackin and Rustin (1995) study: children who stutter performed more poorly than the normally fluent children in tracking the simple sine wave. Zebrowski et al. interpreted their results as suggesting that children who stutter may have difficulty either developing or accessing an internal model with which to predict articulator movement, thus, they may have to rely on various feedback modes (e.g. visual or kinesthetic) to produce smooth articulator movements.

Both the predictive (feedforward) and the response-based (feedback) modes are important for effective motor control for both speech and non speech actions. Feedback information plays an important role in motor learning (setting up the "program" for articulators.). The feedforward control plays an important role in controlling learned movements and adjusting upcoming control actions (Kelso, Tuller, Vatikiotis-Bateson et al., 1984). The research undertaken by Adams, Weismer and Kent (1993) proposed another context for feedback and feedforward control processes. They studied velocity profiles across five different speaking rates (from very slow to very fast). Across those rates, the velocity profile changed from a symmetrical, single-peaked function at the fast speaking rate to an asymmetrical and multipeaked function at the slow speaking rates. This variation in velocity profile shape was interpreted by the researches as support for the view that alterations in speaking rate were associated with changes in motor control strategies. They conjectured that the control strategy for speech gestures produced at fast speaking rates may involve unitary movements that are predominantly preprogrammed, whereas gestures produced at slow speaking rates may consist of multiple submovements that are influenced by feedback mechanisms.

The feedback mode of control, however, has an important limitation: the delays in most feedback channels are too long to allow effective control of a motor sequence

(Kent, 1997) especially at high rates of movements. This makes this type of control less optimal for fast articulator movements during speech. If people who stutter have to rely mostly on feedback control of their articulator movements they may have difficulty producing smooth speech at faster speaking rate. This hypothesis is supported by empirical evidence that speaking at slow rates is a powerful fluency-enhancing technique for people who stutter (Bloodstein, 1950; 1995).

In summary, the findings from studies of both speech motor sequencing and phonological abilities of people who stutter lend support to the hypothesis that procedural memory may be less robust in this population, which may lead to difficulties with performance of automatized sequences and learning of new sequences in speech and non speech systems. However, there is a paucity of research that either directly or indirectly assessed procedural memory in PWS.

Procedural Memory and Stuttering: Implications for Neural Substrates

Recently, several researchers have suggested that the basal ganglia system may be involved in developmental stuttering (Alm, 2004; Smits-Bandstra & De Nil, 2007). Several research findings and clinical observations lend support to this hypothesis. Studies of patients with confirmed basal ganglia involvement, like Parkinson's disease, and Tourette's syndrome showed that these individuals have marked speech deficits that closely resemble stuttering. Patients with Parkinson's disease, among other symptoms, exhibit inappropriate pausing and sound repetitions and prolongations which according to the well established criteria can be considered stuttering-like disfluencies (Goberman, Blomgren, & Metzger, 2008). Use of external sensory cues for movement and focused attention/de-automatization of movement (in a form of metronome or chorus speech) facilitate fluency in both people with Parkinson's disease and people who stutter (PWS).

Both populations have shown sensitivity to fluctuating dopamine levels or dopamine-moderating medication (Alm, 2004; DeLong, 2000; Smits-Bandstra & De Nil, 2007). It has been shown that L-Dopa has adverse effects for fluency in PWS, however, dopamine antagonists, like haloperidol, risperidone and olanzapine, dramatically increased fluency in PWS, indicating that PWS may be in a hyper-dopaminergic state (Maguire, Yu, Franklin, et al., 2004). Patients with a diagnosed Tourette's syndrome may also produce speech disfluencies that resemble developmental stuttering, and it is estimated that as many as 50% of all patients with developmental stuttering may have an undiagnosed Tourette's syndrome (Jankovic, 2001).

Further evidence of basal ganglia involvement comes from recent neuroimaging studies of speech production of people who stutter. Watkins et al. (2008) found that during speech production irrespective of fluency, PWS showed bilaterally hyperactivity in the anterior insula, cerebellum and midbrain at the level of the substantia nigra, red nucleus and subthalamic nucleus relative to people who do not stutter. The authors interpreted their results as supporting the hypothesis of an abnormal function of the basal ganglia and excessive dopamine in people who stutter. Earlier studies by Wu, Maguire and Riley (1995; 1997) revealed an abnormal metabolism at the level of the basal ganglia in developmental stuttering. They used PET to study 6-FDOPA uptake at rest in adults who stutter and normally fluent controls. They found that PWS had elevated 6-FDOPA uptake in medial prefrontal cortex, deep orbital and insular cortex, amygdala, auditory cortex and the tail of the caudate nucleus.

A recent meta-analysis of imaging studies of developmental stuttering in adults reported that similar brain areas were involved in both stuttered and fluent speech, however, primary motor cortex, supplementary motor area, cingulate motor area and cerebellar vermis were over-activated in both stuttered and fluent speech of PWS (Brown, Ingham, Ingham, et al., 2005). The authors noted that their analysis highlighted three neural substrates that were specific to the stuttering group – overactivation of

anterior insula, underactivation in auditory areas bilaterally and overactivation in the vermis of the cerebellum. Taking into consideration the evidence that increased skill is associated with a concurrent decrease in brain activation, and the less competent performance is associated with an increased activation, the findings were interpreted as suggesting that the overactivity may be a compensatory response, especially overactivation in the cerebellum.

Giraud et al. (2008) did an fMRI study that looked at the correlation between the severity of stuttering and activity in the basal ganglia during fluent speech before and after fluency-shaping therapy in 9 people with developmental stuttering. They found that before therapy stuttering severity positively correlated with a distinct pattern of activation that included bilateral caudate nuclei and this pattern disappeared after therapy, leaving only a very small cluster of activation in the caudate nuclei that still correlated with initial stuttering severity. However, authors reported no significant correlation between the gain in fluency due to therapy and the increase in activation in the caudate nucleus, which would have been expected if the caudate nucleus was actively driving compensation.

Neuroimaging studies of acquired stuttering provide additional evidence for basal ganglia involvement in stuttering. Several studies reported basal ganglia involvement in acquired stuttering, with putamen being listed most often (see Ludlow & Loucks, 2003; Neumann et al., 2003; 2005). Ciabarra, Elkind, Roberts and Marshall (2000) evaluated three cases of acquired stuttering with brain MRI. Two of their patients were found to have a subcortical infarct involving left putamen and extending to left corona radiata. Examination of spontaneous speech, reading, and repetition in both patients showed that the speech was slow but grammatically correct with initial prolongations of consonants and repetitions of initial syllables.

Kono, Hirano, Ueda and Nakajima (1998) reported another case of acquired stuttering resulting from a striatocapsular infarction. They described their patient's speech as very slow, characterized by repetitions and prolongations, with absence of any

aphasia or word-finding problems. Brain CTs and MRIs revealed a striatocapsular infarction extending from the putamen to the caudate nucleus in the left hemisphere.

Ludlow, Rosenberg, Salazar, Grafman, and Smutok (1986) reported ten cases of acquired stuttering following penetrating missile wounds sustained during the Vietnam War. None of the patients had a history of developmental or chronic adult stuttering. In comparison with other head-injured subjects and normal control subjects, the subjects with acquired stuttering had significant deficits in skilled rapid hand movements and oral and speech movements, suggesting a generalized motor control disorder. The identified brain lesions of the acquired stuttering group were on the right in five subjects, on the left in four, and bilateral in one. The internal and external capsules, the frontal white matter, and the striatum were involved in the acquired stuttering group.

Overall the basal ganglia circuits have been shown to be important for speech. Speedie, Wertman, Ta'ir, and Heilman (1993) reported a case where following a right basal ganglia lesion, a right-handed man, age 75, was unable to recite familiar verses. Serial automatic speech, singing, recitation of rhymes, and swearing were impaired and only idioms and social greetings were preserved. Speech no longer contained overused phrases, but the patient's comprehension of automatic speech and propositional speech was preserved as well. The authors concluded that right basal ganglia lesions may impair production but not comprehension of automatic speech.

Intraoperative electrical stimulation during surgery for tumors involving the caudate nucleus or putamen in the language dominant hemisphere further revealed the importance of the basal ganglia for speech (Robles, Gatignol, Capelle et al., 2005). Eleven patients with cortico-subcortical low grade gliomas were operated on while awake, and striatal functional mapping was done. Intraoperative direct electrical stimulation was used while the patients performed motor and naming tasks during the surgery. Robles, Gatignol, Capelle, Mitchell, and Duffau reported that in five cases of glioma involving the dominant putamen, stimulations induced anarthria, while in six

cases of glioma involving the dominant caudate, stimulations elicited perseveration. The authors concluded that there appear to be two separate basal ganglia systems in language, one mediated by the putamen which might have a motor role, and one by the caudate nucleus which might have a role in cognitive control.

To summarize the research findings – the basal ganglia has been shown to be very important for speech. Lesions to the basal ganglia may result in acquired stuttering. Recent neuroimaging studies of developmental stuttering provide evidence that speech motor control system of adults who stutter is overactivated during both fluent and stuttered speech, leading to a hypothesis that this may a result of compensation for inefficient motor control.

Statement of Purpose

The purpose of the present study was to investigate general motor control and motor procedural learning abilities in the oral and manual systems of people who stutter and compare it with normally fluent people and people with Parkinson's disease. Motor control and procedural learning were assessed using visuomotor tracking – a method that has been used to confirm hypothesized deficits in motor control and procedural memory abilities of people with known neurological impairments (e.g. Flowers, 1978; Soliveri et al. 1997). An important advantage of this method among other methods of testing motor control and procedural memory is that it allows for assessment of motor sequence learning and automatization without tapping into phonological memory, thus we can look into the motor system of speech production separating it from language demands.

Knowing if procedural learning is less robust in people who stutter is important for several reasons:

1. Procedural learning has been shown to be crucial for motor and non-motor learning; it may be involved not only in performance of speech sequences and other motor sequences but also in phonology and grammar acquisition.

2. Procedural learning and procedural memory are largely dependent on the basal ganglia circuits; assessing the strength of procedural learning abilities of people who stutter and comparing them to people with abnormal basal ganglia function and people with no neurological impairment may provide some evidence for basal ganglia's role in developmental stuttering.

Participants in this study are asked to track various sine waves with their jaw and with the dominant hand. Specifically, we compared their tracking of (1) a simple sine wave, (2) a complex periodic sine wave (composed of three different amplitudes) and (3) a complex aperiodic wave that cannot be learned or predicted by the participant. The advantages of this method is that tracking of a sinusoidal target requires precise jaw control in an unfamiliar task, and that it is a pure measure of articulation since subjects do not have to produce any linguistic units (Folkins et al. 1995).

Based on the review of literature on procedural learning and speech and non-speech sequence learning in people who stutter (PWS), we hypothesize that PWS have difficulty accessing an internal plan or implementing a feedforward control system, which would allow them to maintain smooth continuous tracking of a predictable sine wave motion. Instead, they may have to rely on the feedback, responsive control system, which requires them to constantly adjust movements of their articulators. Their performance may be similar to that of individuals with Parkinson's disease in that the both groups have to rely mostly on the feedback mechanism for movement control. Based on the research evidence of generalized motor control differences in people who stutter, we hypothesize that their tracking performance with the hand will be similar to the one with the jaw. The working hypotheses in the present study are:

1. People who stutter will perform more poorly (they will have higher tracking error) than normally fluent people while tracking the predictable tracking signals with the jaw and dominant hand.

2. People who stutter will perform as well as normally fluent people while tracking the unpredictable tracking signals.
3. People who stutter may perform similar to the group of people with Parkinson's disease in that they would have more difficulty with tracking the predictable signals than their controls.

Research Questions

The present investigation addressed the following questions:

1. Are there differences in jaw tracking accuracy for the four groups in the current study?
   - Do people who stutter (PWS) differ from age-matched controls who do not stutter (CPWS) in the accuracy with which they track both predictable and unpredictable signals with the jaw?
   - Do people with Parkinson's disease (PPD) differ from age-matched controls without neurological impairment (CPPD) in the accuracy with which they track both predictable and unpredictable signals with the jaw?
2. Are there differences in hand tracking accuracy for the four groups in the current study?
   a) Do people who stutter (PWS) differ from age-matched controls who do not stutter (CPWS) in the accuracy with which they track both predictable and unpredictable signals with the dominant hand?
   b) Do people with Parkinson's disease (PPD) differ from age-matched controls without neurological impairment (CPPD) in the accuracy with which they track both predictable and unpredictable signals with the dominant hand?
3. Are there within and between group differences in both jaw and hand tracking accuracy over time? (i.e. procedural learning)

CHAPTER II: METHOD

Participants and Procedure

Participants

Sixty people participated in this investigation. There were fifteen participants in each of the following test groups: (1) people who stutter (PWS); (2) age and gender-matched normally fluent control participants (CPWS); (3) people with Parkinson's disease (PPD); (4) age and gender-matched control participants who have no neurological impairments (CPPD). Participants with Parkinson's disease were part of a larger sample of Parkinson's disease patients who participated in a research study at The University of Iowa Hospitals and Clinics, Movement Disorders Translational Research Laboratory, participants who stutter were partly recruited through Wendell Johnson Speech and Hearing Clinic where they were enrolled in speech therapy for stuttering, all other groups were recruited from University of Iowa community via e-mail advertisements. At the initial contact with potential participants they were interviewed to ensure that they do not have any exclusionary health conditions (e.g. structural brain disease; active epilepsy; acute illness or active, confounding medical, neurological, or musculoskeletal conditions; alcoholism or other forms of drug addiction) and normal or corrected-to-normal vision.

The first group of participants comprised fifteen adults who stutter (1 female), who ranged in age from 18 to 39 years of age. They were self-proclaimed to be stuttering, started stuttering in childhood and had no known neurological impairments, all but one participant in this group underwent therapy for stuttering at one time in their life. Stuttering severity of this group was assessed with Stuttering Severity Instrument (Riley, 1972). The second group comprised fifteen healthy normally fluent adults (1 female), who were age and gender-matched to people who stutter. Participants in this group ranged in age from 18 to 41 years of age.

The third group of participants comprised fifteen people (6 females) who have a diagnosed mild or moderate Parkinson's disease assessed on a Hoehn-Yahr scale (1967) without any cognitive impairments as diagnosed with a Mini Mental State Exam. Their demographic and clinical characteristics are presented in Table 1. Inclusion criteria for this group were (1) presence of all 3 cardinal features of PD (resting tremor, bradykinesia, and rigidity), which have to be asymmetrical; (2) Hoehn and Yahr Scale stage I-III; (3) stable dopaminergic treatment regimen for at least 4 weeks prior to enrollment. Exclusion criteria for this group were (1) secondary parkinsonism; (2) Parkinson-plus syndromes; (3) Mini Mental State Exam (MMSE) score <24; (4) an unstable dosage of drugs active in the central nervous system (e.g., anxiolytics, antidepressants) during the 60 days before the screening; (5) participation in drug studies or the use of investigational drugs within 30 days before screening. In addition to Hoehn and Yahr rating scale Parkinson's disease progression was assessed using Unified Parkinson's disease scale (UPDRS) (motor and activities of daily living (ADL UPDRS) subscales were used) and Schwab and England Activities of Daily Living Scale (SE). Table 1 provides clinical characteristics of participants in the PPD group.

All participants in this group were tested while on their regular medication for Parkinson's disease. All medication was documented in Levodopa equivalent amount. Participants in this group ranged in age from 57 to 79 years of age. The fourth and final group of participants comprised healthy normally fluent adults (6 females) who were age and gender-matched to participants with Parkinson's disease. Participants in this group ranged in age from 57 to 73 years of age.

Data Collection: Visuomotor Tracking Procedure

Data collection for the study took place at the Wendell Johnson Speech and Hearing Center on The University of Iowa campus; testing was performed in the Stuttering Research laboratory, by the same examiner. All 60 participants were tested

individually over one visit, and the same procedure was carried out for each participant. The visit lasted approximately two to three hours. The University of Iowa Institutional Review Board approved all the procedures used in the current study. Before the testing started, the examiner described the details of the study to the participants, who read and signed the consent form, and filled out two forms asking them for their family and educational history and prescription medication use (Participant history form, medication audit form). A short 10 minute conversational speech sample was recorded from participants who stuttered (PWS) and participants with Parkinson's disease (PPD). All participants received $20 compensation upon completion of the study.

Testing session consisted of a series of tracking tasks performed with the jaw and dominant hand. The order in which participants started tracking was counter-balanced across tracking medium (jaw or hand) and randomized across 13 tracking conditions.

Jaw and hand movements during tracking were recorded using Optotrak (Northern Digital, Waterloo, Ontario, Canada), an optoelectronic position measurement system that tracks the three-dimensional motion of infrared-emitting diodes (IREDs).

Tracking Conditions

There were a total of 10 different tracking conditions for tracking (the same 10 conditions were used for both jaw and hand tracking); the order of presentation of the tracking conditions was randomized for each participant. For the purposes of the description, the 10 conditions can be grouped by speed (frequency) and by pattern of target movement (predictable and unpredictable signals). Three different sinusoidal signals were used during tracking: (1) simple sine wave, (2) complex sine wave where amplitude changed in a regular pattern and (3) complex sine wave where amplitude varied in a quasi-random fashion. Each of these sinusoidal signals was presented at three different rates – 0.3, 0.6 and 0.9Hz. Those frequencies were chosen because research has shown that they are representative of articulatory movements during speech (Moon et al.,

1993; Muller, Abbs, Kennedy and Larson, 1977), and also provided different levels of difficulty for tracking.

Predictable Tracking Conditions

Level 1: Simple Sine Waves

The task in Level 1 conditions is tracking of a simple sine wave. This condition was presented at the frequency of 0.3Hz, 0.6Hz and 0.9 Hz. During tracking participants saw a target that was moving up and down on the computer screen with constant amplitude (see figure 1). The target only moved in a vertical plane. To match the target position, participants had to open and close their jaw. The range of target excursion was set at 12mm (1.2 cm). Each of the simple sine wave conditions was performed twice; the first trial was immediately followed by the second trial.

This condition was designed to assess the ability of all populations to learn a relatively easily discernible pattern of movement, inclusion of two trials allowed for assessment of learning. Frequency of 0.3Hz was perceived as the easiest one since the target was moving relatively slow, the difficulty level increased with increases in target velocity, making 0.9Hz frequency the most challenging of the simple sine wave conditions.

Level 2: Complex Sine Patterns

The task in Level 2 conditions involved tracking of a sine wave that has a constant frequency but is comprised of 3 different amplitudes (see figure 2). The three amplitudes of the wave were set to be 12mm (Large); 8mm (Medium) and 6mm (Small). They were presented in a sequence “L-M-S” that was repeated over and over again. During tracking participants saw a target that was moving up and down on the computer screen with a changing excursion, it changed from large to medium to small and then jumped back up to large. These complex sine patterns were presented at frequencies of

0.3Hz, 0.6Hz and 0.9 Hz. Each of the complex sine pattern conditions was performed three times; the first trial was immediately followed by the second trial and then, the third trial.

The Level 2 conditions were designed to evaluate the ability of the populations to extract and learn a more complex motor pattern, not as visually obvious as the one in Level 1. As with the Level 1 conditions, the perceived difficulty of tracking depended on frequency: the frequency of 0.3Hz was perceived as the easiest one, followed by 0.6 and 0.9Hz.

Unpredictable Tracking Conditions

Level 3: Variable Amplitude Waves

The task in Level 3 conditions involved tracking of a sine wave that has a constant frequency but uses variable amplitude that changes in a pseudo- random fashion (see figure 3). Even though the sequence of amplitude changes was preprogrammed, it was long and complex enough so that subjects were not able to recognize when the pattern repeats itself. The maximum jaw excursion required during tracking of this signal was set to 12mm and the minimum to 6mm. As with the Level 1 and 2 conditions, the Variable Amplitude Waves were presented at three frequencies (0.3, 0.6 and 0.9Hz) in order to vary the difficulty of tracking. Each of the level 3 conditions was performed once.

The Level 3 conditions required participants to constantly match the jaw position with the moving target without being able to anticipate the target position. The motor pattern in this type of signal could not be learned and the motor system was not able to "prepare" for the upcoming target movement.

Level 4: Variable Amplitude and Frequency Wave

The task in Level 4 condition involved tracking of a complex sine wave that has variable frequency and variable amplitude that both change in a pseudo- random fashion (see figure 4). This tracking signal was composed of several simple one-cycle sine waves, thus throughout the duration of the signal both frequency and amplitude changes occurred from cycle to cycle of this complex sine-wave based signal. The maximum jaw excursion required during tracking of this signal was set to 12mm and the minimum to 6mm. There was one trial for this condition. This condition was designed to evaluate participant's ability to constantly match the jaw position with the moving target with the added difficulty of having to match constantly changing speed of the target in addition to its changing position.

Jaw Tracking

The participants were seated in front of a computer screen 1.25 meters away from the screen to avoid saccadic eye movement (Cassell, 1973). Two IREDs were attached to the participant's face with the use of adhesive tape – one marker was placed on the forehead and another marker was placed under the chin (see figure 5). During test trials a sinusoidal target signal, corresponding to one of the 10 conditions (see above) appeared on the computer screen as a vertically moving black square which was 1.5 cm wide (see figure 6). Movement signals from the jaw were transduced via the Optotrak system and represented on the computer screen as a white square 1cm wide. The subjects were instructed to keep "the white square" inside "the black square" as best as they could. They were also instructed to keep their head still and only move their jaw during tracking.

The maximum extent of jaw movement was calibrated by asking participants to close their mouth comfortably with their lips together without clenching their teeth. A position of the IREDs in this configuration was acquired, which corresponded to the

maximum closed jaw position. Then, the participants were asked to hold a 15 mm bite block between their incisors, and a second sample of IRED positions was acquired, which corresponded to the maximum open jaw position for calibration. The actual tracking range was set to 70% of the calibration distance (maximum open position – maximum closed position), so that the maximum excursion for the jaw was set at 12mm, a distance shown to correspond to jaw opening amplitude during speech (Edwards & Harris,1990). This setup also allowed us to maintain a comfortable tracking range and avoid making the subjects close their mouth completely or open it too wide during tracking. The calibration of the Optotrak system was done separately for each participant and was performed before a pre-test practice session.

The pre-test practice trial lasted for 30 seconds. It allowed the participants to get acquainted with the way the movement of their jaw translated to the movement of the white square on the computer screen. During the practice trial only the white square controlled by the participant's jaw movement was displayed on the computer screen. Participants were encouraged to open and close their jaw and observe the way this movement is represented on the computer screen. After the practice trial the examiner inquired if the participant understood the task, and felt ready to start. After confirming that the participant was ready to start, the examiner started the testing trials in the order unique to each participant. Every testing trial started with a warning tone and after a one-second-delay a moving target appeared on the computer screen for participants to track.

Trial Duration

Each tracking trial lasted for 60 seconds. After each trial participants were given a 10-15 second break, they could request a longer break if needed. During jaw tracking trials participants were asked to refrain from swallowing and wait for the break to swallow if they could. A glass of water was offered to help participants avoid dry mouth

and make swallowing on purpose during the breaks easier. Participants were given a 10-15 minute break before they started manual tracking tasks.

Manual Tracking

In the manual tracking trials, participants were seated 1.25 meters away from the screen, a small portable table was placed next to the participant's chair. Participants were asked to rest their dominant hand on the table top during tracking. The height of the table was adjusted for each participant to make their arm feel comfortable during tracking. The table also had marks used for calibration of the Optotrak and two stationary bars attached to each side of the table for re IRED placement.

An IRED marker was attached to the participant's middle finger on the dominant hand with the use of adhesive tape (see figure 7). Participants were instructed to slide their hand horizontally while keeping it rested on the tabletop to pursue the target, they were asked to move their hand together with the lower arm as if it was a hand of a clock or a pendulum. To prevent movement of the wrist during tracking, participants had to wear a commercially available wrist stabilizer during tracking. Movements of the hand were transduced via the Optotrak system to appear on the computer screen. Movements of the hand were referenced to a marker that was stationary and was placed on one of the special bars on the tabletop. The maximum extent of hand movement was calibrated by asking participants to align their middle finger (with the marker placed on it) with two lines marked on the tabletop: one corresponding to the maximally closed position, and the other corresponding to the maximally open position. The effective tracking range was 10.6cm and used 70% of the maximal range (15cm) to avoid touching the ends of the tracking range with the hand during tracking. Before the start of each tracking trial participants were asked to align their middle finger with the line marking the center of the tracking space on the table top. A warning signal preceded the start of each trial; the target appeared on the computer screen with a one second delay after that.

All the tracking conditions used for jaw tracking were also used for manual tracking. One important difference between the jaw and manual tracking was in the plane of the sine wave motion: the sine waves were moving in a horizontal as opposed to vertical plane during manual tracking.

Data Analysis

Movements of the jaw or dominant hand during tracking were measured from the Optotrak outputs and were sampled with the rate of 50Hz into a Microsoft Access database. The tracking data were recorded as the track the participant produced, the sinusoidal target track, and the corresponding time track. Approximately 3000 data points were sampled for each 60 second trial for each track. In addition to those values, participant's identification number, tracking medium (jaw or hand), type of condition, number of the trial, and calibration values were recorded. After the data collection procedure, each participant's data were extracted into separate Excel files, jaw and hand tracking data were saved separately.

Due to the sinusoidal nature of both the target and the participant's tracking movements, amplitude and phase were chosen to quantify accuracy of participants' tracking relative to the target. Those two measures were chosen because they precisely describe a sinusoidal signal of a known frequency. Frequency was constant for the target signal and was assumed to be constant for the participant's tracking signal, which was a reasonable assumption to make since participants always had visual feedback during tracking.

Three custom-written Matlab functions were used for data processing and analysis. The first function read in data from multiple MS Excel files and placed the data in matrices for subsequent analysis. The data were saved in a Matlab data file under three variable names: *Target* was a matrix of target amplitudes (3000 data points for each trial/matrix column). Each column was one 60-second condition. *Tracking* was a matrix

of subject response amplitudes (their tracking of the target). Each column in this matrix had a corresponding column in the *Target* matrix.

The second function analyzed tracking data that had been saved by the first function. The analysis was designed for the tracking of sinusoidal targets of a known, constant frequency. It was assumed that frequency was constant throughout each recording (each column of the data matrix). It was also assumed that the target amplitude is constant across each cycle of the sinusoid, but may differ from one cycle to the next. Each sinusoidal cycle was therefore analyzed separately. A least-squares fitting procedure was used to find the sinusoid that provided the best fit to the target, and another one that was the best fit to the subjects tracking. The fitting was done over one half of a cycle of the sinusoid, with half cycle overlap, which resulted in three data points for both amplitude and phase for each cycle of the target and subject sinusoids. Depending on the frequency of the target signal (0.3, 0.6 or 0.9Hz), our analysis resulted in 51, 105 or 159 amplitude and phase data points for one 60 second tracking trial for each subject.

Test Variables

We were looking to find a single measure of tracking accuracy that would incorporate both amplitude and phase fluctuations of subject's tracking signal relative to the target signal. Using the amplitude and phase data for each cycle of a target and subject sinusoids, five parameters were calculated: '*Gain*', '*Delay*', '*Gains*',' *Delays*', and '*Error*'. '*Gain*' refers to the sinusoidal amplitude produced by the subject's tracking relative to the target. Gain was expected to be close to 1 for "good trackers". '*Gains*' was a matrix of smoothed '*Gain*' values used for subsequent error calculation, smoothing was performed using a Matlab library function "csaps" which performs a cubic spline smoothing to the data.

‘*Delay*’ refers to the relative time difference of the sinusoid produced by the subject’s tracking relative to the target. ‘*Delay*’ was calculated by subtracting the tracking phase from the target phase to yield a phase difference measured in radians. A negative value indicated a phase lag in the response, while a positive value indicates a phase lead. The phase difference is converted to a time delay in seconds by dividing by radian frequency. For “good trackers”, delay was expected to be close to zero. ‘*Delays*’ was a matrix of smoothed ‘*Delay*’ values used for subsequent error calculation, smoothing was performed using a Matlab library function “csaps” (please refer to Figure 8).

The ‘*Error*’ variable was calculated based on smoothed gain and delay data (‘*Gains*’ and ‘*Delays*’). This variable was computed using the following equation:

ERROR =√ ((GAINs-1) ^2 + DELAYs ^2)

The ‘*Error*’ variable reflected the magnitude of subject’s deviations from the target both in terms of amplitude and phase since it incorporated subject’s gain and delay during tracking. ‘*Error*’ was chosen as a measure of tracking accuracy and learning to be used in subsequent statistical analysis.

For each of the five variables calculated (‘*Gain*’, ‘*Delay*’, ‘*Gains*’,’ *Delays*’, and ’*Error*’) our analysis resulted in 51 data points for one 60 second tracking trial for target conditions with 0.3Hz frequency, 105 data points for one 60 second tracking trial for target conditions with 0.6Hz frequency and 159 data points for one 60 second tracking trial for target conditions with 0.6Hz frequency. In the statistical analyses these data points were averaged resulting in one observation per participant per trial, thus each cell had 15 observations.

Chapter II Tables and Figures

Table 1. Demographic and clinical characteristics of participants with Parkinson's disease.

Variable	Minimum	Maximum	Mean	Std. Deviation
Age	55	79	65.18	6.53
Education	12	20	15.75	2.38
Hoehn-Yahr	1	3	1.87	0.59
Motor UPDRS	3	38	18.66	11.42
ADL UPDRS	1	20	9.19	5.83
MMSE	26	30	29	1.26
SE	75	100	87.5	6.58

Gender: 6 females, 9 males.

Table 2. Demographic and clinical characteristics of participants who stutter.

Variable	Minimum	Maximum	Mean	Std. Deviation
Age	18	39	27	5.84
Education	11	23	14.73	3.51
Years in therapy	0	11	5	3.40

Gender: 1 female, 14 males

Figure 1. Level 1 Conditions: Simple Sine Waves of Three Different Frequencies (0.3, 0.6 and 0.9 Hz)

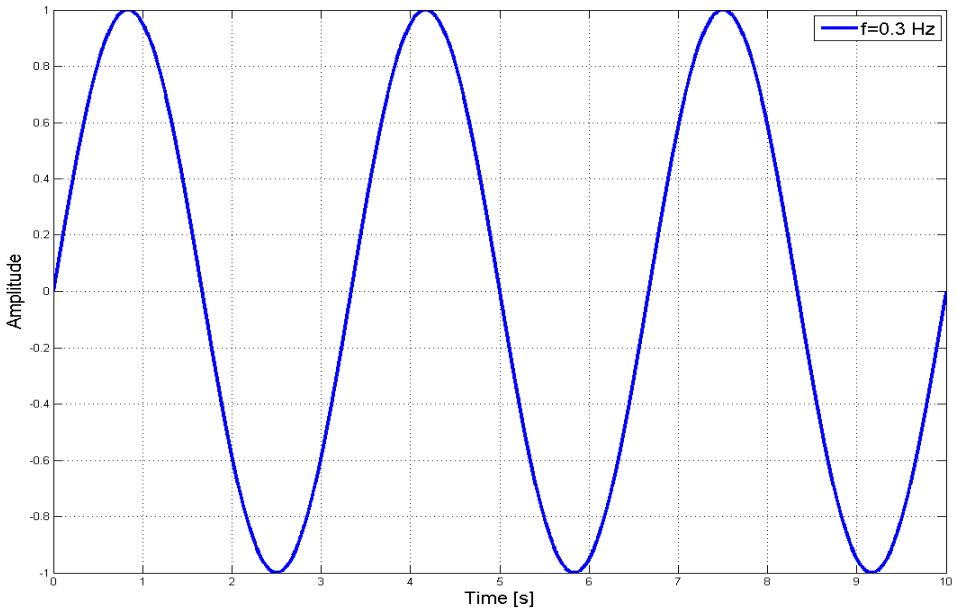


Figure 2. Level 2 Conditions: Complex Sine Patterns

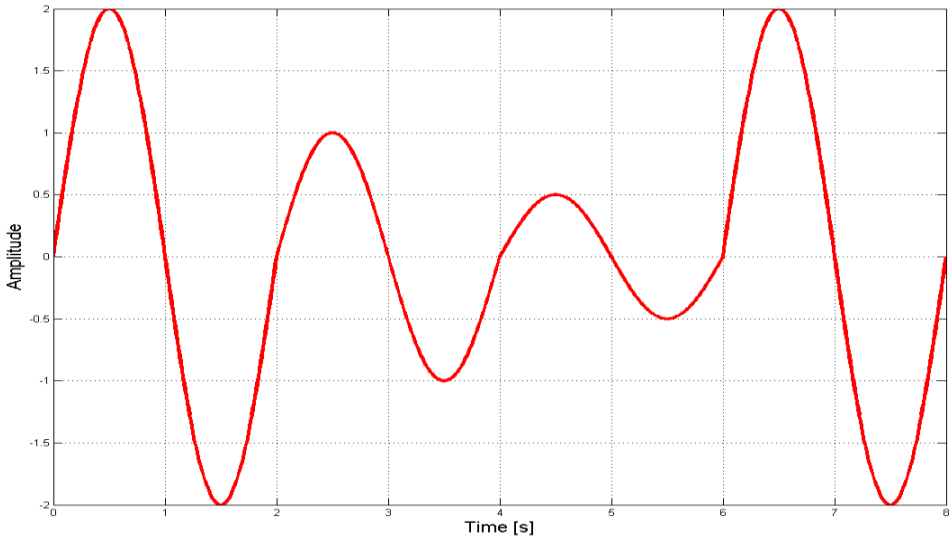


Figure 3. Level 3 Conditions: Variable Amplitude Waves

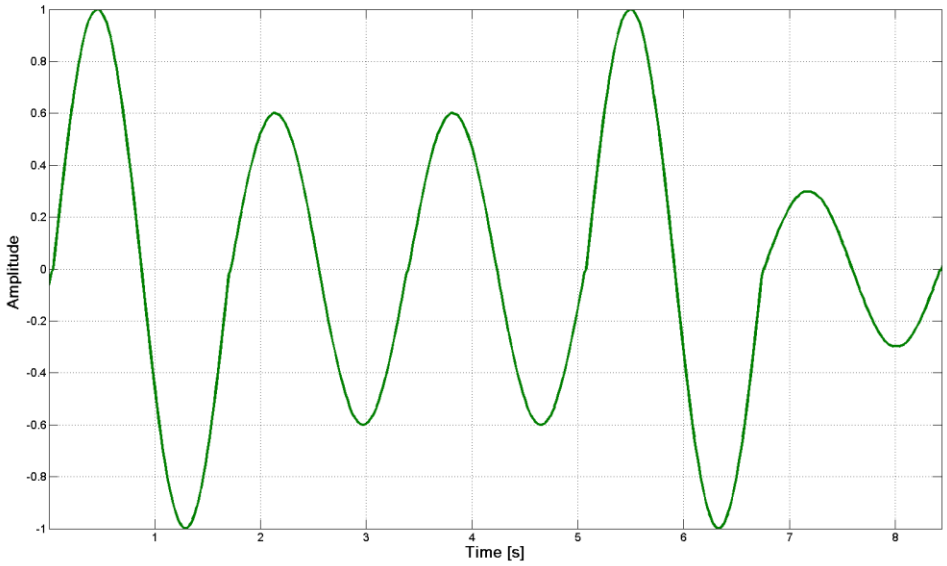


Figure 4. Level 4: Variable Amplitude and FrequencyWave

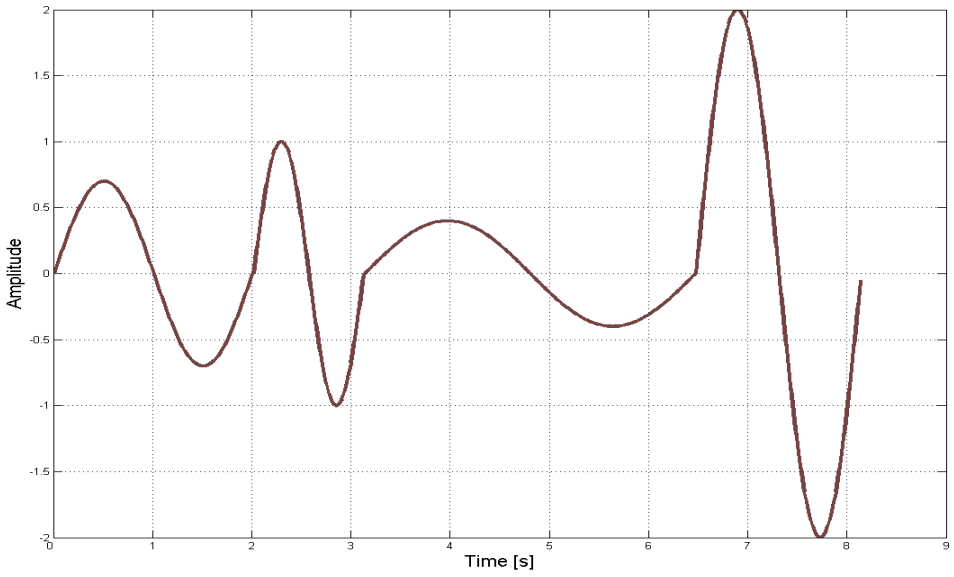


Figure 5. Experimental Set Up for Jaw Tracking

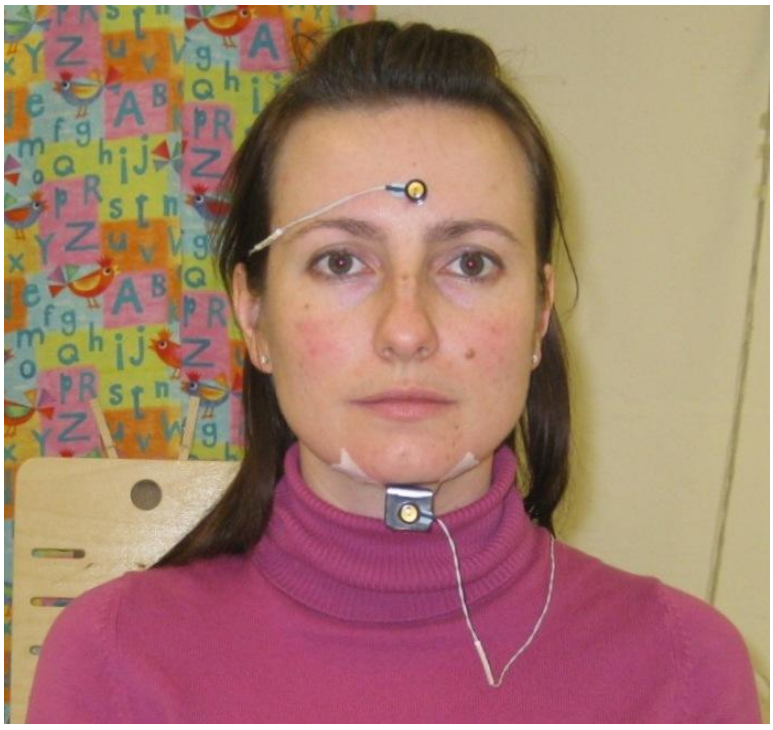


Figure 6. Graphical User Interface.

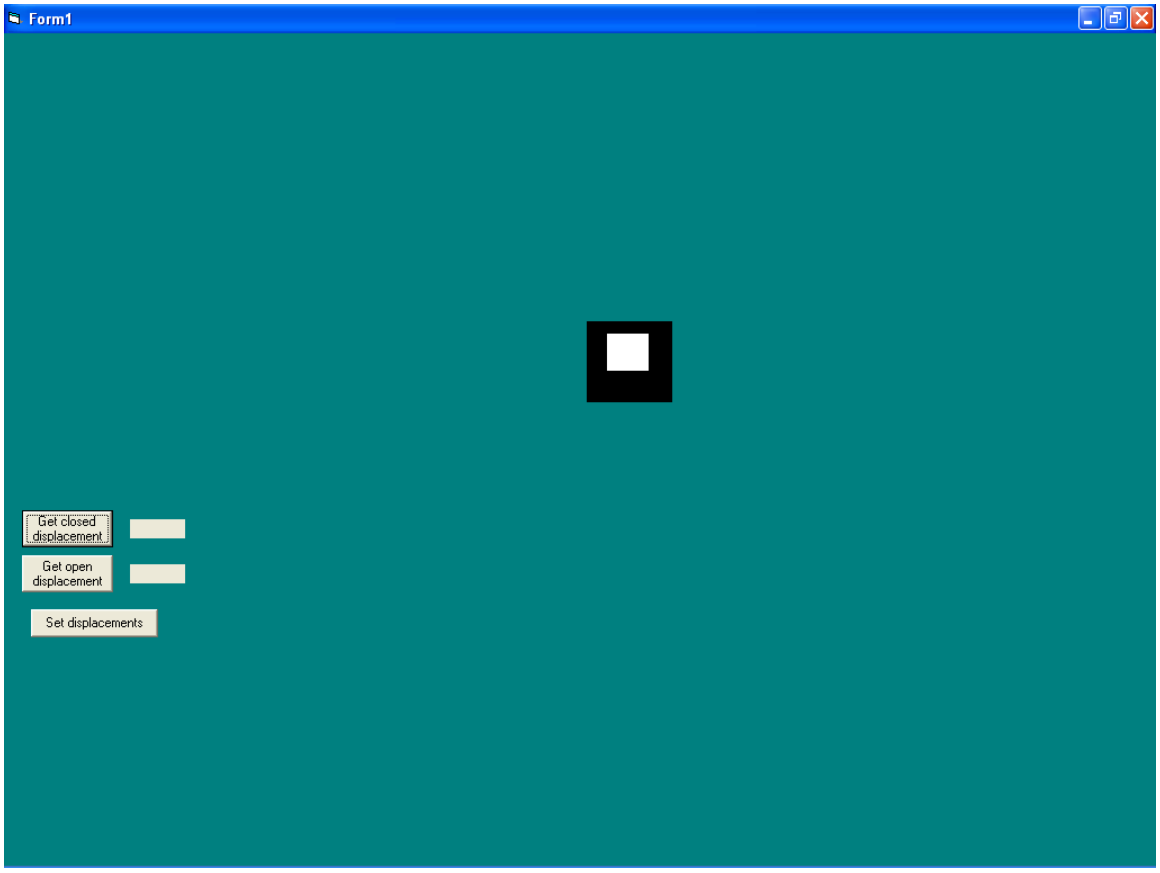


Figure 7. Experimental Set Up for Hand Tracking

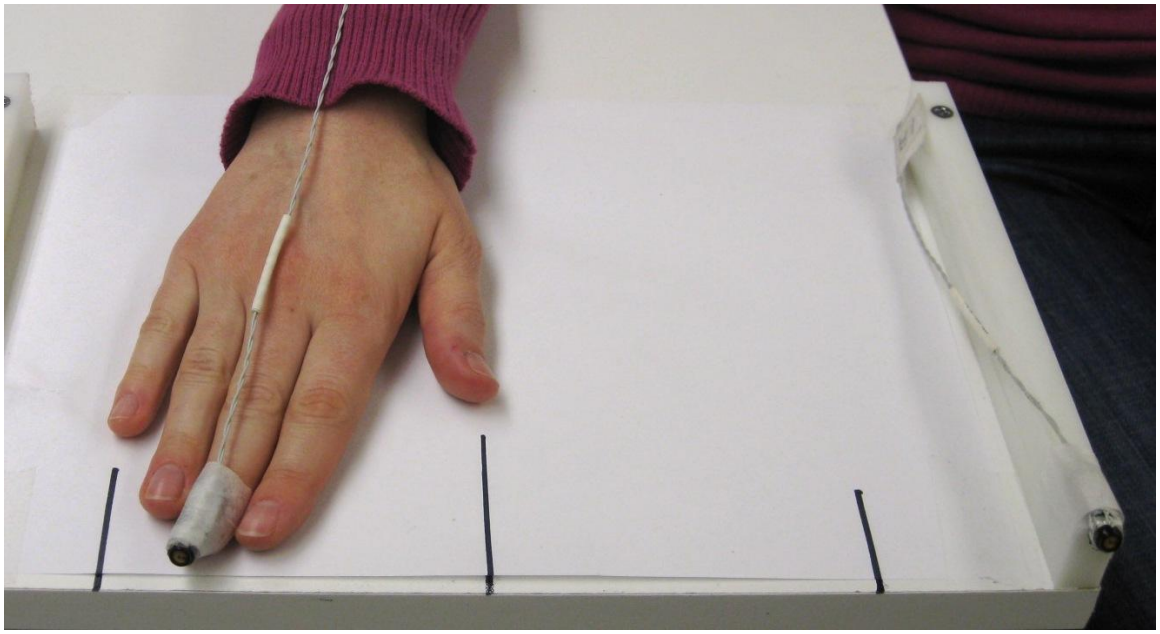
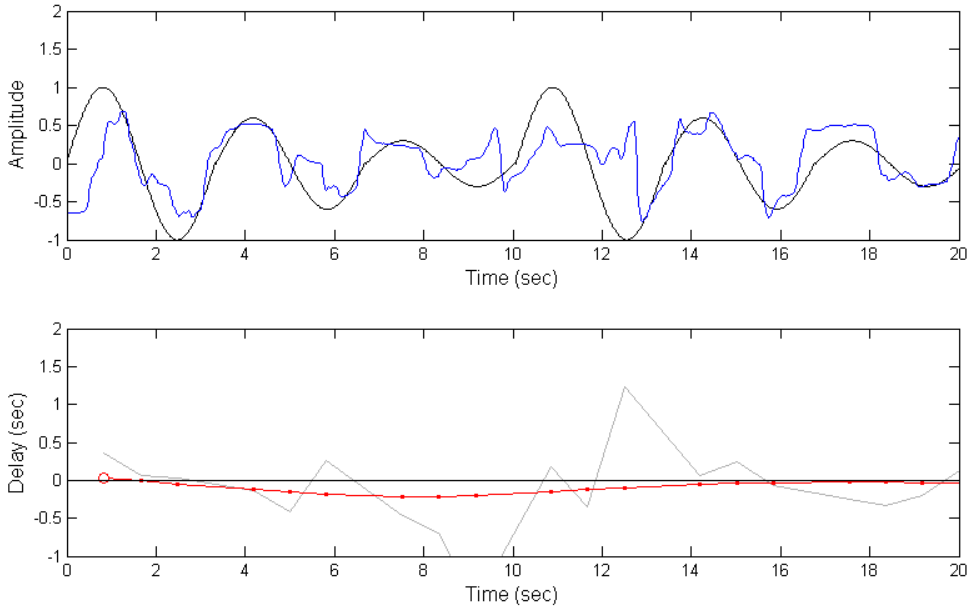


Figure 8. Target and Subject Tracking Sinusoids



Note: On the top graph: black line indicates target sinusoid, blue line indicate subject tracking signal. On the bottom graph, gray line indicates delay variable ('*Delay*') and red line indicates smoothed delay variable ('*Delays*')

CHAPTER III: RESULTS

Recall that the purpose of the current investigation was to explore both procedural learning and accuracy in jaw and hand tracking in people who stutter and people with Parkinson's disease, and compare their performance to age-matched controls. Procedural learning in the current investigation was defined as improvement in tracking accuracy over time (both within and between consecutive trials of the same condition). Further, we were interested in the relationship between tracking accuracy and condition, that is, do the groups perform differently while tracking a predictable pattern (i.e. sine wave with constant and varying amplitude), or the one that is unpredictable. Finally, we were interested to know if accuracy improved over time (procedural learning) and if accuracy differentiated the jaw and dominant hand. To explore these questions, a descriptive and statistical analysis of tracking performance using two-way and one-way analysis of variance (ANOVA) and two-way repeated measures ANOVA was conducted. Post hoc pair wise comparisons were conducted using the Bonferroni adjustment for multiple comparisons. Statistical analysis was performed using SPSS software.

The following section is organized by research questions in the order in which they were presented in the review of literature (see page 21).

Research Question 1: Jaw Tracking Accuracy

Do people who stutter (PWS) differ from age-matched controls who do not stutter (CPWS) in the accuracy with which they track both predictable and unpredictable signals with the jaw; and do people with Parkinson's disease (PPD) differ from age-matched controls without neurological impairment (CPPD) in the accuracy with which they track both predictable and unpredictable signals with the jaw?

Predictable signals were the ones in the Level 1 and 2 conditions. This set of conditions was designed to assess the ability of all groups to track a predictable pattern (a simple one as in the level 1, and a more complex one as in the level 2) of movement at

different paces. Unpredictable signals were in the Level 3 and 4 conditions. These conditions were designed to evaluate participant's ability to constantly match the jaw position with the moving target at a slow, medium and fast speed (level 3) and at a constantly changing speed (as in the level 4 condition).

Descriptive analysis of participants' tracking performance revealed that participants had higher accuracy during tracking of predictable conditions than unpredictable conditions. For predictable conditions age was a factor that influenced tracking accuracy: younger participants (CPWS and PWS) were always tracking with a lower error scores than older participants (CPPD and PPD). Age did not differentiate participants' level of accuracy as much for the unpredictable conditions; all groups had a much more similar accuracy level. Among the four participant groups, PPD had the biggest error values overall, however, the gap between their accuracy level and the other groups was minimal at variable (level 3) conditions at 0.3 and 0.6Hz .With the increase in frequency (at 0.9Hz) this gap grew large, suggesting that higher speeds and tracking of predictable patterns pose more difficulty for PPD than for the other groups. Variable frequency and amplitude condition (level 4) was notable for similar performance of all groups. Tracking accuracy for this condition was the lowest out of all tracking conditions; however, all groups had similar tracking accuracy level. It was fluctuating depending on the difficulty of the tracking signal at each point in time.

Of interest was the existence of tracking variability fluctuations within tracking trials. Overall, CPPD and PPD's tracking was associated with higher variability (higher standard deviation values) than CPWS and PWS. PPD's data is remarkable for the highest variability among the four groups.

Analysis of mean and standard deviations for the jaw tracking data for predictable conditions showed that CPWS had the lowest tracking error followed by PWS, CPPD and PPD. Mean error for CPWS was .136 (SD = .038), ranging from .100 to .255. Mean error for PWS was .149 (SD = .037), ranging from .115 to .332. Mean error for CPPD was

.211 (SD = .088), ranging from .131 to .468. Mean error for PPD was .274 (SD = .099), ranging from .139 to .463.

Descriptive analysis of the jaw tracking data for unpredictable conditions showed that CPWS had the lowest tracking error followed by PWS, CPPD and PPD. Mean error for CPWS was .186 (SD = .043), ranging from .116 to .263. Mean error for PWS was .232 (SD = .082), ranging from .134 to .426. Mean error for CPPD was .283 (SD = .136), ranging from .147 to .587. Mean error for PPD was .331 (SD = .097), ranging from .146 to .438. The descriptive statistics for tracking accuracy is summarized in table 3.

Separate analyses using two-way ANOVA were performed for all predictable and all unpredictable conditions for both jaw and hand tracking. In all four analyses, group, and condition were fixed factors and error was the dependent variable.

ANOVA analysis of jaw tracking of predictable signals showed significant main effects of group ($F=77.37$; $p<.00001$) and tracking condition ($F=10.34$; $p<.00001$), there was no interaction between these factors. Multiple comparisons tests revealed no significant differences between PWS and CPWS in tracking of predictable conditions with the jaw. PPD, however, were less accurate than CPPD, and both CPPD and PPD had significantly lower accuracy than CPWS and PWS, revealing the age effect. Means for the four groups are presented in figure 49.

Analysis of jaw tracking accuracy for unpredictable signals revealed significant main effects of group ($F=13.43$; $p<.00001$) and condition ($F=14.7$; $p<.00001$) in the absence of significant interaction between them. Multiple comparisons tests revealed no significant differences between PWS and CPWS and between PPD and CPPD in tracking of unpredictable conditions with the jaw. PPD were significantly less accurate than CPWS and PWS. CPPD were significantly less accurate than CPWS only, thus the age effect did not determine the tracking accuracy as much as in the predictable conditions. Means for the four groups are presented in figure 50.

Research Question 2: Hand Tracking Accuracy

Do people who stutter (PWS) differ from age-matched controls who do not stutter (CPWS) in the accuracy with which they track both predictable and unpredictable signals with the hand; and do people with Parkinson's disease (PPD) differ from age-matched controls without neurological impairment (CPPD) in the accuracy with which they track both predictable and unpredictable signals with the hand?

Descriptive analysis of participants' tracking performance revealed that similar to jaw tracking, participants had higher accuracy during hand tracking of predictable conditions than unpredictable conditions. However, the difference in accuracy between them was smaller than in jaw tracking. Age was still a factor that influenced accuracy of tracking, and it was still more pronounced for predictable conditions. The most prominent characteristic of hand tracking performance was the fact that CPWS, CPPD and PWS showed relatively similar tracking performance whereas PPD maintained higher error than any of the other groups for all tracking conditions but the level 4 condition (a variable amplitude and frequency signal). All four groups had similar accuracy level for that condition, it varied according to the difficulty of the target movement.

Analysis of mean and standard deviations for the hand tracking data for predictable conditions showed that CPWS had the lowest tracking error followed by PWS, CPPD and PPD. Mean error for CPWS was .101 (SD = .028), ranging from .075 to .199. Mean error for PWS was .118 (SD = .047), ranging from .085 to .218. Mean error for CPPD was .156 (SD = .072), ranging from .119 to .371. Mean error for PPD was .282 (SD = .144), ranging from .154 to .598.

ANOVA test of hand tracking accuracy for predictable signals revealed significant main effects of group ($F=128.82$; $p<.00001$) and condition ($F=7.76$; $p<.00001$) in the absence of significant interaction between them. Multiple comparisons tests revealed no significant differences between PWS and CPWS. PPD had significantly

lower accuracy than CPPD, and both CPPD and PPD performed poorer than CPWS and PWS. Means for the four groups are presented in figure 51.

Descriptive analysis of the hand tracking data for unpredictable conditions showed that CPWS had the lowest tracking error followed by PWS, CPPD and PPD. Mean error for CPWS was .144 (SD = .033), ranging from .103 to .238. Mean error for PWS was .163 (SD = .04), ranging from .098 to .231. Mean error for CPPD was .202 (SD = .07), ranging from .141 to .374. Mean error for PPD was .303 (SD = .102), ranging from .145 to .513.

ANOVA test of hand tracking accuracy for unpredictable signals revealed significant main effects of group ($F=37.29$; $p<.00001$) and condition ($F=13.16$; $p<.00001$) in the absence of significant interaction between them. Multiple comparisons tests revealed no significant differences between PWS and CPWS. PPD were significantly less accurate than CPPD. CPPD were less accurate than CPWS, but not significantly different from PWS. Means for the four groups are presented in figure 52.

Research Question 3: Procedural Learning

Are there within and between group differences in both jaw and hand tracking accuracy over time? Please recall that procedural learning in the present study was defined as increases in accuracy over time. Predictable conditions (level 1 and level 2) were chosen for the analysis of learning. The data was first plotted and analyzed descriptively, which allowed us to choose the most appropriate statistical procedure that would capture learning. Below is the description of the data followed by the statistical analysis of learning.

Descriptive Analysis of Jaw Tracking Accuracy

The task in Level 1 conditions was tracking of a simple sine wave (see figure 1). This condition was presented at 0.3, 0.6 and 0.9 Hz. Each of the simple sine wave conditions was performed twice; that is the first 60 second trial was immediately

followed by the second trial. This set of conditions was designed to assess the ability of all groups to track a predictable pattern of movement at different rates, inclusion of two trials allowed for assessment of learning. The task in level 2 conditions was tracking of a sine wave that had a constant frequency of 3 different amplitudes (see figure 2). These patterns were presented at the frequency of 0.3, 0.6 and 0.9 Hz. Participants produced three consecutive trials of each pattern. This set of conditions was designed to assess the ability of all groups to track a more complex (not as visually obvious as the one in level 1) predictable pattern at different speeds. Three, rather than two trials for this condition were performed because of the complexity of this signal, and pilot data that showed the most improvement happened across three trials of this condition.

Visual inspection of consecutive trials of level 1 and 2 conditions showed that all groups had a decrease in error values over the initial 10 seconds of tracking, after that the error values stayed relatively constant for most of each trial and error increased again over the last two cycles of each trial. Fatigue could explain the decrease in tracking accuracy towards the end of the trials. Visual inspection of the mean error values suggests that fatigue came faster during the second and third consecutive trials.

Most of accuracy improvement occurred within each trial, in the initial 10 second segment, however, between trial improvements were also noted. Participants had a tendency to start the second trial with a lower error score than their initial error in the first trial. They also achieved their best accuracy level faster in the second trial than in the first trial, and maintained low error for longer. All of which was taken as signs of learning. Overall, most learning occurred in the first 10 seconds of tracking of each trial and all four groups had a better accuracy in the second trial than the first trial; however CPPD and PPD were not able to maintain low error scores as CPWS and PWS. PWS and CPWS had similar tracking accuracy with CPWS tracking a little better. PPD had highest error and most variable performance of all groups. A faster frequency of 0.9 Hz was remarkable for posing more difficulty for the older participants – CPPD and PPD. With

this faster speed of target movement PWS and CPWS seem to have improvement in accuracy over initial 15 cycles of a sinusoid (around 17 seconds). CPPD and especially PPD had much less of a drop in error value relative to its initial value, suggesting that they learned less than CPWS and PWS. Moreover, while PWS and CPWS were able to maintain a better accuracy throughout the trial, CPPD and PPD showed a steady increase in error as the trial progressed, suggesting that they succumb to fatigue faster. Level 2 conditions were associated with much more variability for all groups compared to level 1 conditions.

Mean and standard deviation for error values for jaw tracking for each participant group are presented in figures 9 through 28.

Overall, descriptive analysis of the data revealed that there were error decreases within a tracking trial as well as between consecutive trials of the same condition. Those two phenomena were analyzed separately. First, we examined changes in tracking accuracy within a first trial for level 1 and 2 conditions. Several repeated measures ANOVAs with group (PWS, CPWS, PPD and CPPD) as the between-group factor and time as the within-group factor with repeated measures (tracking error was averaged over 6 non-overlapping consecutive 10-second time intervals) were used. Ten second time interval was chosen based on descriptive analysis results which showed that the most decrease in accuracy happened during the first 10 seconds of tracking. In the report of results we refer to each consecutive 10 second time interval as time1, time2, time3, time4, time5 and time6. Each predictable tracking condition was analyzed with a separate repeated measures ANOVA test. The extent of within trial increases in accuracy (i.e. procedural learning) between groups was analyzed using the Bonferroni corrected multiple comparisons at each time interval. Results of statistical analyses are presented in the following section and summarized in tables 4-15.

Statistical Analysis of Within-Trial Procedural Learning

Level 1 Conditions: 0.3 Hz

ANOVA revealed significant main effect of group and time. Test of within-subject contrasts showed that the best fit for the difference in error between six subsequent time intervals was a quadratic fit ($F=10.822$; $p=.002$), there was no interaction between group and time, suggesting that all groups had the same trend in accuracy changes over 6 time intervals.

Multiple pairwise comparisons using the Bonferroni corrected alpha level revealed that PPD were significantly different from CPWS and PWS, their tracking accuracy was lower than the one exhibited by CPWS and PWS at time2, time3, time4, time5 and time6, and they were significantly different from CPPD at time6. There was no difference between CPWS and PWS at any of the time segments.

0.6 Hz

ANOVA revealed significant main effect of group and time. Test of within-subject contrasts showed that the best fit for the difference in error between six subsequent time intervals was a quadratic fit ($F=21.033$; $p=.0001$), there was a significant interaction between group and time ($F=2.568$, $p=.006$), suggesting that groups had different trends in accuracy changes over time.

Multiple pairwise comparisons using the Bonferroni corrected alpha level revealed that PPD were significantly different from CPWS and PWS, their tracking accuracy was lower than the one exhibited by CPWS and PWS at time2, time3, time4, time5 and time6. There was no difference between CPWS and PWS or CPPD and PPD at any of the time segments.

0.9 Hz

ANOVA revealed significant main effect of group. Test of within-subject contrasts showed that the best fit for the difference in error between six subsequent time intervals was a 4^{th} order polynomial fit ($F=5.502$; $p=.023$), there was a marginally significant interaction between group and time ($F=1.819$, $p=.056$).

Multiple pairwise comparisons using the Bonferroni corrected alpha level revealed that PPD were significantly different from CPPD, CPWS and PWS: their tracking accuracy was lower than the one exhibited by CPPD and CPWS at time1; their tracking accuracy was lower than the one exhibited by all other groups at time2; their tracking accuracy was lower than the one exhibited by CPWS and PWS at time3, 4, 5 and 6. PWS were not significantly different from their controls at any of the time segments.

Level 2 Conditions: 0.3 Hz

ANOVA revealed significant main effect of group and time. Test of within-subject contrasts showed that the best fit for the difference in error between six subsequent time intervals was a linear fit ($F=6.724$; $p=.012$), there was no interaction between group and time.

Multiple pairwise comparisons using the Bonferroni corrected alpha level revealed that PPD differed significantly only from CPWS (at time 2 and 6). There was no difference in tracking accuracy between PPD and their control group (CPPD) and PWS and their control group (CPWS).

0.6 Hz

ANOVA revealed no significant main effects. Test of within-subject contrasts showed that the best fit for the difference in error between six subsequent time intervals was a quadratic fit ($F=6.006$; $p=.017$). There was a significant interaction between group and time ($F=2.144$; $p=.024$).

Multiple pairwise comparisons using the Bonferroni corrected alpha level revealed no difference in tracking accuracy between any groups at any time segment.

0.9 Hz

ANOVA revealed a significant main effect of time. Test of within-subject contrasts showed that the best fit for the difference in error between six subsequent time intervals was a quadratic fit ($F=15.363$; $p<.0001$). There was a significant interaction between group and time ($F=3.767$; $p<.0001$).

Multiple pairwise comparisons using the Bonferroni corrected alpha level revealed a significantly lower tracking accuracy of PPD, relative to CPWS and PWS at time 6. CPPD and PPD did not show significant difference in tracking, the same was true for CPWS and PWS.

Summary of the Jaw Tracking Results

Statistical analysis of the tracking data showed that there is evidence of increases in accuracy within a tracking trial (i.e. procedural learning) for all groups. Most dramatic increase in accuracy occurred from the first to the second 10-second time intervals. It is of interest, however, that for several tracking conditions all groups after initial decrease in error and a segment of stable performance where the error stayed relatively constant were showing an increase in error in the last couple of tracking cycles (the best fit for accuracy changes over time in many trials was quadratic). The fact that the error curve over 6 time segments is best fit by a quadratic function suggests that all groups showed both learning at the start of tracking trials and fatigue in the end of trials.

There was no statistically significant difference in tracking accuracy changes between CPWS and PWS for any of the tracking conditions, which leads to the conclusion that they learned to the same extent. There was no statistically significant difference in tracking accuracy changes between CPPD and PPD for all but one condition – tracking of simple sine wave of 0.9Hz frequency, where PPD showed significantly

higher tracking error throughout the trial. Thus, the results suggest that PPD were able to learn the task as well as CPPD and maintain the same accuracy level, however with the increased difficulty of the task (higher rate of target movement) they could not sustain good tracking accuracy.

PPD, however, had significantly higher tracking error than CPWS for all conditions but a complex sine pattern at 0.6Hz. PPD had significantly higher error compared to PWS for all simple sine wave conditions; there was no significant difference for any other conditions. Age difference between CPWS, PWS and PPD precludes us from making direct comparisons of those there groups; these results, however, imply that age was a factor that determined tracking accuracy in our participants.

Descriptive Analysis of Hand Tracking Accuracy

Level 1 and 2 conditions were used in this analysis. Both of those conditions were tracked at 0.3, 0.6 and 0.9 Hz. Level1 conditions had to consecutive tracking trials, a more complex level 2 conditions had three consecutive trials. Overall the trends observed for the jaw tracking performance were also observed for the hand tracking. All of the groups showed a decrease in error values over the first 2-3 tracking cycles (initial 10 seconds), after that the error values stayed relatively constant until the end of the trial. Similar to jaw tracking performance, there were error increases in the last couple of tracking cycles for all groups. They were more pronounced for the faster conditions of 0.6 and especially 0.9 Hz. Similar to jaw tracking, increases in accuracy for all groups seemed occur more within each trial and much less across trials. However, trends of lower initial error and quicker decrease in error were noted in the second and third trials than in the first trial – all of those were taken as signs of learning. Tracking of PPD was characterized by highest error and highest variability of performance. Level 2 conditions were associated with a more pronounced improvement across trials than the level 1 conditions, which were relatively simple. A frequency of 0.9 Hz in level 2 signal was

associated with least amount of improvement in error and most variability of tracking among all the predictable conditions. Mean and standard deviation for error values for hand tracking for each group are presented in figures 29 through 48.

Each predictable tracking condition was analyzed with a separate repeated measures ANOVA test. Group was the between-group factor and time was the within-group factor with repeated measures. Just as for jaw tracking, tracking error was averaged over 6 non-overlapping consecutive 10-second time intervals. In the report of results we refer to each consecutive 10 second time interval as time1, time2, time3, time4, time5 and time6. The extent of within trial increases in accuracy (i.e. procedural learning) between groups was analyzed using the Bonferroni corrected multiple comparisons at each time interval. Results of statistical analyses are presented in tables 4-15.

Statistical Analysis of Within-Trial Procedural Learning

Level 1: Conditions: 0.3 Hz

ANOVA revealed significant main effect of group and time. Test of within-subject contrasts showed that the best fit for the difference in error between six consecutive time intervals was a linear fit ($F=47.455$; $p<.0001$), there was no interaction between group and time.

Multiple pairwise comparisons using the Bonferroni corrected alpha level revealed that PPD were significantly different from CPPD, CPWS and PWS, their tracking accuracy was lower than the one exhibited by all other groups at time2, time3, time5, and they were significantly different from CPWS only at time6. There was no difference between CPWS and PWS at any of the time segments.

0.6 Hz

ANOVA revealed significant main effect of group and time. Test of within-subject contrasts showed that the best fit for the difference in error between six

consecutive time intervals was a quadratic fit (F=29.634; p<.0001), there was no significant interaction between group and time.

Multiple pairwise comparisons using the Bonferroni corrected alpha level revealed that PPD were significantly different from CPPD, CPWS and PWS, their tracking accuracy was lower than the one exhibited by all other groups at time1, time2, time4. They performed significantly worse than CPWS and PWS only at time3, time5 and time6. There was no difference between CPWS and PWS at any of the time segments.

0.9 Hz

ANOVA revealed significant main effect of group and time. Test of within-subject contrasts showed that the best fit for the difference in error between six consecutive time intervals was a cubic fit (F=18.613; p<.0001), there was no significant interaction between group and time.

Multiple pairwise comparisons using the Bonferroni corrected alpha level revealed that PPD were significantly different from CPPD, CPWS and PWS, their tracking accuracy was lower than the one exhibited by all other groups at time1, time2, time4 and 5. They performed significantly worse than CPWS and PWS only at time3, and time6. There was no difference between CPWS and PWS at any of the time segments.

Level 2 Conditions: 0.3 Hz

ANOVA revealed significant main effect of group and time. Test of within-subject contrasts showed that the best fit for the difference in error between six consecutive time intervals was a linear fit (F=30.636; p<.0001), there was no interaction between group and time.

Multiple pairwise comparisons using the Bonferroni corrected alpha level revealed that PPD differed significantly only from CPWS and PWS at time1, time 2, time 3, time 4, time 5, time 6. They had significantly lower tracking accuracy from CPPD only

at time4. There was no difference in tracking accuracy between PWS and their control group (CPWS).

0.6 Hz

ANOVA revealed a significant main effect of group and time. Test of within-subject contrasts showed that the best fit for the difference in error between six consecutive time intervals was a linear fit ($F=10.814$; $p=.002$). There was no significant interaction between group and time.

Multiple pairwise comparisons using the Bonferroni corrected alpha level revealed that PPD overall differed significantly only from CPWS and PWS. Multiple comparisons at different time segments showed that PPD had significantly lower tracking accuracy from CPWS and PWS at time 1, time 2, time 3, time 4, time 5, and time 6. They also had significantly lower tracking accuracy from CPPD at time5. There was no difference in tracking accuracy between PWS and their control group (CPWS).

0.9 Hz

ANOVA revealed a significant main effect of group and time. Test of within-subject contrasts showed that the best fit for the difference in error between six consecutive time intervals was a 4^{th} order polynomial fit ($F=14.593$; $p<.0001$). There was a significant interaction between group and time.

Multiple pairwise comparisons using the Bonferroni corrected alpha level revealed that PPD overall differed significantly from all other groups. Multiple comparisons at different time segments showed that PPD had significantly lower tracking accuracy from CPWS and PWS at time 2, and from all groups (CPPD, CPWS, PWS) at time3, time4, time5, and time6. There was no difference in tracking accuracy between PWS and their control group (CPWS).

Summary of the Hand Tracking Results

Statistical analysis of the tracking data showed that there was evidence of increases of accuracy within a tracking trial (i.e. procedural learning) for all groups. Most dramatic increase in accuracy occurred between the first and second 10 second time interval.

There was no statistically significant difference in tracking accuracy over time between CPWS and PWS for any of the tracking conditions. This suggests that PWS were able to learn as well as their controls. PPD had significantly lower accuracy than CPPD while tracking all simple sine wave conditions (0.3, 0.6 and 0.9Hz), and complex pattern condition at 0.9Hz frequency. PPD had significantly lower accuracy than PWS for all predictable tracking conditions. Thus, the hand tracking results suggest that PPD were not able to learn as well as other groups. The rapid learning observed in the tracking tasks suggests that the tasks were simple and the learning system was not taxed much, this could also explain why the PPD group learned to the same extent as their controls.

Procedural Learning: Between-Trial Accuracy Changes

Mean tracking accuracy across three subsequent trials of the same condition was examined to see if any significant learning occurred between trials in any of the participant groups. Based on the descriptive analysis, level 2 conditions (complex sine pattern waves) were chosen for this analysis since they were more challenging than simple sine waves and allowed for more learning to occur. We used one-way ANOVAs with trial as a factor (three levels: first, second and third trial) and error as the dependent variable. Separate ANOVAs were performed for each condition and each participant group. Jaw and hand tracking data were analyzed separately. Results of statistical analyses are presented in tables 16-39.

Analysis of variance showed that neither CPPD nor PPD had significant difference between accuracy of jaw tracking for the three subsequent trials of the same

predictable condition for any of the frequencies at which they were presented. PWS had a significant improvement in accuracy over trials during tracking of a complex sine pattern at 0.6Hz frequency ($F=3.44$, $p=0.041$) and complex sine pattern at 0.9Hz frequency ($F=5.66$, $p=0.0067$). CPWS had a significant improvement in accuracy over trials during tracking of a complex sine pattern at 0.9Hz frequency ($F=6.34$, $p=0.0039$). The data showed a trend of error decrease from first to second trial of the same tracking condition, and little or no decrease in error for the third trial.

Hand tracking results showed that CPWS, PWS and PPD did not have significant difference between accuracy of tracking for the three subsequent trials of the same predictable condition for any of the frequencies at which they were presented. CPPD had a significant improvement in accuracy over repeated trials during tracking of a complex sine pattern at 0.3Hz frequency ($F=6.83$, $p=0.0027$). Similar to jaw tracking, hand tracking data revealed a trend of accuracy increase over the first two consecutive trials.

Summary of Research Findings

Tracking Accuracy

Initial statistical analysis of the data was carried out using a three-way ANOVA with group, tracker (jaw or hand) and condition as factors and error as the dependent variable. This analysis showed significant main effects of all factors and significant interactions of group and tracker, group and condition, condition and tracker. Further analysis of the data was carried out using one-way ANOVAs and two-way repeated measures ANOVAs with Bonferroni-corrected multiple comparisons.

The analysis revealed that PWS do not significantly differ from CPWS in tracking of either predictable or unpredictable signals with the jaw or hand. However, we observed a trend that CPWS had better tracking accuracy than PWS for both predictable and unpredictable signals for both jaw and hand tracking.

PPD performed more poorly than CPPD during tracking predictable conditions with the jaw, this difference was statistically significant. For unpredictable conditions, PPD also did more poorly than CPPD; this difference however was not significant. Hand tracking accuracy of PPD was significantly poorer than CPPD for both predictable and unpredictable signals. PWS had significantly better performance than PPD during both hand and jaw tracking for all tracking conditions; age difference between these two groups precludes us from being able to make direct comparisons based on etiology.

Analysis of within group differences between jaw and hand tracking accuracy revealed that for all groups except the PPD group, hand tracking was significantly more accurate than jaw tracking. There was no such difference for the PPD group.

Procedural Learning

Examination of procedural learning within jaw tracking trials showed that all groups exhibit significant increase in accuracy (i.e. procedural learning) over the initial 10 seconds of tracking, after that initial decrease, the error curve stayed relatively flat and increased towards the end (last 10 seconds) of each tracking trial. Analysis of within-trial accuracy changes for hand tracking revealed that most of the decrease in error occurred within the initial 10 seconds of tracking, after which the error curve stayed relatively constant. Compared to jaw tracking, there was smaller increase in error toward the ends of manual tracking trials, it was apparent for some more complex conditions. Changes in error over time for many trials were best fitted by a quadratic function, revealing learning at the initial tracking segments and possibly fatigue for the last tracking segments within a 60 second trial. Overall, the learning we observed was rapid (happened within the first 10 seconds) suggesting that our tracking tasks were relatively simple and did not tax the learning system.

Examination of procedural learning between consecutive jaw tracking trials of level 2 conditions showed that both PWS and CPWS improved their tracking

performance over trials. This learning occurred for signals that posed a greater level of tracking difficulty due to their rate (0.6 and 0.9 Hz). This suggests that easier tracking conditions did not create enough difficulty to promote learning in PWS and CPWS. There was no significant difference between the accuracy levels for the consecutive trials for the hand tracking conditions, suggesting a possibility that those conditions were also not challenging enough to promote learning. Neither CPPD nor PPD showed significant accuracy increases across trials for the majority of the jaw and hand tracking conditions. It is worth mentioning, however, that the trend showed improvement in accuracy from the first to the second trial for most conditions, and little or no improvement from second to third trial. This trend was seen in both hand and jaw tracking.

Chapter IV Tables and Figures

Figure 9. Summary of participant performance during tracking of a simple sine wave condition of 0.3Hz frequency: mean error values for four groups. Each dot represents a data point within one 60 second trial.

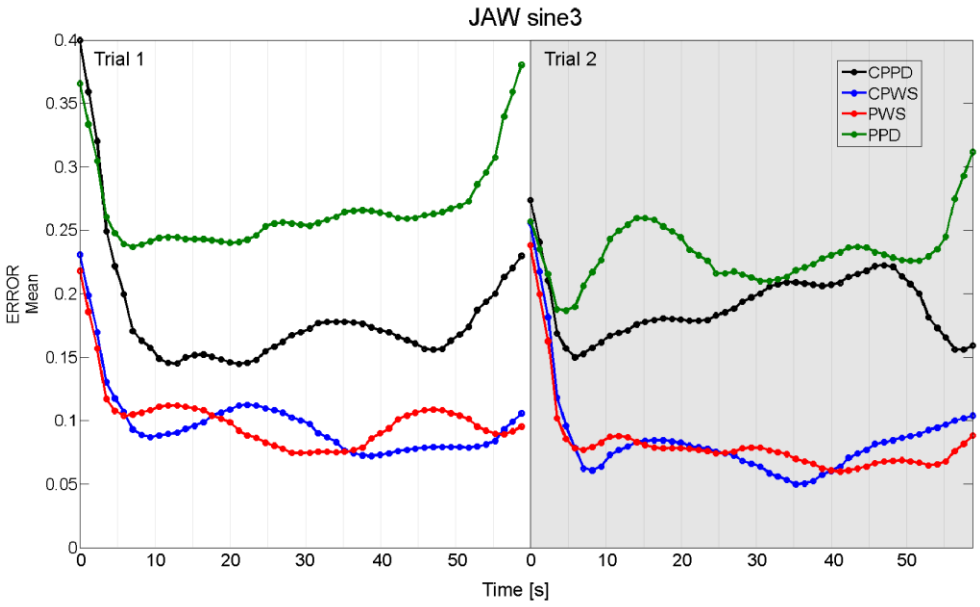


Figure 10. Error standard deviation for a simple sine wave condition of 0.3Hz frequency tracked with the jaw. Each dot represents a data point within one 60 second trial.

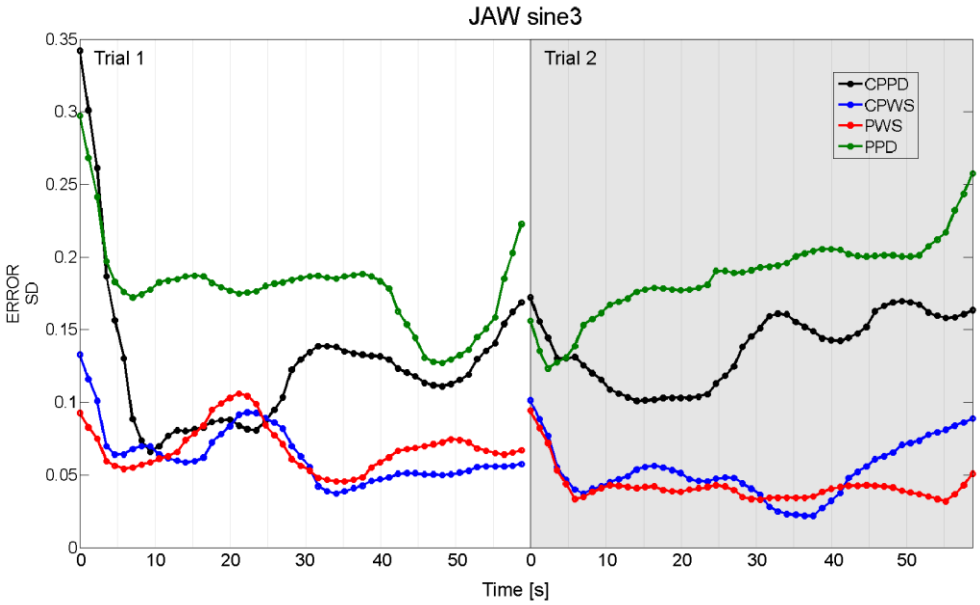


Figure 11. Summary of participant performance during tracking of a simple sine wave condition of 0.6Hz frequency: mean error values for four groups. Each dot represents a data point within one 60 second trial.

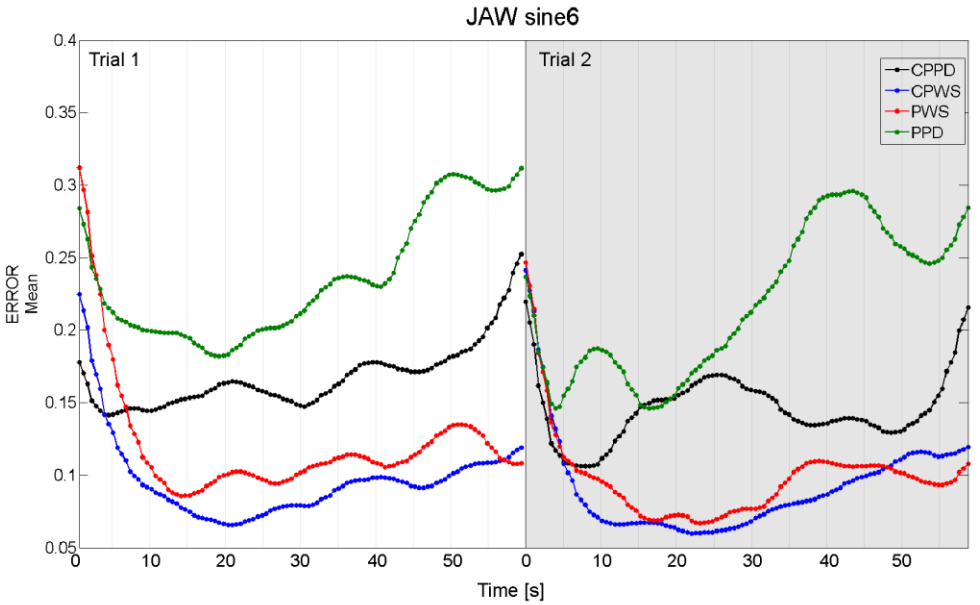


Figure 12. Summary of participant performance during tracking of a simple sine wave condition of 0.6Hz frequency: standard deviation of error values for four groups. Each dot represents a data point within one 60 second trial.

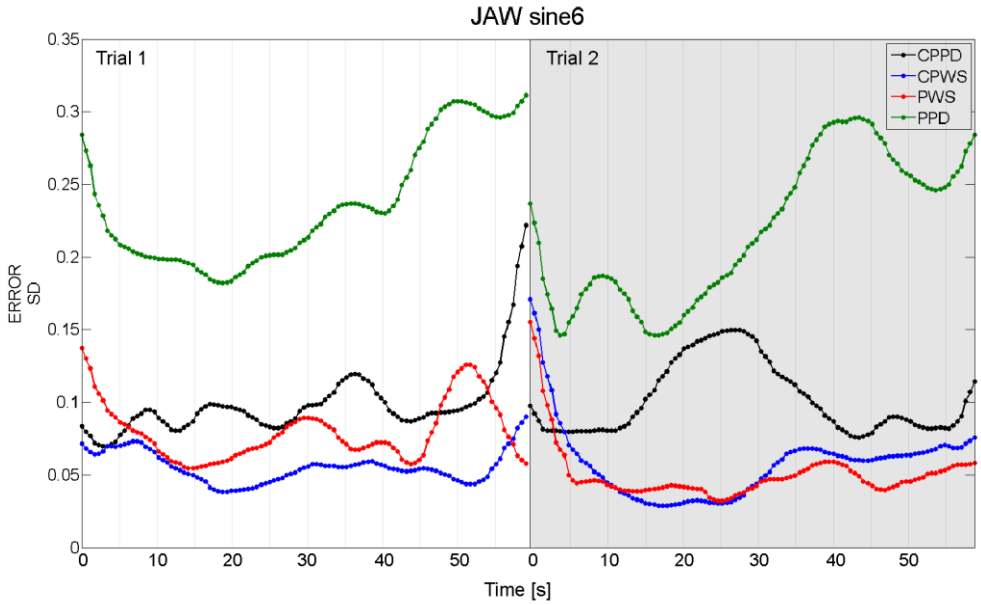


Figure 13. Summary of participant performance during tracking of a simple sine wave condition of 0.9Hz frequency: mean error values for four groups. Each dot represents a data point within one 60 second trial.

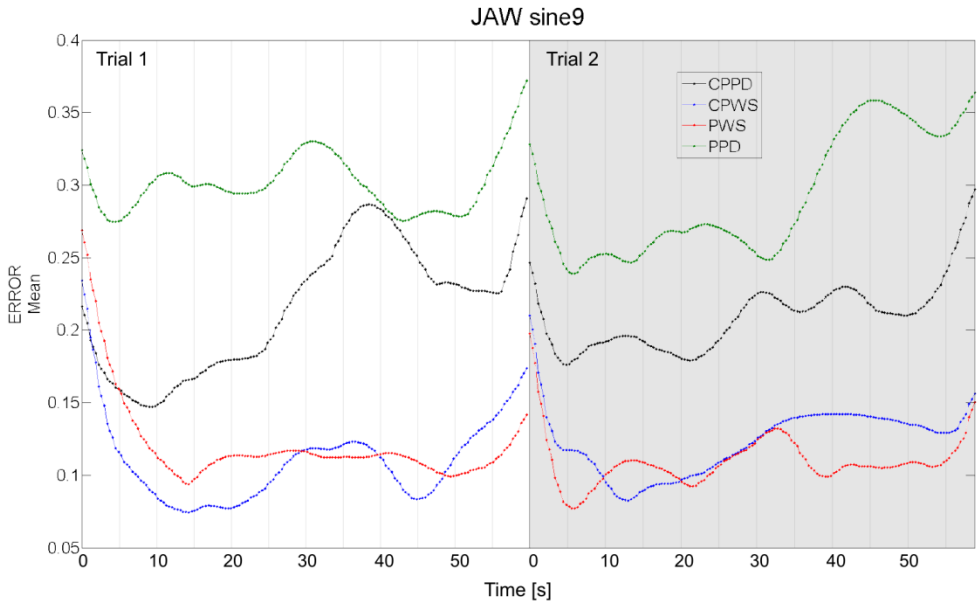


Figure 14. Summary of participant performance during tracking of a simple sine wave condition of 0.9Hz frequency: standard deviation of error values for four groups.

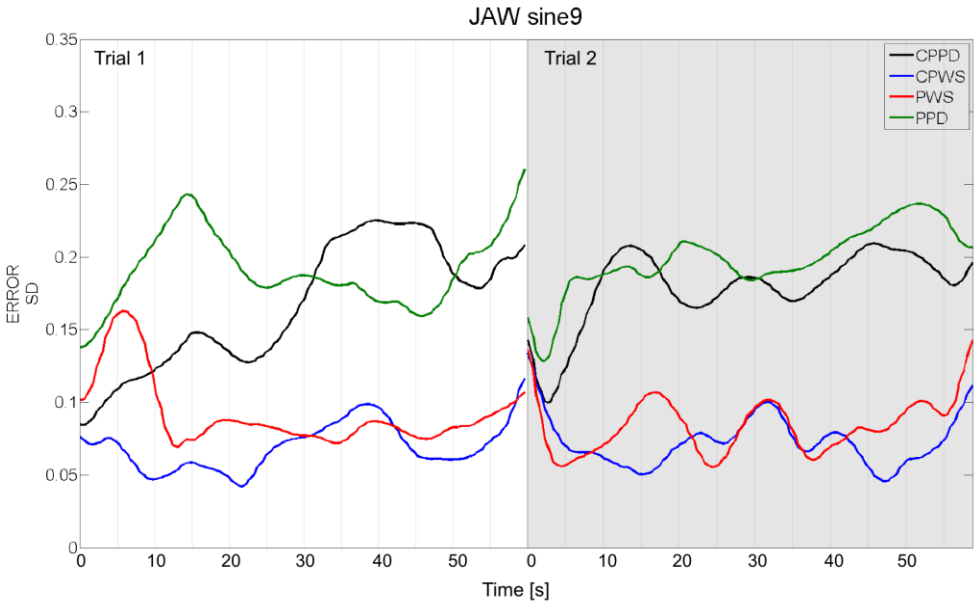


Figure 15. Summary of participant performance during tracking of complex pattern condition of 0.3Hz frequency: mean error values for four groups. Each dot represents a data point within one 60 second trial.

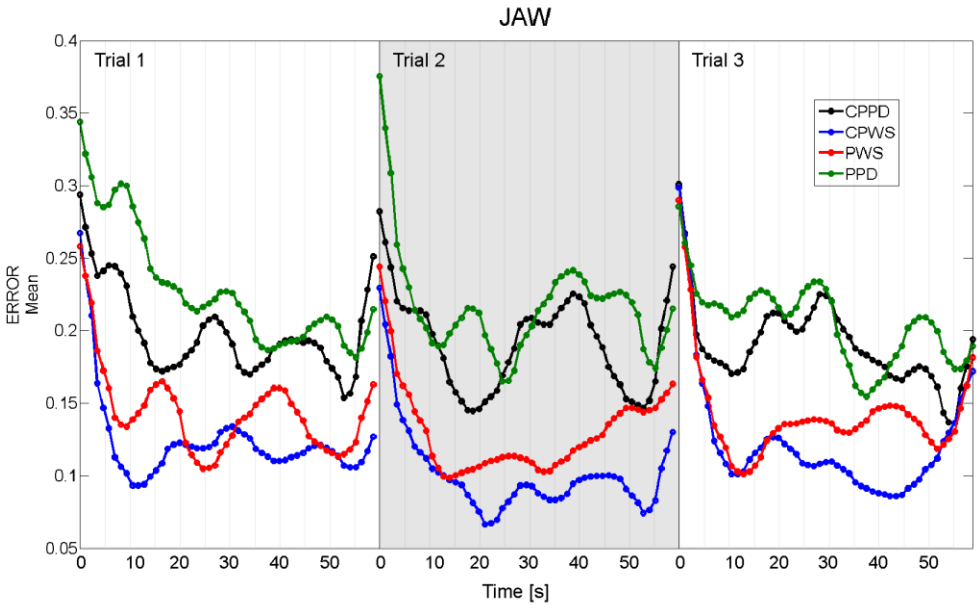


Figure 16. Summary of participant performance during tracking of complex pattern condition of 0.3Hz frequency: standard deviation of error values for four groups. Each dot represents a data point within one 60 second trial.

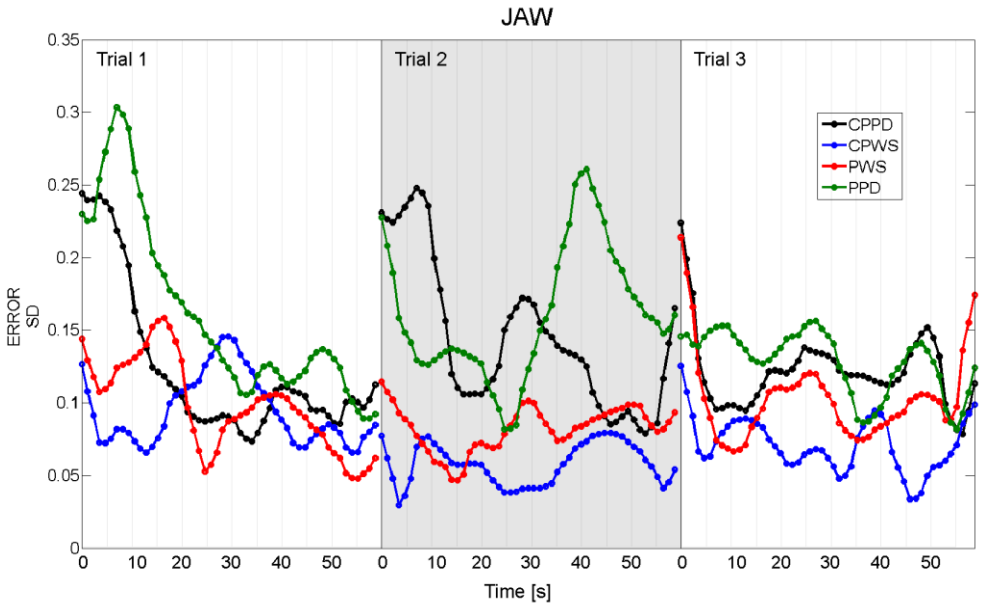


Figure 17. Summary of participant performance during tracking of complex pattern condition of 0.6Hz frequency: mean error values for four groups

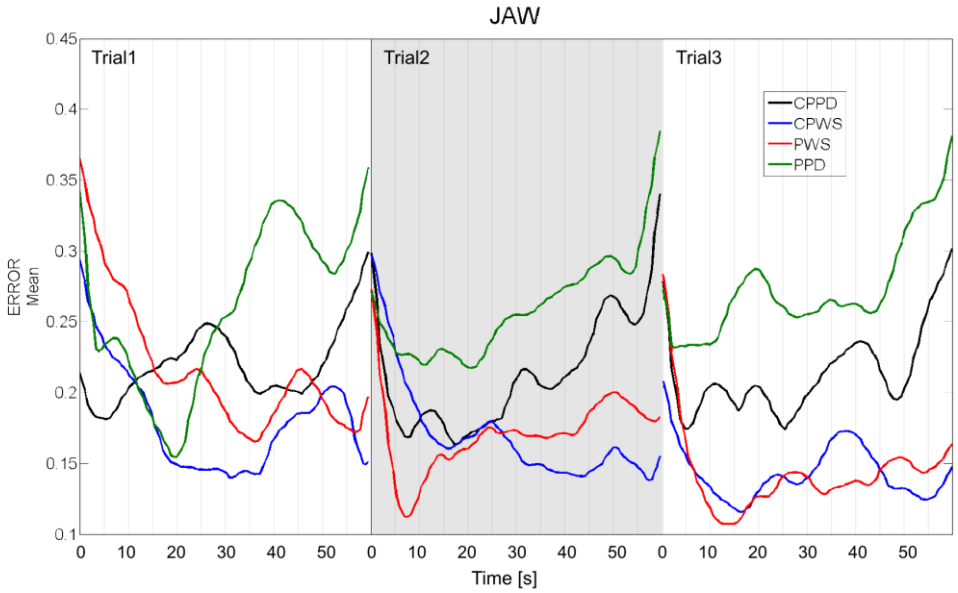


Figure 18. Summary of participant performance during tracking of complex pattern condition of 0.6Hz frequency: standard deviation of error values for four groups

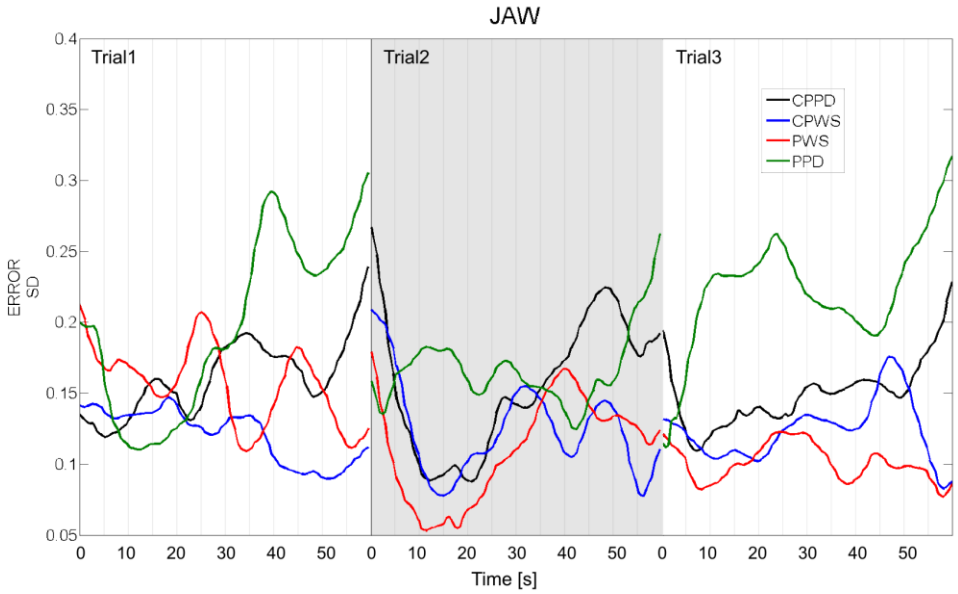


Figure 19. Summary of participant performance during tracking of complex pattern condition of 0.9Hz frequency: mean error values for four groups.

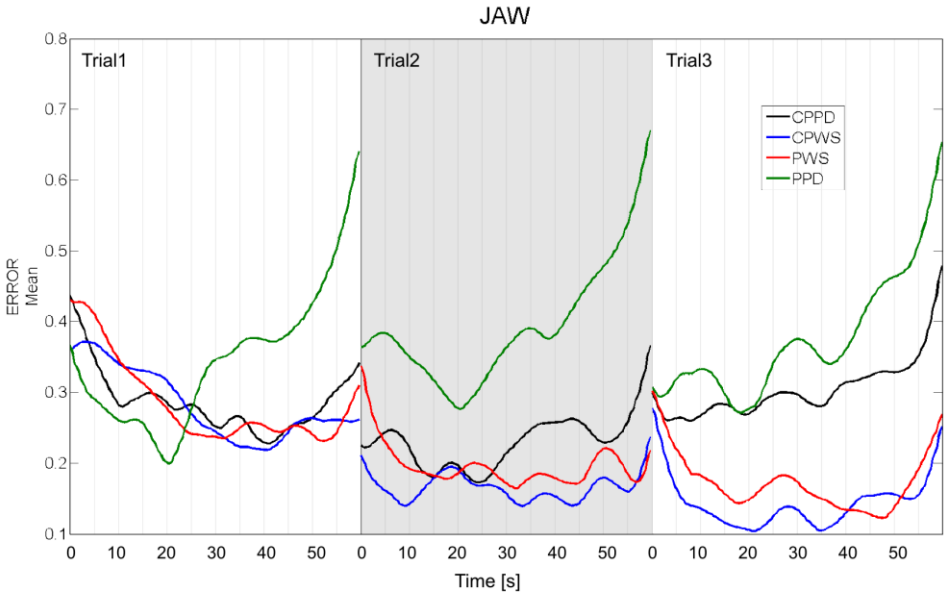


Figure 20. Summary of participant performance during tracking of complex pattern condition of 0.9Hz frequency: standard deviation of error values for four groups.

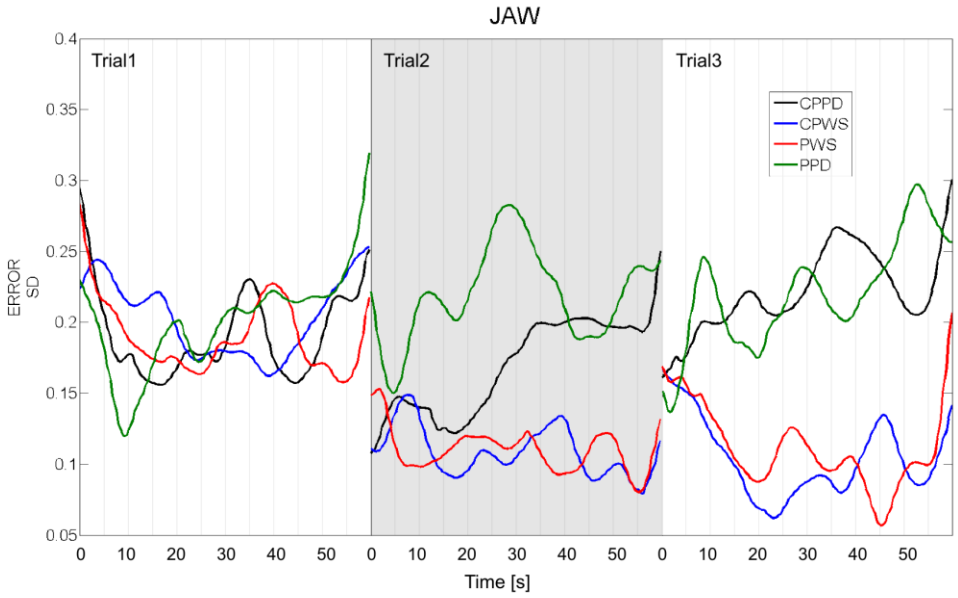


Figure 21. Summary of participant performance during tracking of a variable wave condition of 0.3Hz frequency: mean error values for four groups.

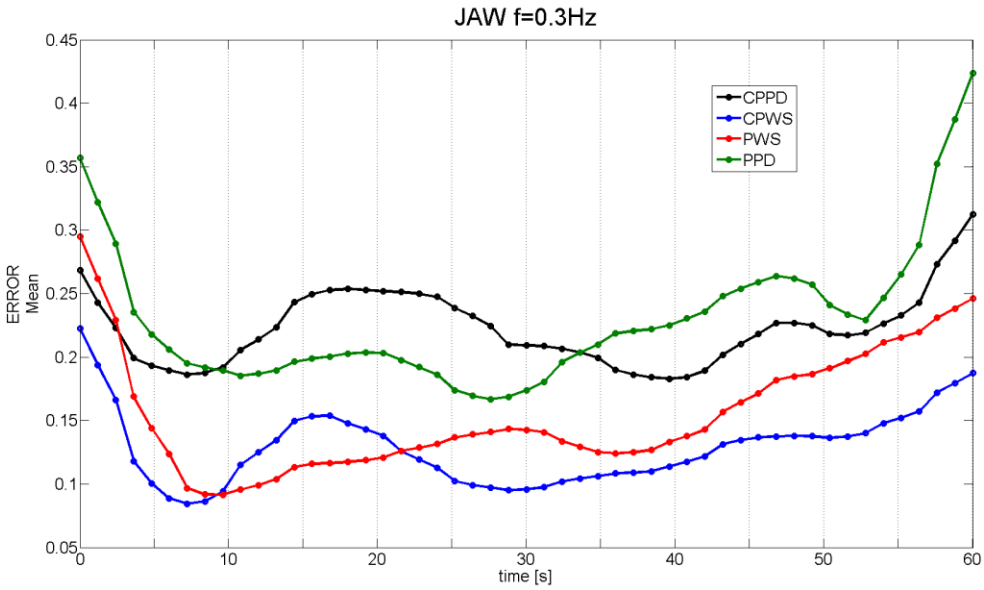


Figure 22. Summary of participant performance during tracking of a variable wave condition of 0.3Hz frequency: standard deviation values for four groups.

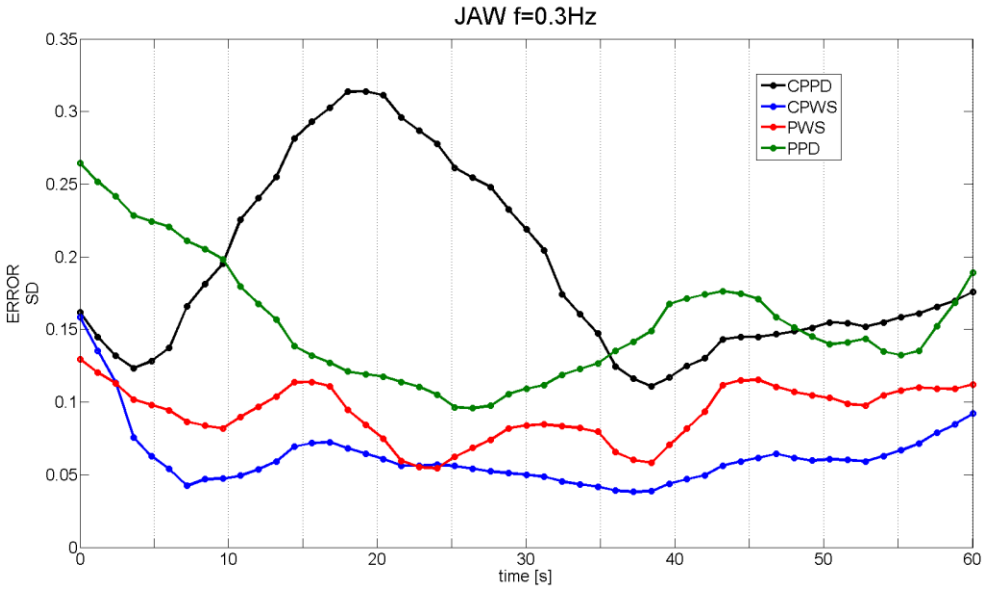


Figure 23. Summary of participant performance during tracking of a variable wave condition of 0.6Hz frequency: mean error values for four groups.

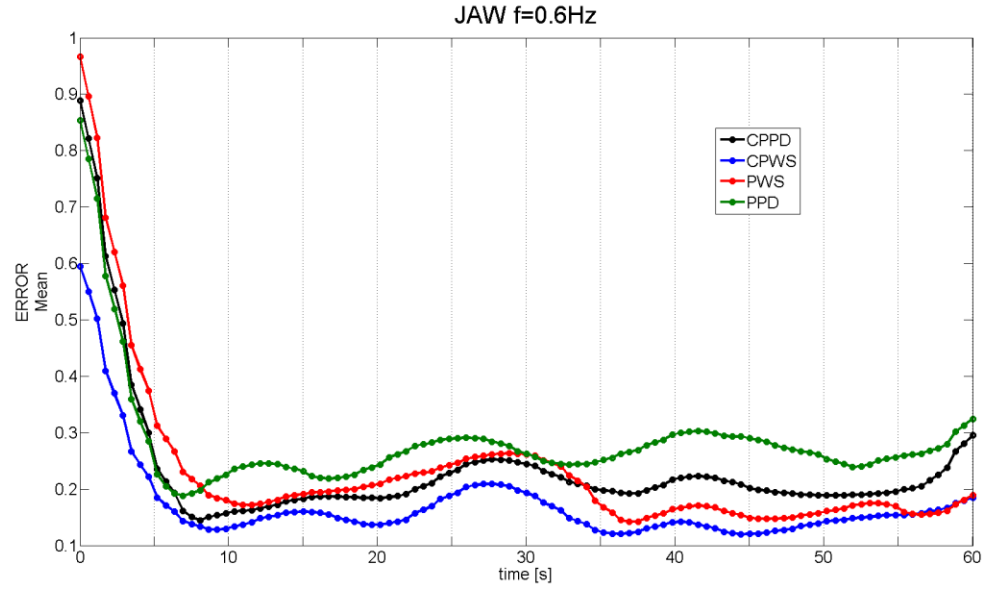


Figure 24. Summary of participant performance during tracking of a variable wave condition of 0.6Hz frequency: standard deviation values for four groups.

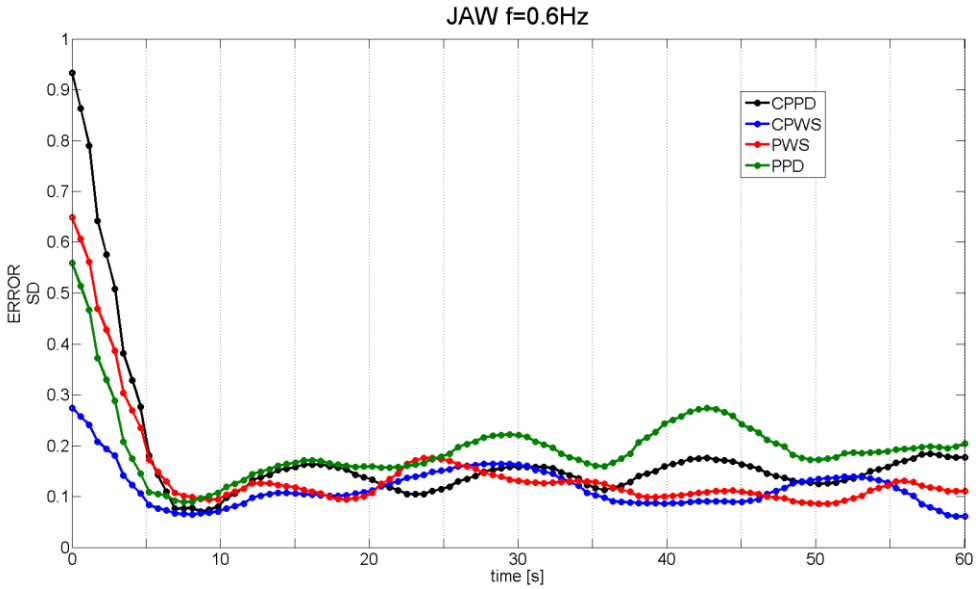


Figure 25. Summary of participant performance during tracking of a variable wave condition of 0.9Hz frequency: mean error values for four groups.

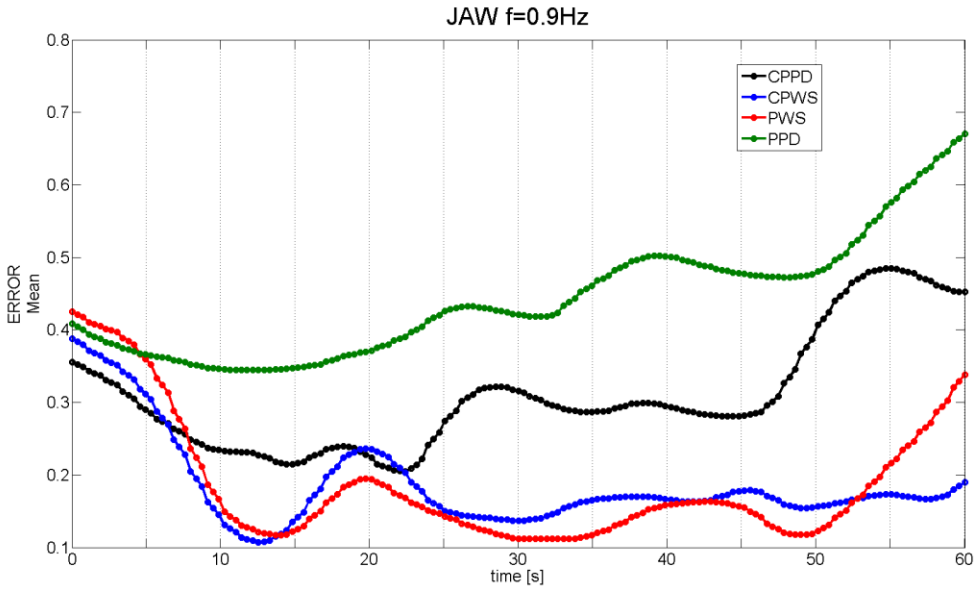


Figure 26. Summary of participant performance during tracking of a variable wave condition of 0.9Hz frequency: standard deviation values for four groups

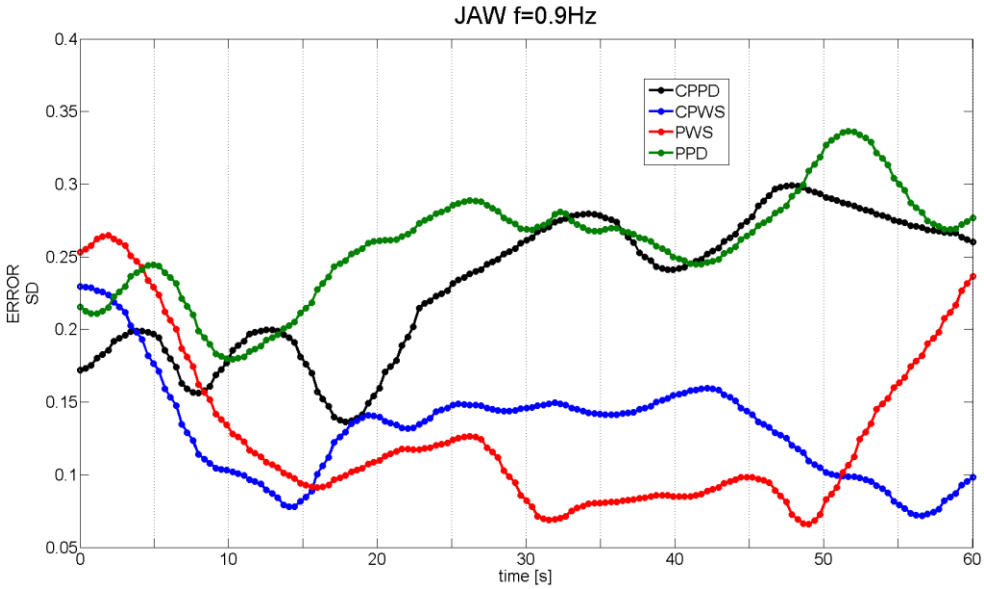


Figure 27. Summary of participant performance during tracking of a variable frequency and amplitude condition: mean values for four groups.

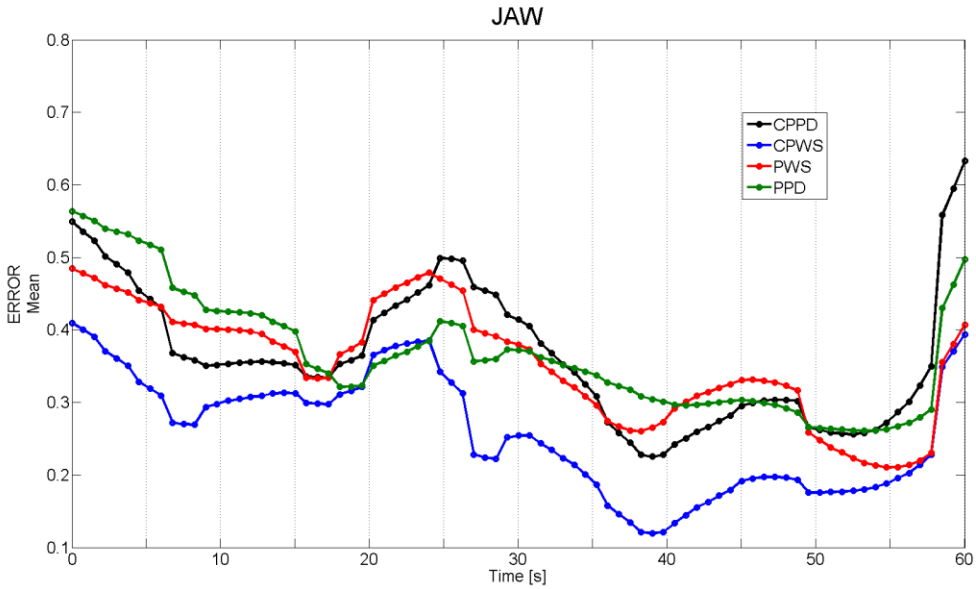


Figure 28. Summary of participant performance during tracking of a variable frequency and amplitude condition: standard deviation values for four groups.

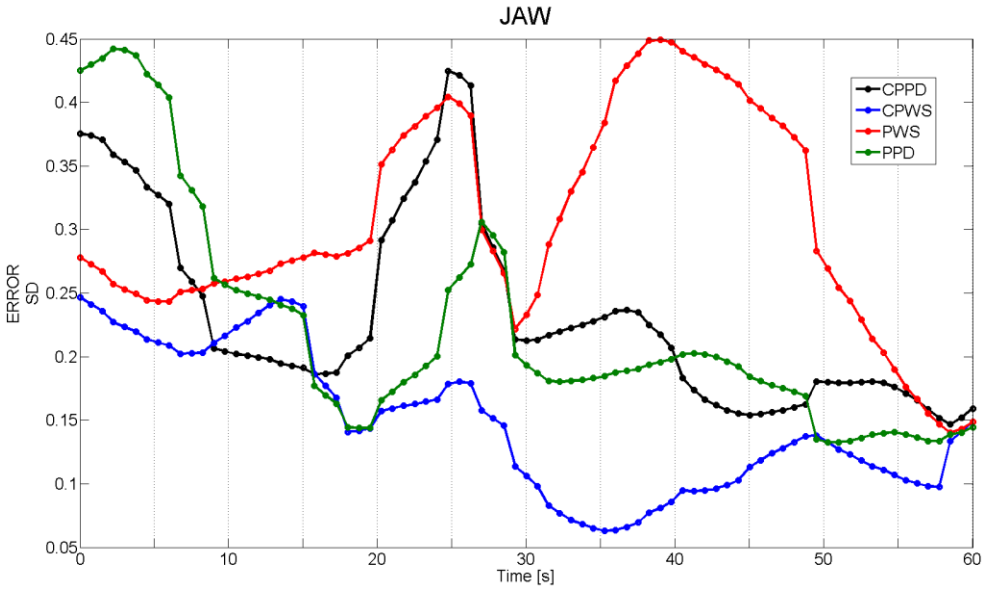


Figure 29. Summary of participant performance during tracking of a simple sine wave condition of 0.3Hz frequency: mean of error values for four groups.

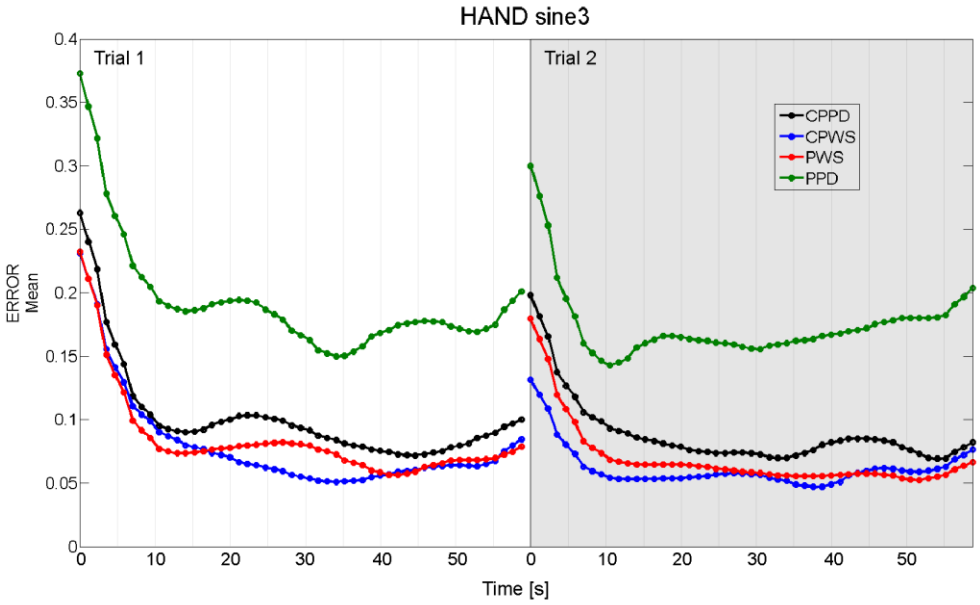


Figure 30. Summary of participant performance during tracking of a simple sine wave condition of 0.3Hz frequency: standard deviation of error values for four groups.

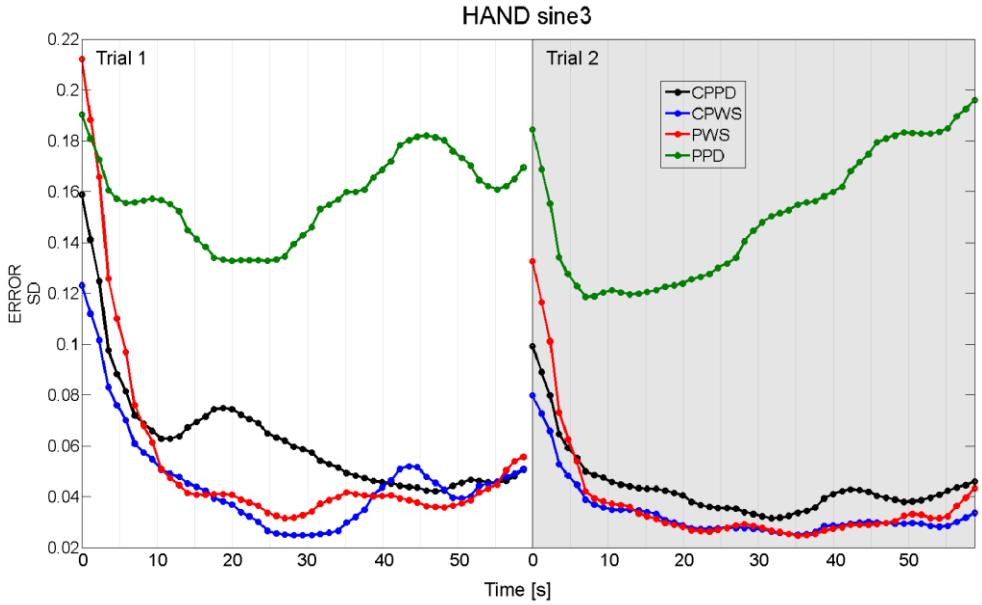


Figure 31. Summary of participant performance during tracking of a simple sine wave condition of 0.6Hz frequency: mean of error values for four groups.

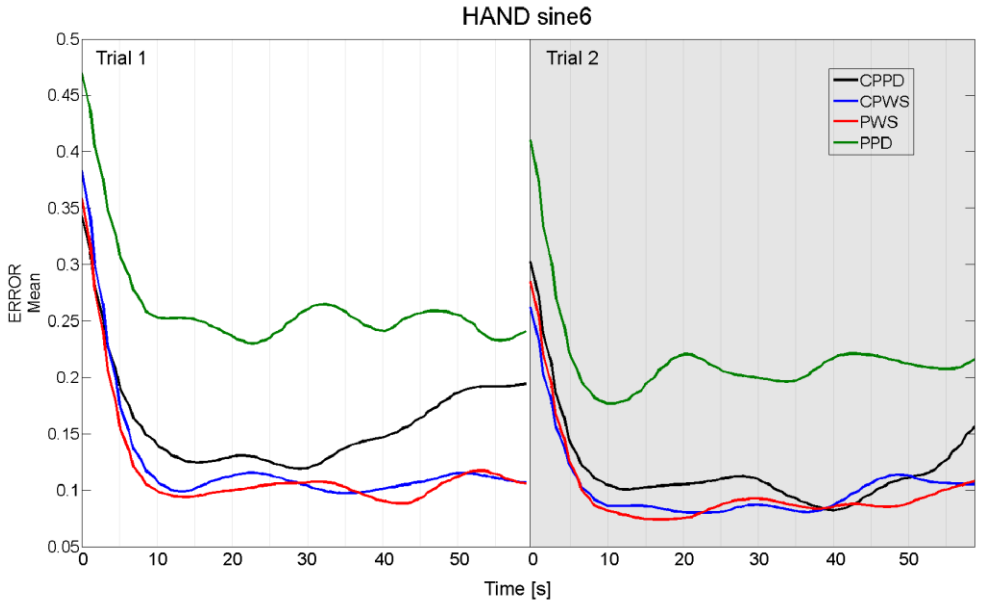


Figure 32. Summary of participant performance during tracking of a simple sine wave condition of 0.6Hz frequency: standard deviation of error values for four groups.

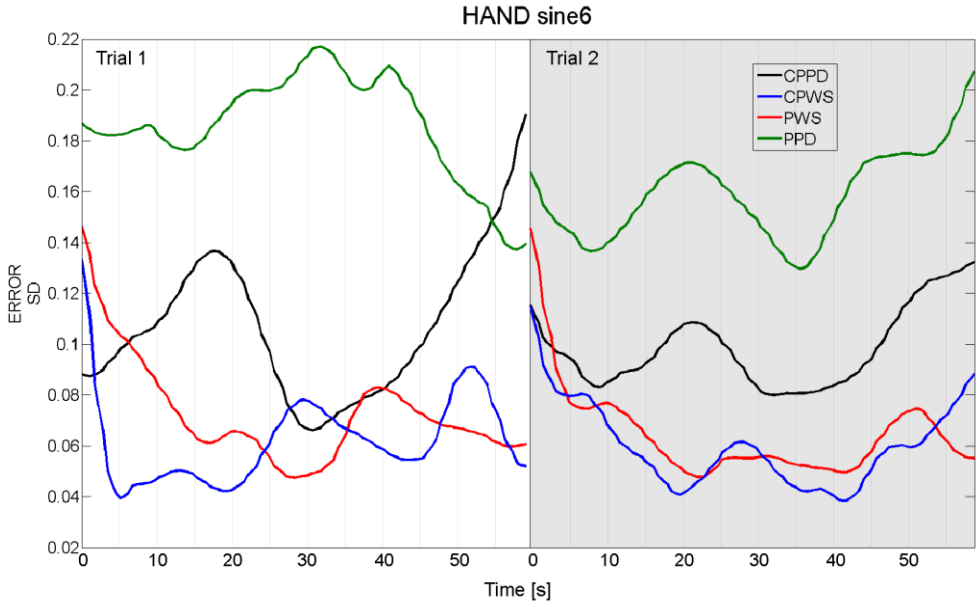


Figure 33. Summary of participant performance during tracking of a simple sine wave condition of 0.9Hz frequency: mean of error values for four groups.

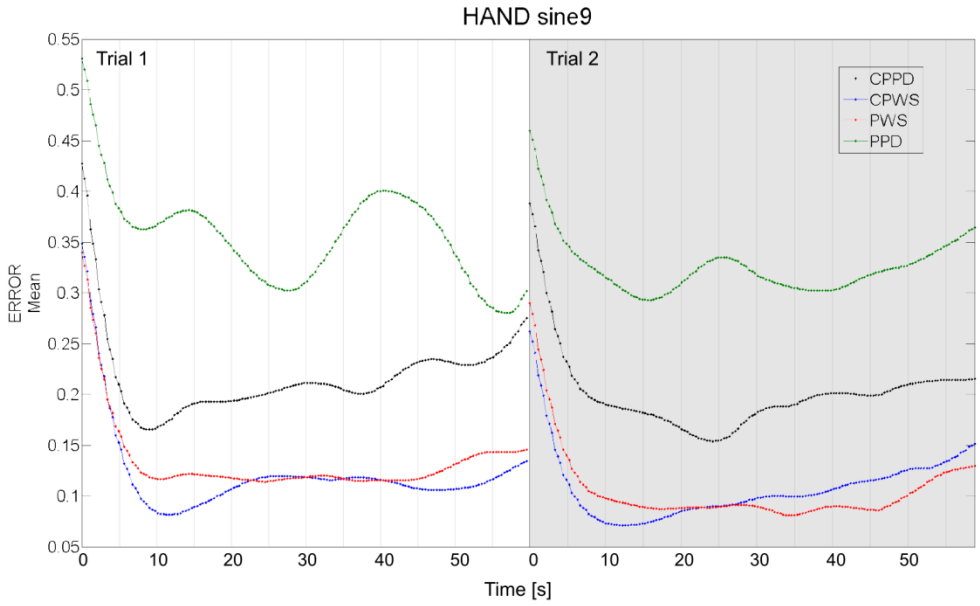


Figure 34. Summary of participant performance during tracking of a simple sine wave condition of 0.9Hz frequency: standard deviation of error values for four groups.

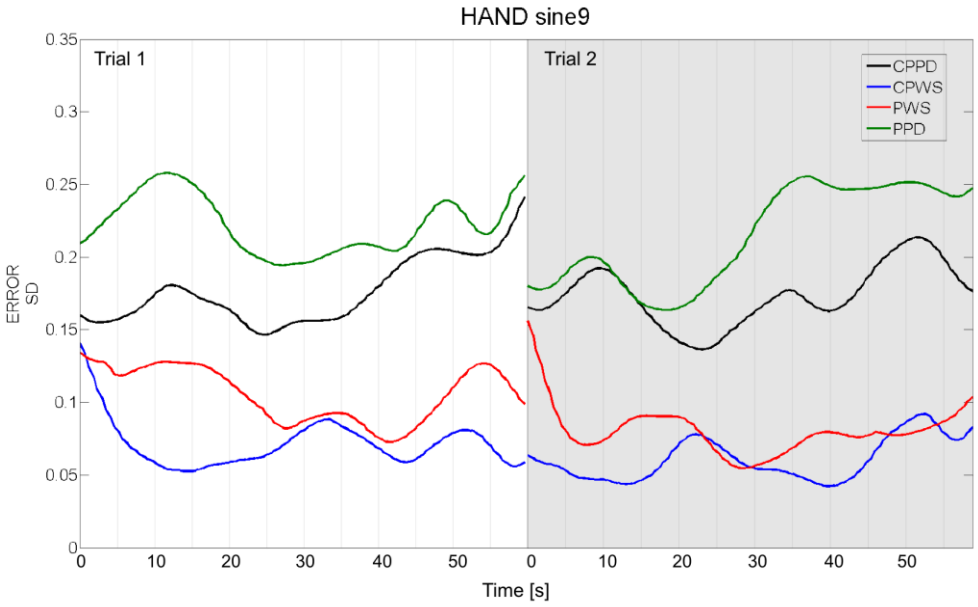


Figure 35. Summary of participant performance during tracking of complex pattern condition of 0.3Hz frequency: mean of error values for four groups.

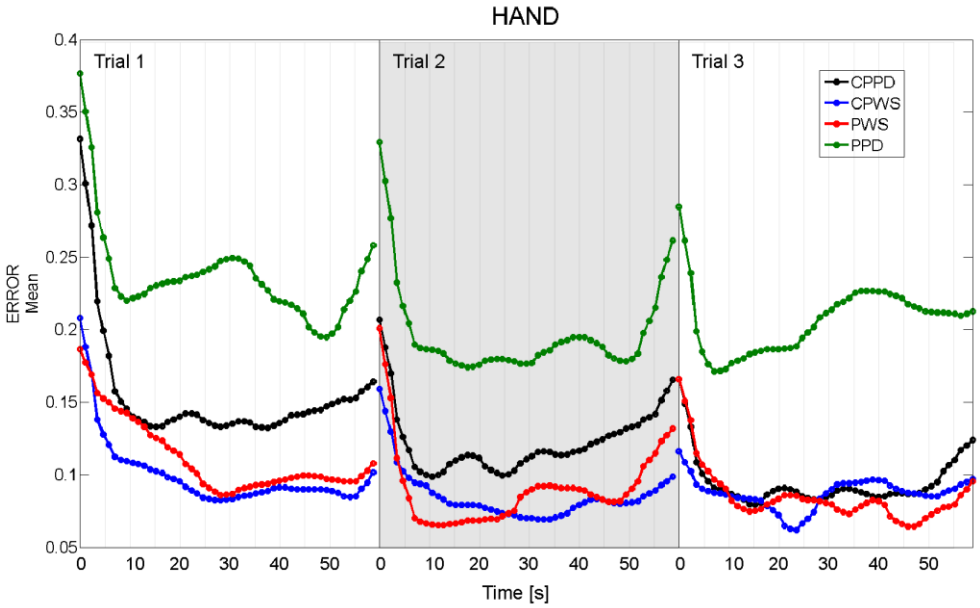


Figure 36. Summary of participant performance during tracking of complex pattern condition of 0.3Hz frequency: standard deviation of error values for four groups.

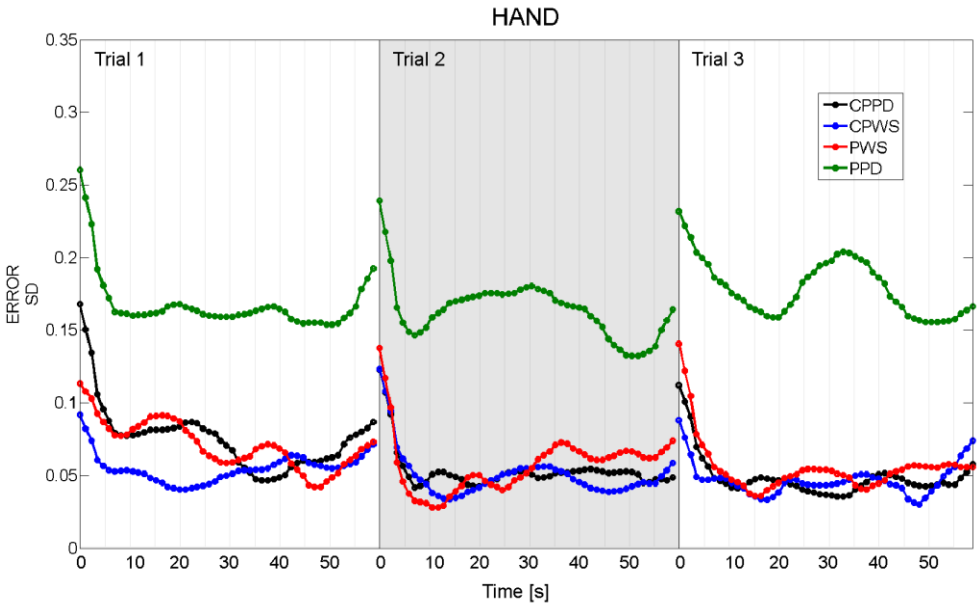


Figure 37. Summary of participant performance during tracking of complex pattern condition of 0.6Hz frequency: mean of error values for four groups.

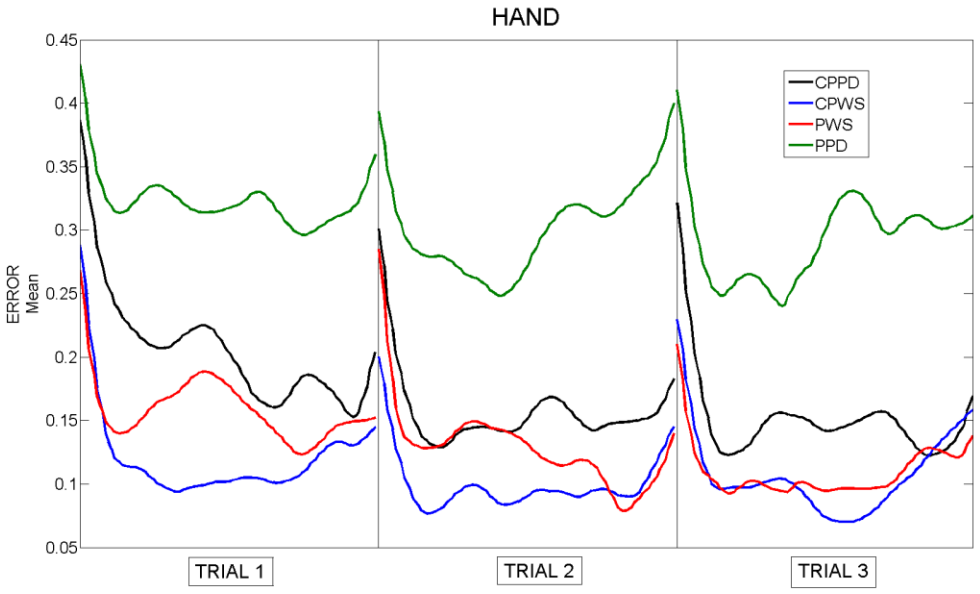


Figure 38. Summary of participant performance during tracking of complex pattern condition of 0.6Hz frequency: standard deviation of error values for four groups.

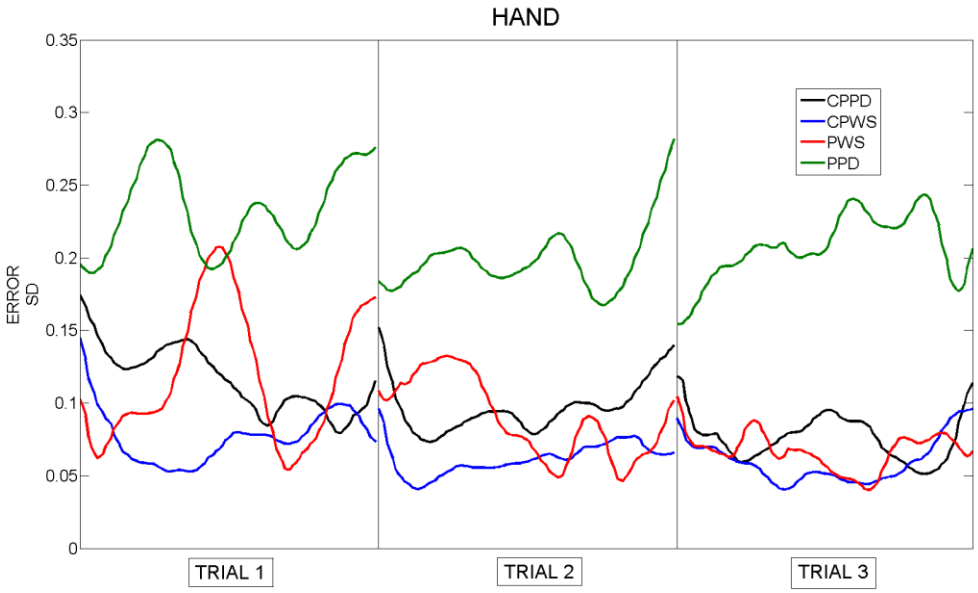


Figure 39. Summary of participant performance during tracking of complex pattern condition of 0.9Hz frequency: mean of error values for four groups.

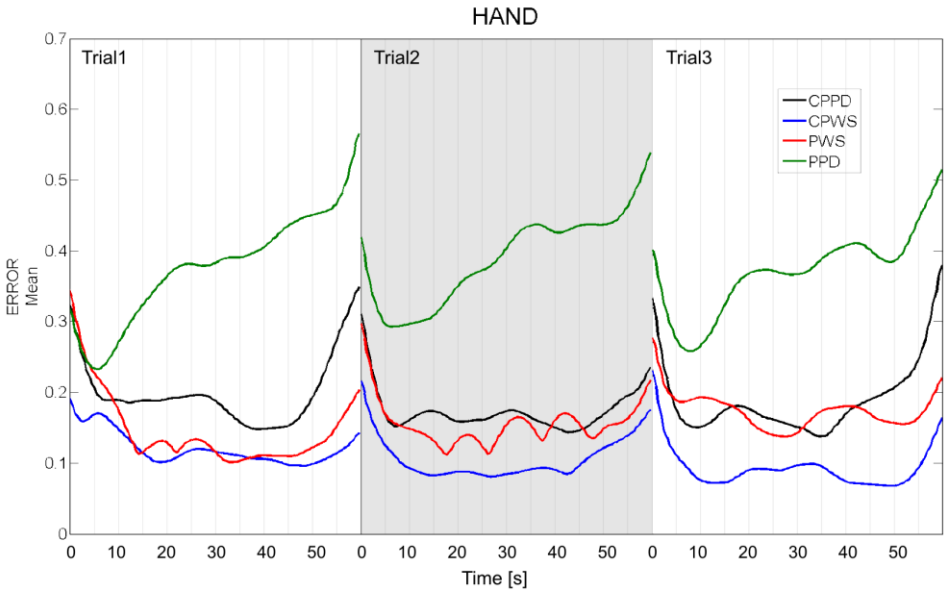


Figure 40. Summary of participant performance during tracking of complex pattern condition of 0.9Hz frequency: standard deviation of error values for four groups.

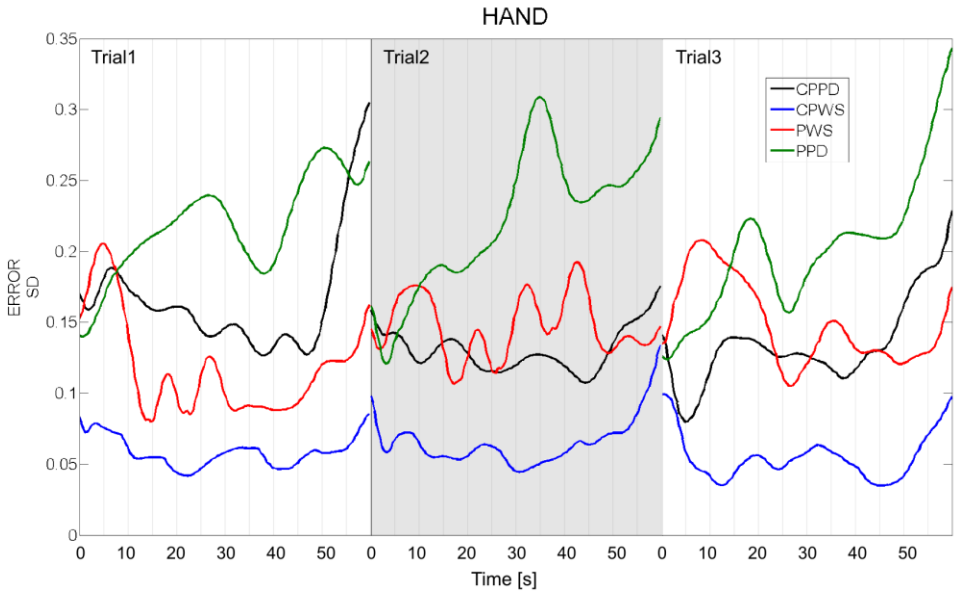


Figure 41. Summary of participant performance during tracking of a variable wave condition of 0.3Hz frequency: mean values for four groups.

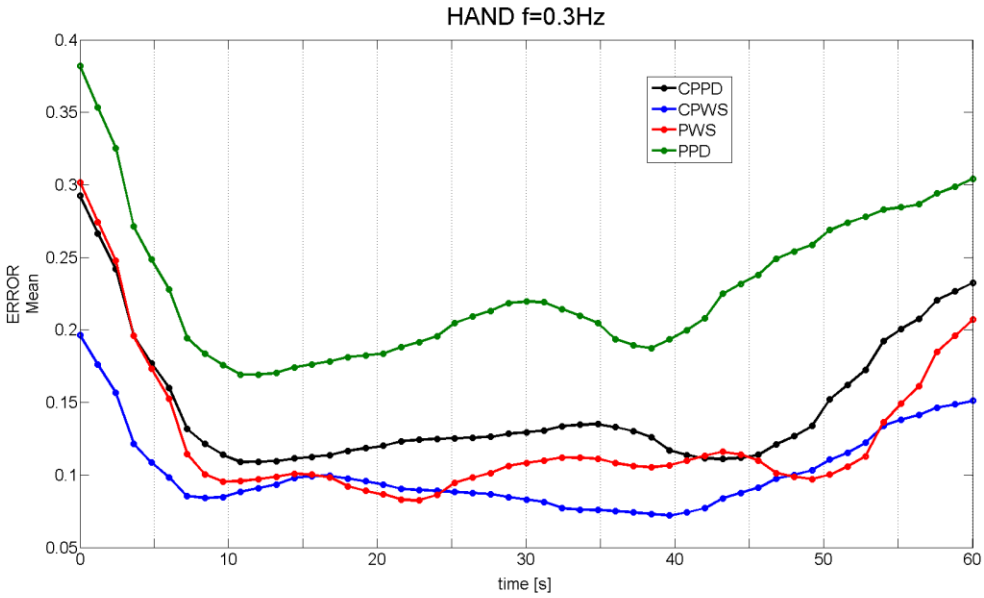


Figure 42. Summary of participant performance during tracking of a variable wave condition of 0.3Hz frequency: standard deviation values for four groups.

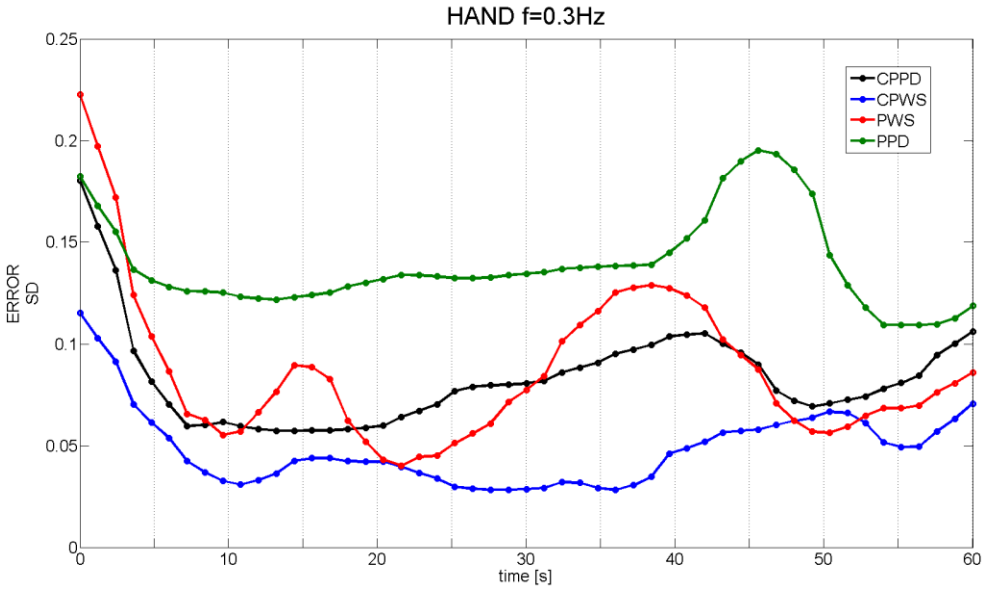


Figure 43. Summary of participant performance during tracking of a variable wave condition of 0.6Hz frequency: mean values for four groups.

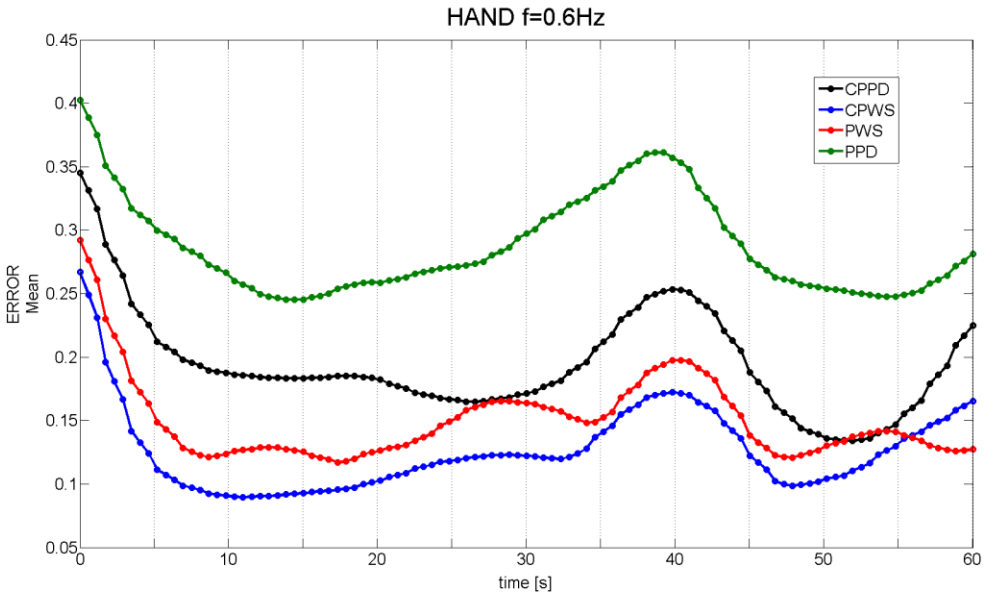


Figure 44. Summary of participant performance during tracking of a variable wave condition of 0.6Hz frequency: standard deviation values for four groups.

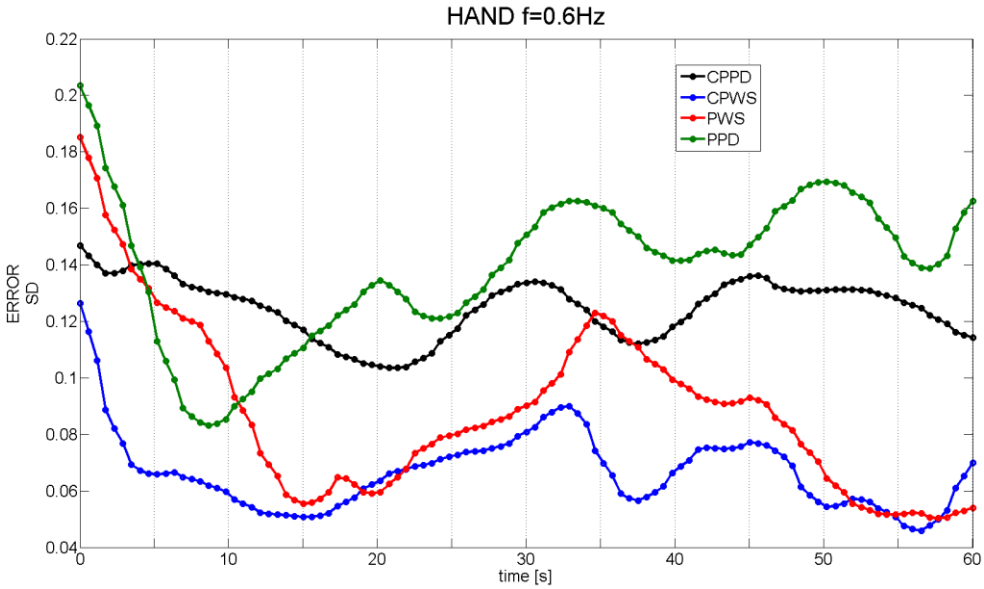


Figure 45. Summary of participant performance during tracking of a variable wave condition of 0.9Hz frequency: mean values for four groups.

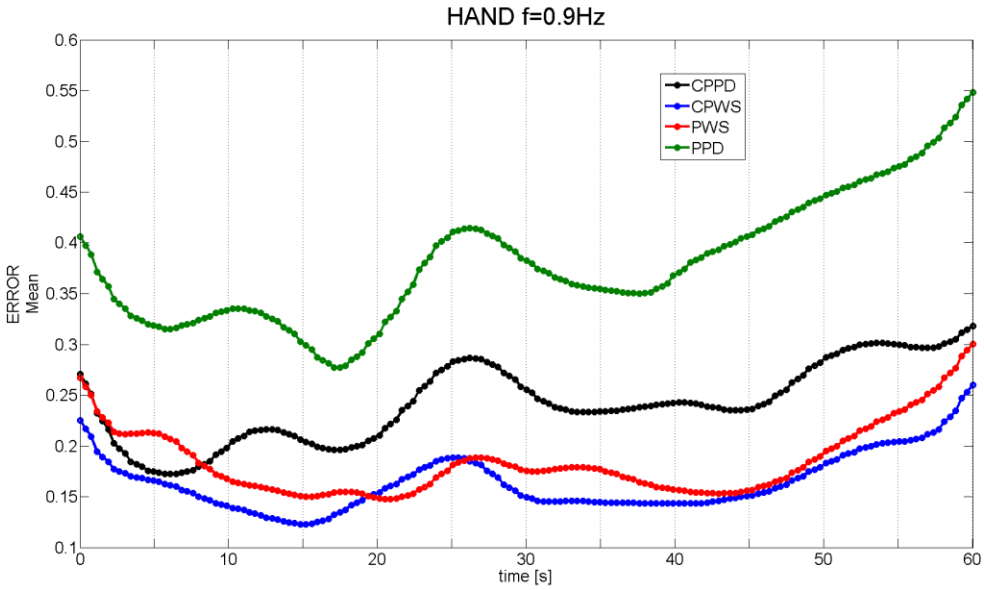


Figure 46. Summary of participant performance during tracking of a variable wave condition of 0.9Hz frequency: standard deviation values for four groups.

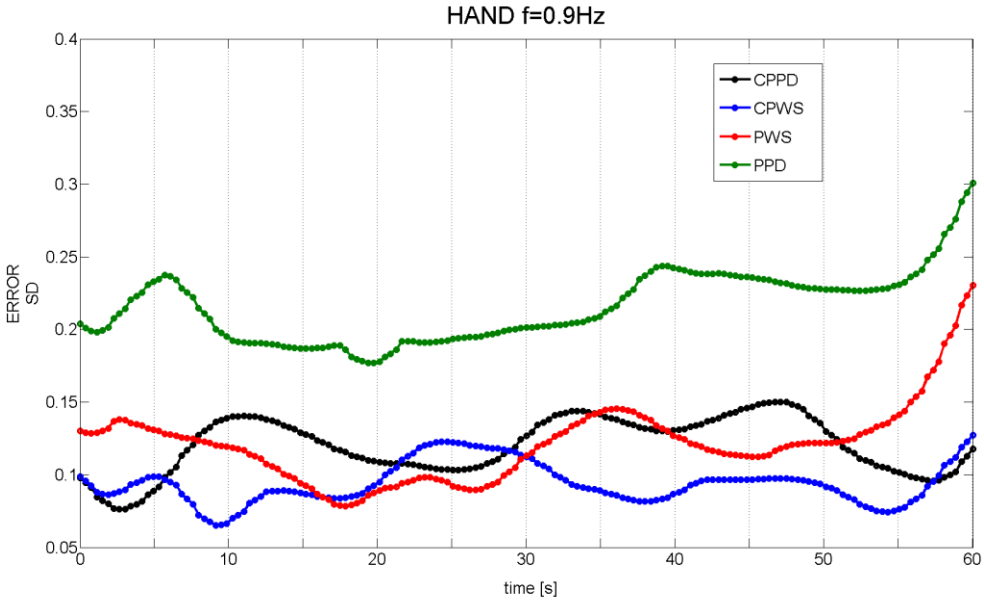


Figure 47. Summary of participant performance during tracking of a variable frequency and amplitude condition: mean values for four groups.

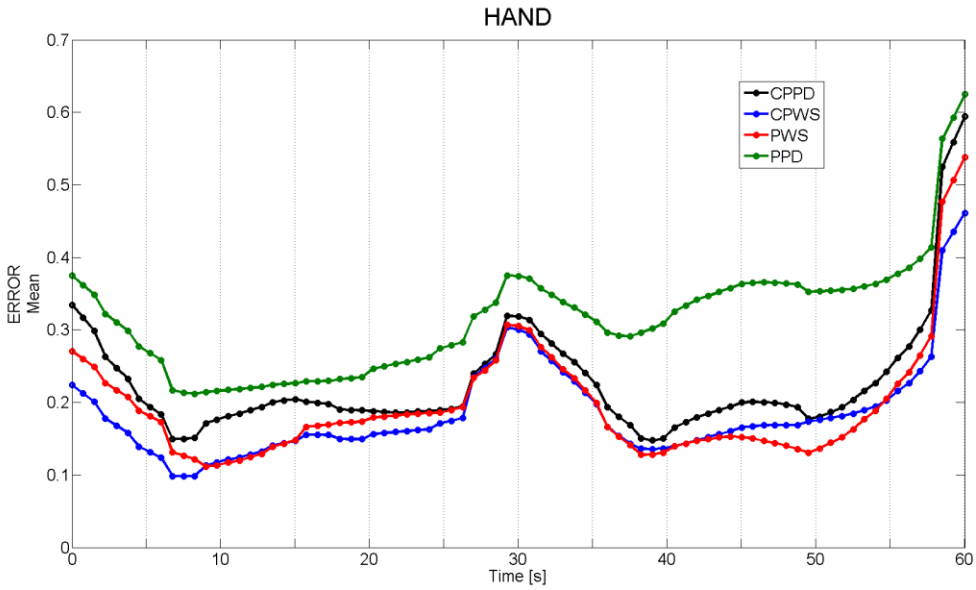


Figure 48. Summary of participant performance during tracking of a variable frequency and amplitude condition: standard deviation values for four groups.

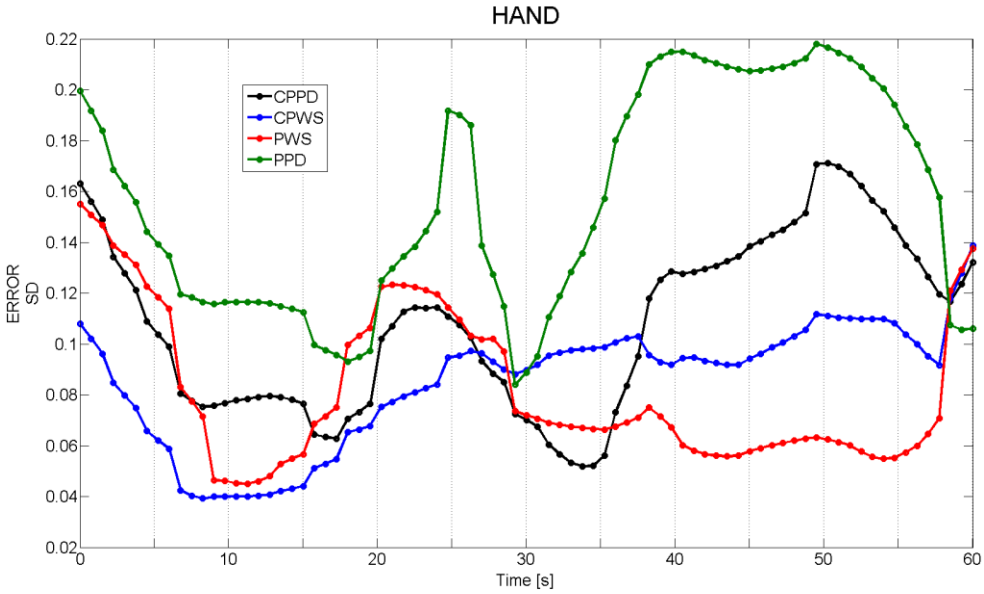


Figure 49. Mean error values for four groups during jaw tracking of predictable conditions only. The circles represent the means for each groups; the length of bars represent 95% confidence intervals.

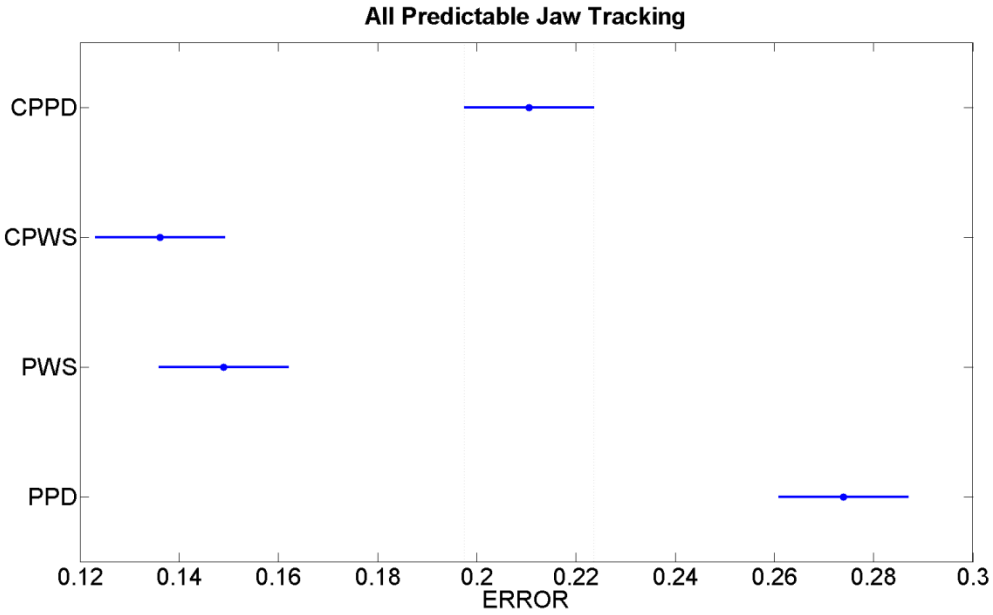


Figure 50. Mean error values for four groups during jaw tracking of unpredictable conditions only. The circles represent the means for each groups; the length of bars represent 95% confidence intervals.

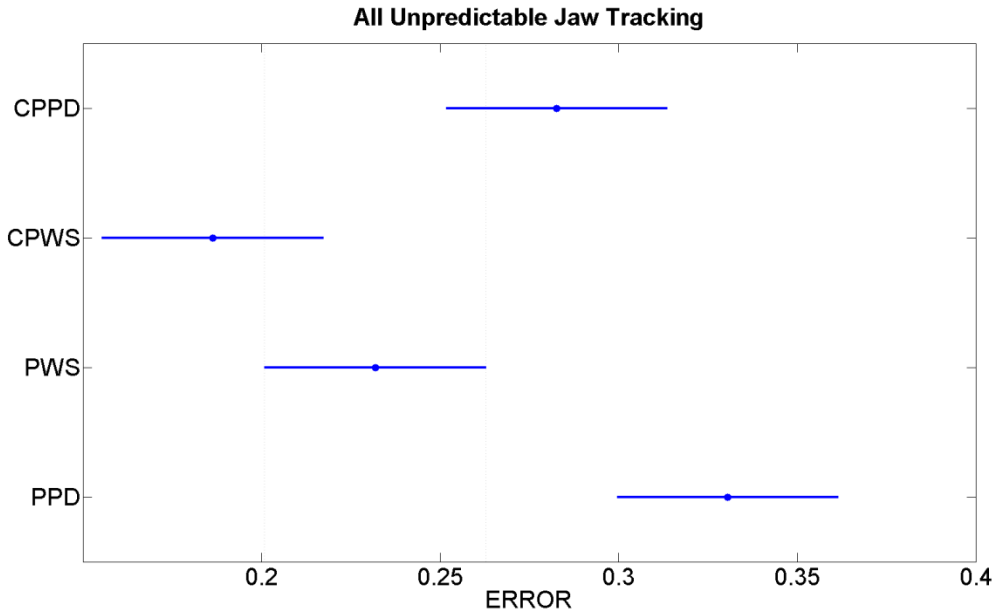


Figure 51. Mean error values for four groups during hand tracking of predictable conditions only. The circles represent the means for each groups; the length of bars represent 95% confidence intervals.

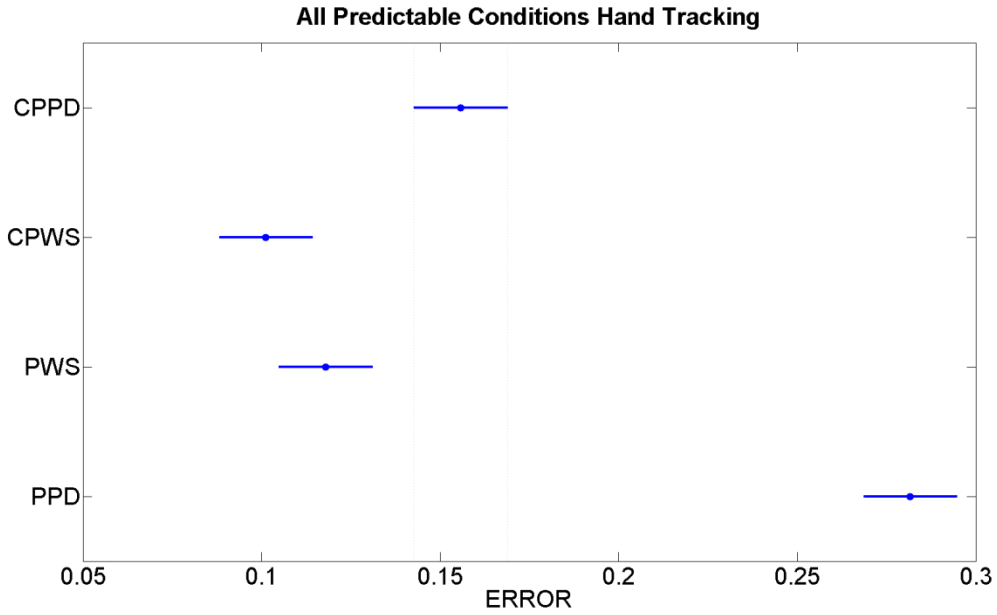


Figure 52. Mean error values for four groups during hand tracking of unpredictable conditions only. The circles represent the means for each groups; the length of bars represent 95% confidence intervals.

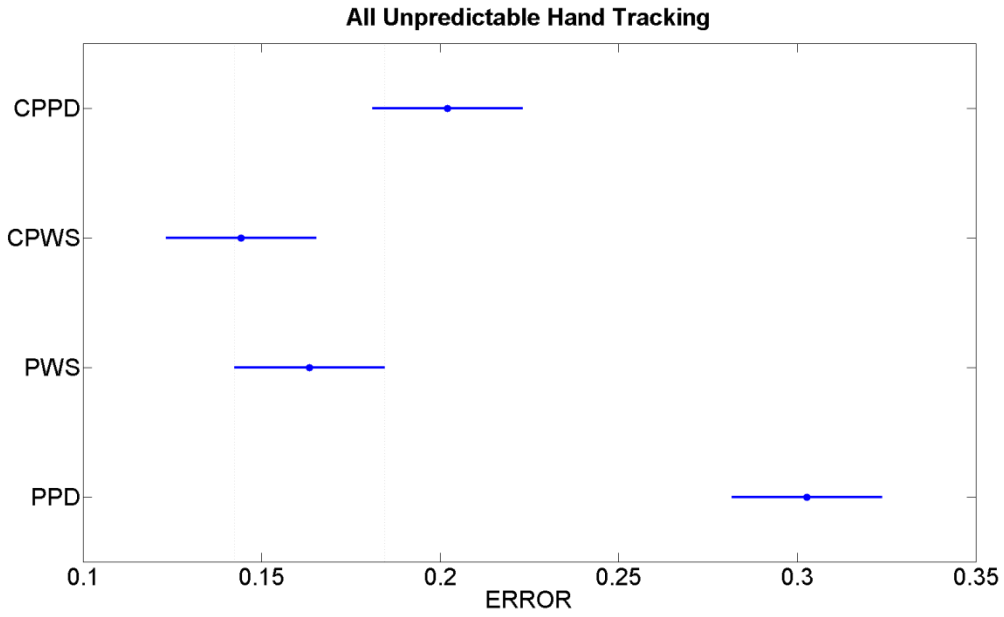


Table 3. Descriptive statistics for the four groups for tracking accuracy

Tracker	Conditions	CPWS		PWS		CPPD		PPD	
		M	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Jaw	Predictable	.136	.038	.149	.037	.211	.088	.274	.099
Jaw	Unpredictable	.186	.043	.232	.082	.283	.136	.331	.097
Hand	Predictable	.101	.028	.118	.047	.156	.072	.282	.144
Hand	Unpredictable	.144	.033	.163	.040	.202	.070	.303	.102

Table 4. Repeated measures ANOVA, Simple Sine Wave 0.3Hz, Jaw Tracking

Source	**df**	**F**	**p**
Group (G)	3	9.506*	0.00004
Error (group)	56	MSE=0.057	
Time Segment (T)	5 (3.326)**	6.008*	0.00003
GxT	15 (9.977)	1.03	0.42
Error (within)	280 (186.24)**	MSE = 0.005 (0.007)	

* p<.05, **Huynh-Feldt correction for non-sphericity

Table 5. Repeated measures ANOVA, Simple Sine Wave 0.6Hz, Jaw Tracking

Source	**df**	**F**	**p**
Group (G)	3	7.482*	0.0001
Error (group)	56	MSE=0.043	
Time Segment (T)	5 (3.325)**	8.389*	0.0001
GxT	15 (9.974)	2.568*	0.006
Error (within)	280 (186.19)**	MSE = 0.004 (0.005)	

* p<.05, **Huynh-Feldt correction for non-sphericity

Table 6. Repeated measures ANOVA, Simple Sine Wave 0.9Hz, Jaw Tracking

Source	**df**	**F**	**p**
Group (G)	3	9.552*	0.0001
Error (group)	56	MSE=0.075	
Time Segment (T)	5 (3.514)**	1.834	0.133
GxT	15 (10.541)	1.819	0.056
Error (within)	280 (196.769)**	MSE = 0.004 (0.10)	

* p<.05, **Huynh-Feldt correction for non-sphericity

Table 7. Repeated measures ANOVA, Complex Sine Pattern 0.3 Hz, Jaw Tracking

Source	**df**	**F**	**p**
Group (G)	3	4.536*	0.006
Error (group)	56	MSE=0.047	
Time Segment (T)	5 (2.611)**	5.335*	0.003
GxT	15 (7.834)	0.404	0.914
Error (within)	280 (146.234)**	MSE = 0.009 (0.017)	

*p<.05, **Huynh-Feldt correction for non-sphericity

Table 8. Repeated measures ANOVA, Complex Sine Pattern 0.6 Hz, Jaw Tracking

Source	**df**	**F**	**p**
Group (G)	3	1.109	0.353
Error (group)	56	MSE=0.079	
Time Segment (T)	5 (3.248)**	1.8	0.144
GxT	15 (9.743)	2.144*	0.024
Error (within)	280 (181.873)**	MSE = 0.009 (0.02)	

*p<.05, **Huynh-Feldt correction for non-sphericity

Table 9. Repeated measures ANOVA, Complex Sine Pattern 0.9 Hz, Jaw Tracking

Source	**df**	**F**	**p**
Group (G)	3	0.538	0.658
Error (group)	56	MSE=0.131	
Time Segment (T)	5 (3.557)**	4.568*	0.002
GxT	15 (10.672)**	3.767*	0.0001
Error (within)	280 (199.212)**	MSE = 0.016 (0.022)	

*p<.05, **Huynh-Feldt correction for non-sphericity

Table 10. Repeated measures ANOVA, Simple Sine Wave 0.3Hz, Hand Tracking

Source	**df**	**F**	**p**
Group (G)	3	6.255*	0.001
Error (group)	56	MSE=0.041	
Time Segment (T)	5 (2.301)**	40.095*	0.0001
GxT	15 (6.902)	0.377	0.913
Error (within)	280 (128.833)**	MSE = 0.002 (0.005)	

* p<.05, **Huynh-Feldt correction for non-sphericity

Table 11. Repeated measures ANOVA, Simple Sine Wave 0.6Hz, Hand Tracking

Source	**df**	**F**	**p**
Group (G)	3	7.671*	0.0001
Error (group)	56	MSE=0.053	
Time Segment (T)	5 (2.912)**	16.453*	0.0001
GxT	15 (8.735)	0.549	0.832
Error (within)	280 (163.047)**	MSE = 0.005 (0.009)	

* p<.05, **Huynh-Feldt correction for non-sphericity

Table 12. Repeated measures ANOVA, Simple Sine Wave 0.9Hz, Hand Tracking

Source	**df**	**F**	**p**
Group (G)	3	9.552*	0.0001
Error (group)	56	MSE=0.075	
Time Segment (T)	5 (2.721)**	6.05*	0.0001
GxT	15 (8.162)	1.098	0.368
Error (within)	280 (152.362)**	MSE = 0.007 (0.012)	

* p<.05, **Huynh-Feldt correction for non-sphericity

Table 13. Repeated measures ANOVA, Complex Sine Pattern 0.3 Hz, Hand Tracking

Source	**df**	**F**	**p**
Group (G)	3	6.496*	0.0001
Error (group)	56	MSE=0.052	
Time Segment (T)	5 (3.007)**	23.343*	0.0001
GxT	15 (9.02)	1.209	0.292
Error (within)	280 (168.379)**	MSE = 0.002 (0.003)	

*p<.05, **Huynh-Feldt correction for non-sphericity

Table 14. Repeated measures ANOVA, Complex Sine Pattern 0.6 Hz, Hand Tracking

Source	**df**	**F**	**p**
Group (G)	3	6.909	0.0001
Error (group)	56	MSE=0.101	
Time Segment (T)	5 (3.546)**	5.894	0.0001
GxT	15 (10.638)	1.151	0.325
Error (within)	280 (198.581)**	MSE = 0.005 (0.008)	

*p<.05, **Huynh-Feldt correction for non-sphericity

Table 15. Repeated measures ANOVA, Complex Sine Pattern 0.9 Hz, Hand Tracking

Source	**df**	**F**	**p**
Group (G)	3	11.530*	0.0001
Error (group)	56	MSE=0.103	
Time Segment (T)	5 (2.739)**	4.627*	0.005
GxT	15 (8.218)**	7.238*	0.0001
Error (within)	280 (153.411)**	MSE = 0.006 (0.011)	

*p<.05, **Huynh-Feldt correction for non-sphericity

Table 16. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.3Hz, jaw tracking, CPPD

Source	df	F	p
Trial	2	0.04	0.958
Error	42	MSE=0.007	

Table 17. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.3Hz, jaw tracking, CPWS

Source	df	F	p
Trial	2	1.03	0.365
Error	42	MSE=0.002	

Table 18. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.3Hz, jaw tracking, PWS

Source	df	F	p
Trial	2	0.21	0.812
Error	42	MSE=0.004	

Table 19. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.3Hz, jaw tracking, PPD

Source	df	F	p
Trial	2	0.2	0.823
Error	42	MSE=0.011	

Table 20. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.6Hz, jaw tracking, CPPD

Source	**df**	**F**	**p**
Trial	2	0.02	0.983
Error	42	MSE=0.012	

Table 21. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.6Hz, jaw tracking, CPWS

Source	**df**	**F**	**p**
Trial	2	0.67	0.516
Error	42	MSE=0.008	

Table 22. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.6Hz, jaw tracking, PWS

Source	**df**	**F**	**p**
Trial	2	3.44*	0.041
Error	42	MSE=0.006	

*$p<0.05$

Table 23. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.6Hz, jaw tracking, PPD

Source	**df**	**F**	**p**
Trial	2	0.03	0.968
Error	42	MSE=0.025	

Table 24. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.9Hz, jaw tracking, CPPD

Source	**df**	**F**	**p**
Trial	2	1.02	0.368
Error	42	MSE=0.021	

Table 25. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.9Hz, jaw tracking, CPWS

Source	**df**	**F**	**p**
Trial	2	6.34*	0.0039
Error	42	MSE=0.013	

*p<0.01

Table 26. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.9Hz, jaw tracking, PWS

Source	**df**	**F**	**p**
Trial	2	5.66*	0.0067
Error	42	MSE=0.009	

*p<0.01

Table 27. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.9Hz, jaw tracking, PPD

Source	df	F	p
Trial	2	0.3	0.7389
Error	42	MSE=0.028	

Table 28. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.3Hz, hand tracking, CPPD

Source	df	F	p
Trial	2	6.83	0.0027
Error	42	MSE=0.002	

Table 29. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.3Hz, hand tracking, CPWS

Source	df	F	p
Trial	2	0.71	0.4987
Error	42	MSE=0.001	

Table 30. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.3Hz, hand tracking, PWS

Source	df	F	p
Trial	2	1.26	0.2937
Error	42	MSE=0.002	

Table 31. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.3Hz, hand tracking, PPD

Source	df	F	p
Trial	2	0.25	0.7769
Error	42	MSE=0.025	

Table 32. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.6Hz, hand tracking, CPPD

Source	df	F	p
Trial	2	2.32	0.1112
Error	42	MSE=0.006	

Table 33. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.6Hz, hand tracking, CPWS

Source	df	F	p
Trial	2	0.78	0.4651
Error	42	MSE=0.002	

Table 34. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.6Hz, hand tracking, PWS

Source	df	F	p
Trial	2	1.83	0.1725
Error	42	MSE=0.005	

Table 35. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.6Hz, hand tracking, PPD

Source	df	F	p
Trial	2	0.1	0.904
Error	42	MSE=0.038	

Table 36. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.9Hz, hand tracking, CPPD

Source	df	F	p
Trial	2	1.02	0.368
Error	42	MSE=0.021	

Table 37. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.9Hz, hand tracking, CPWS

Source	df	F	p
Trial	2	0.17	0.8476
Error	42	MSE=0.016	

Table 38. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.9Hz, hand tracking, PWS

Source	df	F	p
Trial	2	0.22	0.8064
Error	42	MSE=0.014	

Table 39. One-way ANOVA for difference in accuracy over trials, complex sine pattern 0.9Hz, hand tracking, PPD

Source	**df**	**F**	**p**
Trial	2	0.05	0.9524
Error	42	MSE=0.033	

CHAPTER V: DISCUSSION

The first purpose of this study was to examine the accuracy of jaw and hand tracking in PWS, using PDD and age-matched controls as comparison groups. The second aim was to observe procedural learning (defined as increased accuracy over time) in these groups. The underlying hypothesis was that PWS would show reduced motor tracking and procedural learning performance as compared to CPWS, suggesting that similar to PDD, PWS show deficits in producing the temporal cues necessary for both movement execution and the performance of automatized movements. This speculation has received considerable attention from researchers who argue that stuttering is a timing disorder related to basal ganglia deficiency in generating timing cues for initiation of speech segments (Alm, 2004).

This section will be divided into three sections. The first section will discuss the findings for participants who do and do not stutter. The second section will provide a discussion of the results for those participants with Parkinson's diseases as compared their age-matched controls. In the third section, we will discuss the significance of age in both tracking accuracy and procedural learning. Finally, limitations of the study and ideas for future research will be presented.

Tracking Accuracy and Procedural Learning in PWS

There were two main findings in this study related to tracking accuracy and procedural learning in adults who do and do not stutter. First, our accuracy analyses revealed that there was no significant difference between PWS and CPWS in the accuracy of tracking of either predictable or unpredictable conditions for either the hand or the jaw, although a trend was observed in which PWS performed more poorly in both for decreased accuracy. Second, there was no significant difference between PWS and CPWS in improvement in jaw or hand accuracy over time within condition (i.e. early versus late time segments). However, regardless of group, all participants showed

significantly improved within-trial accuracy. Both groups showed accuracy improvement across repeated trials, it was significant for more complex conditions. In other words, both people who do and do not stutter showed evidence of procedural learning to the same extent.

Our findings of non-significant jaw tracking differences between PWS and CPWS corroborate prior work in which a similar visuomotor tracking paradigm was used in children (Zebrowski, Moon, and Robin, 1997). Zebrowski et al. found no difference in jaw tracking accuracy in children who do and do not stutter (mean age of 12:11 years, months) for predictable tracking conditions performed at 0.3, 0.6 or 0.9Hz. However, an earlier study found that children who stutter (aged 9:8 years, months) performed significantly more poorly than their age-matched normally fluent peers while tracking a predictable sinusoid signal at 3Hz with the jaw (Howell, Sackin, and Rustin, 1995), which could be attributed to a higher complexity of the target signal due to its fast frequency. Our hand tracking results corroborate a recent study that showed that PWS were less accurate in both random and sine wave hand tracking than CPWS, but the accuracy difference did not reach significance (Jones et al., 2002). Jones et al. 2002 attributed the observed accuracy difference between PWS and CPWS to the impaired visuoperceptual function of PWS. Our results do not support this hypothesis, by providing evidence of unimpaired motor control abilities of PWS when visual feedback is available to guide movements.

It has been suggested in the literature that the PWS skill level may be located toward the less efficient or lower end of the motor control continuum (Van Lieshout, Hulstijn, & Peters, 2004; Namasivayam & Van Lieshout 2008). This suggestion was brought about by research showing that PWS have lower motor control abilities but not significantly different from CPWS. Present study results add to this literature – PWS in our study performed more poorly than CPWS, in the absence of significant differences between them.

There is one important factor that may have determined participants' tracking performance in our task – during tracking the visual feedback was always available to guide movement. Prior work showed that children who stutter (Howell et al., 1995) and adults who stutter (Loucks and De Nil, 2006) performed as well as people who do not stutter in non-speech jaw movement task when visual feedback was available, and performed significantly poorer in the absence of visual feedback. Research shows that both feedback and feedforward modes of control are required for skilled motor control and in the process of skill acquisition the balance between feedback and feedforward operation shifts towards feedforward commands (Schmidt, & Lee, 2005). New evidence from modeling research shows that disfluencies can be produced in a computer model when it is biased away from feedforward control and relies too much on the feedback (Civier, Tasko, & Guenther, 2010). This evidence was interpreted to suggest that PWS overrely on feedback, which makes their speech prone to disruptions.

Overall, the finding that PWS were not significantly different from CPWS in tracking with both the dominant hand and jaw and in the strength of their procedural learning abilities suggests that there is no underlying deficit in fine and gross motor coordination for PWS and that motor systems of PWS are stable provided there are no added demands (e.g. linguistic or emotional). However, we cannot rule out the hypothesis that they may operate at the lower end of the motor continuum (Van Lieshout, Hulstijn, & Peters, 2004; Namasivayam & Van Lieshout 2008), which could lead to increased susceptibility to breakdowns when the system is stressed with linguistic (Smith et al, 2010) or emotional (Conture et al., 2006) demands.

Contrary to the previous reports (Hulstijn, Summers, Van Lieshout, & Peters, 1992; Max & Yudman, 2003; Zelaznik et al. 1997) we did not see increased variability in the non-speech (oral or manual) systems of PWS as measured by the standard deviation of the tracking error. However, an important notion that the current study did not examine is whether there are within group dissociations in tracking accuracy and its variability.

This becomes increasingly important given the findings that PWS may have similar performance to people who are normally fluent in linguistic and non-linguistic domains, but distribution of their performance may be a bimodal in nature (Olander, Smith, & Zelaznik 2010), supporting the existence of subgroups.

Tracking Accuracy and Procedural Learning in PPD

There were two main findings in this study related to tracking accuracy and procedural learning in adults who have Parkinson's disease and age-matched controls. First, tracking accuracy analyses revealed that PPD performed significantly less accurate than CPPD during jaw tracking of predictable conditions, but they were not significantly different from CPPD in jaw tracking of unpredictable conditions. During hand tracking PPD differed significantly from CPPD in tracking of both predictable and unpredictable conditions for their less accurate performance. Second, there was no significant difference between PPD and CPPD in the improvement in jaw accuracy over time, apart from one condition – tracking of a simple sine wave at 0.9Hz, where the PPD group showed less improvement over time than the CPPD. Overall this suggests that in the oral motor domain both PPD and CPPD showed evidence of procedural learning to the same extent. Analysis of procedural learning during hand tracking offered different results. The PPD group improved less with time than the CPPD while tracking simple sine waves at all frequencies (0.3Hz, 0.6 Hz and 0.9 Hz) and a complex sine pattern at 0.9 Hz. This suggests that the PPD group was not able to learn as well as their control group in the manual motor domain.

The fact that PPD were less accurate during tracking than CPPD agrees with what is known about the disease effect on the motor system with cardinal features of the disease being tremor, rigidity and bradykinesia (Jankovic, 2008). It is important to note here that all people with Parkinson's disease in this study performed study tasks while on their regular medication. The finding of less accurate tracking is also consistent with

previous research showing that PPD have particular difficulty in integrating different coordinate systems in order to guide movement (Adamovich et al., 2001; Krebs et al., 2001). Tracking accuracy in the present study depended on the ability of participants to translate movements of the target and the tracker on the screen to movements of their jaw and hand (the process that would involve integrating visual and proprioceptive feedback). Thus, taken in light of the previous findings (Adamovich et al., 2001; Krebs et al., 2001), our results suggest that for all our other groups sensorimotor response generation occurred quicker and led to more accurate movements in a novel environment. By contrast, the PPD group had a difficulty with this process. However, the fact that PPD were not profoundly impaired during either jaw or hand tracking, did not differ from CPPD in jaw tracking of unpredictable conditions and also showed evidence of accuracy improvement over time speaks to the previous findings that PD patients are able to successfully use visual and proprioceptive feedback to control movements (Bloxham et al., 1984; (Day, Dick, & Marsden, 1984; Flowers, 1978; Flash et al., 1992; Ghilardi et al., 2000; Liu et al., 1999). The dissociation between jaw tracking accuracy for the predictable versus unpredictable conditions suggests that whereas tracking of the signals that require constant matching of the target and do not allow for anticipation of the target should to be harder overall, those signals pose equal difficulty for PPD and CPPD alike. Our finding corroborate other studies which found that predictive motor strategy does not confer as great an advantage in reducing tracking error in PPD compared to normally aging participants (Day, Dick, Marsden, 1984; Flowers, 1978).

The finding of no difference between the extent of procedural learning between PPD and CPPD was unexpected. Our results suggest that medicated non-demented patients in the mild stages of illness show relatively normal motor procedural learning. Prior research using similar tracking paradigms has shown that such subgroup of PPD may exhibit normal improvement in performance across trials, but can be affected by the speed of the target (faster speed corresponded with poorer performance) (Bondi and

Kazniak, 1991; Harrington et al., 1990). Our results corroborate this finding, providing more evidence that PPD were not able to improve their tracking (either with the jaw or the hand) when the conditions were associated with increased speed or complexity. Based on prior findings and present results we conclude that medicated non-demented patients in the early stages of illness show relatively normal motor procedural learning.

Age Effect

Analysis of tracking accuracy from our sample indicated that younger participants (PWS and CPWS) in the age range of 18-40 had the best accuracy during both jaw and hand tracking. Older individuals without neurological impairments and people with Parkinson's disease (both populations in the age range of 57-79) had lower accuracy during jaw and hand tracking, with people with Parkinson's disease showing the least accurate performance. Overall, age seemed to be an important factor determining tracking accuracy. Our findings are corroborated by previous studies of age-related changes in tracking accuracy. For example Ballard et al. (2001) using a visuomotor tracking with the jaw and lip found that performance older adults (aged 45:1 to 84:3, years: months) was poorer than that of younger adults (aged 17:1 to 45:0). Age has been shown to affect procedural learning, with older people performing poorer on learning and retention using a serial reaction time task than younger individuals (Boyd, Vidoni and Siengsukon, 2008).

Procedural Learning

Our analysis of changes in accuracy over time revealed that learning largely occurred within trials, with the most improvement happening in the initial 10 seconds of tracking exposure. The best fit for the learning curves was a quadratic function. One interesting aspect of performance of all groups for jaw tracking was the increase in error toward the end of tracking trials (last 10 seconds) which happened for all groups after the initially rapid improvement. This could be caused by the inability of participants to

sustain attention and increasing fatigue, although our analysis did not allow for this hypothesis to be tested. Another interpretation for the observed trend of accuracy increase in the first 10 seconds of tracking and a decrease in the last couple of cycles of tracking could come from the feedback/feedforward theory of movement control. We observed this trend mostly in the predictable conditions where participants could anticipate target movements – we conjecture that the initial tracking strategy that participants employ is feedback. Using this type of motor control they acquire the motor plan and modify it to reach the optimal level of performance, based on our data we can say that this happens in the first 10 seconds and requires more time for more complex patterns. After that participants may rely mostly on feedforward control, which allows them to sustain a high accuracy of tracking. However, as our data shows, people decrease their accuracy towards the end of each tracking trial, which could mean that they need to switch back to feedback control and "re-sample" or "re-set" parameters of the motor program. Time scales of motor learning have been extensively researched, however, few have specifically looked at the progression of learning in the first minutes if exposure to a particular task. Mostly, the available data was averaged over first minutes of exposure, thus the information about the participants performance specific to this segment in time was lost.

While accuracy increases within trials occurred for all participant groups, accuracy increase across repeated trials of the same condition was significant only for PWS and CPWS, suggesting that learning between trials occurred only for these two groups. It is, however, of interest that, although insignificant, the overall trend showed improvement in accuracy from the first to the second trial for most predictable conditions, and little to no improvement from second to third trial. This trend varied somewhat between jaw and hand tracking performance. There was also a between-group difference related to age. For example, older participants (CPPD and PPD) did not show any improvement in jaw tracking of complex sine patterns at any frequency (apart from

one condition – pattern at 0.9 Hz where the CPPD did show improvement between the first and second trial). By contrast, our younger participants (PWS and CPWS) showed consistent trends of increases in jaw tracking accuracy between the first and second trials at all frequencies. These results suggest that learning in a novel challenging task, like jaw tracking, might depend more on the complexity of the pattern to be learned and the age of participants, than the disease or fluency status of the participants. Our results, however, should be interpreted with caution – our paradigm was not designed to assess long term accuracy improvement and did not allow for prolonged or varied practice to take effect. Rather, all we can discuss is immediate or "early" learning (Krebs et al., 2001).

Conclusion

In this study we examined motor ability of four different populations in a dynamic environment, using a visuomotor tracking method. The analysis of tracking accuracy from our sample indicated that age and neurological health play a role in motor control. Our results indicated that there is no underlying deficit in speech and manual motor coordination for PWS when the visual feedback is present to guide movements. Present results offer no evidence of procedural learning impairment in PWS, at least in the "early" learning stage.

Analysis of PPD performance suggests that this group may have difficulty integrating different coordinate systems in order to guide movement. The finding that PPD showed immediate learning that was comparable to that of the age-matched controls provides evidence that medicated individuals in the early stages of the disease in the absence of cognitive impairments do not show profound impairments in motor procedural learning.

Limitations

The main limitation of the current study is that our paradigm did not allow for differentiation of the influence of motor coordination abilities and visual and attention

mechanisms to tracking performance. Related to that is the issue of processing and taking advantage of the visual feedback for movement control. It has been shown that PWS did not differ from their controls on motor tasks when visual feedback was present. By contrast, they did not perform as well as their controls in tasks without feedback. Thus, future research should incorporate motor control and learning tasks performed with and without the feedback, to elucidate the role it plays in motor control of people who stutter.

Among other limitations of this study we should mention the age confound between PWS and PPD. Significant age difference between these two groups precluded us from making direct comparisons of these population based on etiology.

Another limitation of the study was that methods employed only allowed for assessment of immediate learning. Having participants come back after several times over days or weeks to perform the same task would enable the researcher to look at long term increases in accuracy and consolidation, a very important stages of procedural learning mechanisms.

Future Research

The present investigation assessed motor procedural learning in the speech and manual systems of people who stutter. Knowing the importance this type of learning plays for non-motor abilities (language learning among them), future studies examining procedural learning in the non-motor cognitive domains in people who stutter are warranted. Aside from visuomotor paradigms that require some type of motor response, it may be useful to examine learning in the absence of any motor or verbal response. Use of event-related potential paradigms would allow for that. Moreover, in light of the findings that presence of visual feedback determines the accuracy of motor performance in both PWS and PPD, future studies should assess learning and accuracy during motor tasks in these populations in the absence of visual feedback.

In the present investigation we used a combined error measure that incorporated both amplitude and phase difference between the target and the tracking signal. In light of the hypothesis that stuttering is caused by timing difficulties and inability of the motor system to initiate and smoothly transition between sequential movements, it is warranted to examine participants error in the timing domain using only phase difference in the tracking error estimation. This would allow for assessment of timing accuracy of participants tracking and whether it can differentiate people who stutter from their age-matched controls.

Another direction for future research is to examine development and changes in procedural learning ability of children who stutter close to the onset of stuttering with parallel assessment of their speech and language development. This may provide valuable information to shed light on possible causes of childhood stuttering.

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