Motor Learning Abilities in Adults who Stutter

by

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A thesis submitted in conformity with the requirements for the degree of Speech-Language Pathology

Department of Speech-Language Pathology

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Abstract

This dissertation is comprised of three studies investigating the hypothesis that people who stutter (PWS) differ from people who do not stutter (PNS) in their motor skill learning abilities. The first study in this dissertation examined the ability to learn a novel sequential speech task following a 24-h retention period. Despite slower sequence durations compared to the PNS, PWS showed the ability to retain what they had learned for all measured variables on day one and following a 24-h consolidation period. The second study in this dissertation examined the ability to learn a sequential finger tapping task by observing the ability to produce the sequence under both tests of retention and interference. For tests of retention, PWS showed the ability to retain improvements in performance for all measured variables, albeit at slower speeds compared to PNS. For tests of interference, a significant interaction for reaction time and sequence duration revealed that PNS’ performance reached a relative plateau while PWS’ performance continued to show improvement.

The third study in this dissertation investigated the extent to which individual differences in motor learning are associated with differences in stuttering treatment outcome. PWS participating in an intensive fluency treatment program were assessed for their working memory ability and their motor
learning performance on a syllable reading and finger tapping task. Treatment success was measured at pre-treatment, post-treatment and six months follow-up using percent syllables stuttered, introspective clinical characteristics (OASES; Yaruss, 2010) and fluency effort. The relationship between motor learning and treatment outcome was examined using multiple regression analyses. Results did not support the hypothesis that the ability to learn a simple speech and nonspeech motor task is predictive of treatment outcome. Although treatment proved successful as evidenced by percent syllables stuttered and OASES scores, scores of fluency effort indicated that participants had not automated their newly learned fluency skills when speaking in everyday conversations.

Together, these studies do not support the hypothesis of a motor learning deficit in PWS but rather support the assumption of limited motor abilities. Limited motor abilities are discussed as having implications to stuttering treatment outcome.
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CHAPTER I
INTRODUCTION AND LITERATURE REVIEW

Introduction

This chapter is intended to provide an introduction to the disorder of developmental stuttering. This chapter begins with a description of the behavioral characteristics associated with the disorder as well as its incidence and prevalence within the population. This is followed by a discussion on the motor, neurobiological, genetic, and environmental factors that are thought to play an integral role in the etiology of the disorder. This overview, when combined with the description of principles underlying motor practice and learning in chapter 2, will allow me to discuss the data presented in chapter 3 within a framework of motor learning abilities in PWS.

Incidence and Prevalence

Developmental stuttering (DS) typically emerges during the preschool years. Yairi and Ambrose (1999) report that 65% of preschool children begin stuttering before age 2.5 and 85% do so before age 3.5. Andrews (1984) and Yairi, Ambrose, Paden, and Throneburg (1996) reported the prevalence of stuttering in childhood is 5% but decreases to 1% in adulthood. This decline in prevalence suggests that a large proportion of children spontaneously recover from stuttering. Yairi and Ambrose (1999) reported that the usual length of recovery following stuttering onset ranges from two to three years. Several factors have been shown to differentiate children who recover from those who persist such as the frequency and type of stuttering, age of onset, language ability, gender, and family history (Yairi et al., 1996). For those who do not recover, stuttering can have severe negative effects on an individual’s social, academic and vocational success.

Developmental Stuttering

Developmental stuttering (DS) is a communication disorder characterized by a high frequency and/or duration of protractions or blockages in the forward flow of speech (Bloodstein & Bernstein – Ratner, 2008; Guitar, 2006). These stoppages usually take the form of sound, syllable or word repetitions,
sound prolongations, “blocks” of airflow or voicing and the use of interjections (e.g. “um”, “ah”; Craig, 1996; Guitar, 2006).

DS may also include observable concomitants of stuttering such as facial grimacing, head movement, abnormal blinking or breathing patterns, hand or foot tapping, tongue protrusion, pitch and loudness changes or other movements that accompany the disfluent moment. Such behaviors are learned reactions to the disorder and often acquired by the speaker in an attempt to end the stuttering moment or avoid it all together (Guitar, 2006). PWS may also develop strategies to avoid speaking words that contain sounds that they have stuttered on in the past (Bloodstein, 1995). Such avoidance behaviors may prevent the stutter from occurring and as a result provide temporary, emotional relief. It is common for the severity of stuttering to increase under certain speaking situations such as when making introductions, speaking on the telephone, or speaking in front of groups. Due to the emotional strain these situations may impose on a PWS, a great deal of effort is placed on avoiding such situations. For example, a child who stutters may excuse himself from the classroom before it is his turn to speak. Situations such as this can be very disabling emotionally, leading to feelings of inadequacy, which subsequently leads to negative effects on a PWS’ social, academic and vocational success (Craig, Blumgart, & Tran, 2009; Klein & Hood, 2004; Messenger, Onslow, Packman, & Menzies, 2004).

While the etiology of developmental stuttering is inconclusive, it is likely that stuttering onset results from an interaction of multiple genetic, neurobiological and environmental variables (Guitar, 1998). Many factors associated with developmental stuttering have been explored including motor abilities; the anatomy and physiology of neuronal structures; as well as genetics and environmental factors. These areas of investigation will be discussed briefly below.

Motor Abilities and Developmental Stuttering

Numerous studies have reported differences in PWS’ motor abilities compared to controls on tasks ranging from finger tapping (Smits-Bandstra, De Nil, & Saint-Cyr, 2006b; Webster, 1986; Zelaznik,
Smith, Franz, & Ho, 1997) to the production of complex sentences (Bosshardt, Sappack, Knipschild, & Holscher, 1997; Cooper & Allen, 1977). Motor abilities have traditionally been measured using the variables reaction time and movement speed, although kinematic measures have also been used (Kleinlow & Smith, 2000; Namasivayam & Van Lieshout, 2008).

Reaction time and Developmental Stuttering

Voice reaction time measures the initiation of voice in response to a stimulus. It is a complex act that involves a preparatory set to respond, the perception of a stimulus, and the activation of both respiratory and laryngeal muscles and is commonly used to measure motor ability (Schmidt & Lee, 2004). PWS have shown slower voice reaction times compared to PNS on a number of different speech tasks including the production of syllables (Webster, 1979), words (Starkweather, Hirschman, & Tannenbaum, 1976; Wignen & Boers, 1994), and sentences (Hayden, Adams, and Jordahl, 1972); as well as tasks of nonsense syllable sequencing (Huinck, Wouters, Hulstijn, & Peters, 2001), and phrase and sentence repetition (Cooper & Allen, 1977; Logan, 2003). These group differences have been reported to increase with increasing complexity of the response (Bernstein, 1997; Peters, Hulstijn, & Starkweather, 1989); however, others have found no interaction with word size (Van Lieshout, Hulstijn, & Peters, 1996). While some studies have found no significant difference in voice reaction time between groups (Prosek, Montgomery, Walden & Schwartz, 1979; Weber-Fox, Spencer, Spruill, & Smith, 2004; Watson & Alfonso, 1982); others have found the slow reaction times to be task specific (McFarlane & Shilpey, 1981; Reich, Till, & Goldsmith, 1981). For instance, McFarlane and Shilpey (1981) found slower reaction times when producing syllables in response to an auditory cue but not a visual cue.

Finger tapping tasks have elicited more controversial results. Webster and Ryan (1991) reported that PWS were slower at initiating hand movements compared to controls. Cross and Luper (1983) found that the significantly slower speech and finger tapping performance in PWS was highly correlated;
however Starkweather, Franklin, and Smigo (1984) did not find a similar relationship. Several other studies assessing nonspeech reaction times in PWS versus PNS have found no significant group differences (Hurford & Webster, 1985; Prosek et al., 1979).

**Movement Speed and Developmental Stuttering**

PWS have also shown slower movement durations on speech tasks. Chang, Ohde and Conture (2002) found that the formant transition rate, or the speed of movement between articulatory positions, was slower in children who stutter (CWS) compared to controls during the elicitation of single word utterances. Other studies have shown similar results in CWS (Hall, 1999) and adults who stutter (Max & Gracco, 2005). Using a number of different diadochokinetic tasks, Huinck et al. (2001) found PWS to be slower than PNS when repeating sequences of syllables. Several other studies have observed slower movement durations in PWS compared to PNS when repeating words (McMillan & Pindzola, 1986; Van Lieshout, Hulstijn, & Peters, 1996; Zimmerman, 1981) and sentences (Bosshardt, et al., 1997; Cooper & Allen, 1977).

PWS’ slowness of movement is not limited to the speech system, however. Several studies have found differences in the duration of movement across unrelated motor systems. Weinstein, Caruso, Severing, and VerHoeve (1989) found that PWS took longer than PNS to initiate the first saccade (small eye movement) of a multi-saccadic sequence. Max, Caruso and Gracco (2003) found slower finger flexion movement durations in PWS compared to PNS during a finger-to-thumb movement task. Slower finger movements have also been reported by Borden (1983), Webster (1986) and Zelaznik et al. (1997).

**Proprioceptive Abilities and Developmental Stuttering**

PWS appear to have limitations in the processing or use of proprioceptive information for motor control (Loucks & De Nil, 2001). Support for this idea stems from studies which show that PWS produce significantly larger oral movements compared to PNS on tasks that require minimal movements without
visual feedback (Archibald & De Nil, 1999; De Nil & Abbs, 1991). Loucks and De Nil (2006) found less accurate and more variable performance in PWS compared to PNS when performing a jaw opening movement without visual feedback and under time pressure. Max, Guenther, Gracco, Ghosh and Wallace (2004) hypothesized that PWS show an over reliance on sensory feedback in an attempt to compensate for limited motor ability. However, Namasivyam and Van Lieshout (2010) did not find evidence for this in a more recent study that investigated the role of audio, proprioception and tactile feedback at the intra- and intergestural levels of speech coordination in normal and fast speaking rates.

In summary, several studies have reported differences in PWS compared to PNS in the initiation and execution of both speech and nonspeech motor tasks. The following section reviews neuroimaging studies that help explain some of these differences in motor control as aberrant neurological structures and functions mediating the processes involved in movement have been found in PWS compared to PNS.

Neurophysiology and Developmental Stuttering

A large number of functional imaging studies have found atypical activity in brain regions believed to be responsible for motor planning and execution (Braun et al., 1997; Chang, Horwitz, Ostuni, Reynolds & Ludlow, 2011; Fox et al., 1996). Brown, Ingham, Ingham, Laird and Fox (2005) conducted an activation likelihood estimation (ALE) meta-analysis of imaging studies of developmental stuttering and fluent controls. Results showed that the most robust concordance across studies was the significant differences observed within the core motor areas in PWS compared to PNS. Three findings in particular that appeared to be most common across laboratories included (1) an overactivation in the right frontal operculum/ anterior insula, (2) absence of activation in auditory areas bilaterally, and (3) overactivation in the vermal region of lobule III of the cerebellum. These three findings are described in more detail below.

A relatively widespread, right hemisphere overactivation in PWS in motor system areas in both the cerebrum and cerebellum, as opposed to the typical left hemisphere activation observed in PNS, has
been a consistent finding attained from both positron emission topography (PET; Braun et al., 1997; De Nil, Kroll, Kapur, and Houle, 2000; Fox et al., 1996) and functional magnetic resonance imaging (fMRI; Preibisch et al., 2003) studies. Braun et al. (1997) suggested that the right hemisphere may be recruited to compensate for fluency breakdown. This notion is supported by Neumann et al. (2003) where an increase in activity was present before treatment but was eliminated after treatment. Furthermore, Chang et al. (2008) reported that anatomical increases in the right hemisphere were not found in CWS, suggesting that the differences in the right hemisphere in adults who stutter are due to a compensatory effect from a lifetime of stuttering.

PWS show a reduction in activity in auditory areas during vocalization tasks when compared to fluent controls (Braun et al., 1997; Fox et al., 2000; Neumann et al., 2003; Preibisch et al., 2003). For instance, Van Borsel, Achten, Santens, Lahorte, & Voet (2003) found a significant decline in auditory activity in PWS compared to controls during an overt speaking task. When contrasting oral reading from silent reading, De Nil et al. (2000) found increases in auditory activity in the right hemisphere in the PWS, compared to the more typical left hemisphere observed in PNS. Some research suggests that auditory activity levels are linked to stuttering frequency. For instance, Neumann et al. (2003) found that activity in the auditory cortex during an overt reading task correlated negatively with stuttering severity. Also, Stager, Jeffries, & Braun (2003) and Fox et al. (1996) found an increase in auditory activity bilaterally in PWS when performing a fluency – inducing task (i.e. chorus reading) compared to a stuttering – inducing task (i.e. solo reading).

PWS have shown cerebellar activity in the vermal part of lobule III during vocalization tasks (Braun et al., 1997; De Nil et al., 2003; Fox et al., 1996; Ingham et al., 2004). This is contrary to the more typical cerebellar activity observed in lobule VI and the associated vermis (Brown et al., 2005; Turkeltaub, Eden, Jones, & Zeffiro., 2002). In Fox et al. (1996) and Braun et al. (1997), activity in vermis III was only observed in the PWS when performing tasks more likely to elicit stuttering such as
solo reading. During a silent and oral reading task, De Nil et al. (2001) reported an increase in cerebellar activity compared to controls before and immediately after the participation in an intensive fluency treatment program. The authors suggested this to be due to an increased need to monitor sensory or motor processing during the planned movement of speech. At one-year follow up, the PWS who showed reduced cerebellar activity were also the ones who appeared to have automatized the fluency skill to a greater extent. Decreases in cerebellar activity have been reported in other studies (Doyon, Song, et al., 2002; Jenkins, Brooks, Nixon, Fracknowiak, & Passingham, 1994), in response to practicing a new sequence skill, suggesting its important role in learning.

The basal ganglia is also an important structure involved in the motor learning process and differences in neurological activity have been reported within the basal ganglia in PWS compared to PNS. Using fMRI, Giraud et al. (2008) found a positive correlation between activity in the caudate nucleus and stuttering severity level during pre-treatment analysis. Using PET, Wu et al. (1995) showed that the largest difference between PWS and PNS under fluent and stuttered speaking conditions was a decrease in the left caudate nucleus, representing approximately 50% less activity in the PWS. The decrease in striatal activity was suggested to correlate with changes in metabolic activity in a proposed neuroanatomical circuit defect involving a decrease in activity in the substantia nigra, left anterior frontal regions, and limbic systems as well as the cerebellum. A decrease in striatal metabolism was suggested in a subsequent study (Wu, Riley, Maguire, Najafi, & Tang, 1997) to be a potential result of excess dopamine, a neurochemical known to have an inhibitory effect on connected cortical regions. Such claims are in support of Alm’s (2004) theoretical model that describes stuttering as a disruption in the basal ganglia-cortical circuitry which is thought to govern internally driven motor operations.

Differences in the sequencing of cortical activity in PWS compared to PNS were reported in a magnetoencephalography (MEG) study by Salmelin, Schnitzler, Schmitz, and Freund (2000a). While reading sequences of nouns, PNS showed cortical activity that advanced from the left inferior frontal
cortex, areas associated with programming articulatory gestures, to the left lateral sulcus and dorsal preMC, areas responsible for premotor programming. This sequencing of neurological activity was reversed in the PWS, even when the sequences were produced fluently.

Premotor regions show an increase in neurological activity approximately two seconds before the onset of many voluntary movements (Deeck, 1976, 1983; Boschert et al., 1983; Grozinger et al., 1980) and are considered an important component to motor preparation. In an MEG study, Walla, Mayer, Deecke and Thurner (2004) found that this preparatory pre-motor activity was absent in the PWS compared to controls during a word reading task.

Neuroanatomy and Developmental Stuttering

Anatomical differences have been found in PWS in cortical areas of the brain associated with speech and language processing. Foundas, Weisberg, Browning and Weinberger (2001) found atypical asymmetry in the right planum temporal. The planum temporal is an important region for language comprehension and left asymmetry is more typical in normal right-handed speakers. Using voxel based morphography, Janche, Hangley, Steinmetz (2004) found increased white matter volumes in the right hemisphere, including the superior temporal gyrus. Beal, Gracco, LaFaille and De Nil (2007) also found differences in grey matter density in the planum temporal however these differences were bilateral and extended beyond regions of the right superior temporal gyrus, indicating that differences between groups involve other regions of the brain and are not limited to the right hemisphere.

Anatomical deficits in the white matter tracts underlying motor areas in the left hemisphere have been reported in both children and adults. Sommer, Koch, Paulus, Weiler, and Buchel (2002) found reduced white matter integrity in the left inferior arcuate fasciculus, a pathway particularly important for linking temporal and frontal areas for sensorimotor integration during speech production. Chang et al., (2008) also found reduced fractional anisotropy in white matter tracks underlying motor regions for the
face and larynx in children who stutter. In the same study, reduced gray matter volume was also reported in the left inferior frontal gyrus and bilateral temporal regions.

In summary, several neurophysiological and neuroanatomical distinctions in PWS compared to PNS have been reported in regions associated with the preparation and execution of speech production. In addition, some of this aberrant activity has been reported in areas strongly linked to motor learning such as the cerebellum (Grafton, Hazeltine, & Ivry, 1995; Jueptner, Frith, Brooks, Frackowiak, & Passingham, 1997; Karni et al., 1998) and basal ganglia (Doyon et al., 2002; Poldrack et al., 2005). These neuroanatomical and neurophysiological differences found in PWS have been posited to either increase the susceptibility of the disorder (De Nil, 1999; De Nil, 2004) or be a compensatory affect due to years of stuttering (Braun et al., 1997; Chang et al., 2008; Fox et al., 2000). The former view supports the notion that neurological differences in PWS are an effect of heredity. The following section provides a brief overview of heredity factors and DS.

Genetics and Developmental Stuttering

Evidence from family and twin studies has shown a strong biological factor in the etiology of stuttering (Ambrose, Yairi, & Cox, 1996). A high tendency for stuttering has been shown to appear more often in successive generations of the same family compared to that of the general population, ranging from approximately 30-60% in PWS versus 10% in PNS (VanRiper, 1982; Yari, 1983; Ambrose et al., 1993). Also, the prevalence of stuttering in the twin population has shown a higher degree of concordance for stuttering in monozygotic twins versus dizygotic twins (Howie 1981; Andrews, Morris-Yates, Howie, & Martin, 1991; Felsenfeld et al., 2000).

Research investigating the familial aggregation of stuttering has shown an increased incidence of stuttering, by approximately 15%, in first-degree relatives of individuals who stutter, as compared with a 5% lifetime risk in the general population (Kidd 1984; Ambrose et al. 1993). Kidd (1984) reported the
greatest risk of stuttering occurred for relatives of females who stutter (17-20%), which was significantly higher than that for relatives of males who stutter (12.2%). There is also a significant sex bias in the incidence of stuttering with the male to female sex ratio increasing from 2:1 in childhood to 4:1 or 5:1 in adulthood (Bloodstein, 1995; Yairi & Ambrose, 1996). The increase in polarity with age of disordered males versus females suggests the recovery rate for females is much higher than for males (Yairi & Ambrose, 1992).

Genetic studies investigating families with a high incidence of stuttering have found a linkage of stuttering to certain chromosomes (1, 5, 12, 15, 16, and 18; see Riaz et al., 2005; Yairi, Ambrose, 1996). For instance, Suresh et al. (2006) identified chromosome 7 as a possible locus for men who stutter; whereas chromosome 21 was identified in the female data set only. Shugart et al. (2004) identified a potential locus for stuttering on chromosome 18, a site known to be involved in intercellular transmission. Although progress has been made in narrowing down the “stuttering gene”; studies to date have not identified a consistent chromosomal locus (Felsenfeld et al., 2002). This is most likely due to the idea that the combined effect of many genes leads to the expression of stuttering.

It is also important to include impacts from the environment when considering the underpinnings of stuttering. Both Andrews et al. (1991) and Felsenfeld et al. (2000) calculated that approximately 70% of the variance in liability for stuttering could be attributed to additive genetic effects; whereas the remaining 30% was due to nonshared environmental factors. Data such as this indicate that although a predisposition to stuttering is genetically transmitted, the elicitation of stuttering is strongly influenced by the environment. Environmental factors may be developmental (e.g. prenatal) in nature or stem from an individual’s communicative environment (e.g. parental communication style).

In summary, the etiology of DS remains unknown; however, genetic investigations have shown that the disorder is strongly influenced by heredity. Due to its genetic predisposition and its onset in the
early childhood years, developmental and environmental factors are thought to interact with a child’s constitution, to not only elicit stuttering but play a role in perpetuating the problem. The following section describes environmental factors that have appeared to be the most influential to the elicitation of stuttering.

Environment and Developmental Stuttering

Evidence suggests that developmental stuttering results from an interaction between a genetic predisposition to stuttering and environmental and/or self-imposed demands on the system (Bloodstein, 1975; Conture et al., 2006; Guitar, 2006; Yairi & Ambrose, 2005). Some of these demands are thought to precipitate stuttering while others may interact to make remission difficult. Guitar (2004) identified several environmental stresses that will be discussed below.

One of the most important influential factors in a child’s family environment is the parents. Bloodstein and Bernstein-Ratner (2008) reported that parents may unconsciously elicit stuttering by imposing high parental standards of speech or language in the home such as the use of linguistically sophisticated language or competition with a sibling who is more advanced in speech-language development. The University of Iowa (Darley, 1955; Johnson, 1955) conducted a number of studies of parents of both stuttering and nonstuttering children and found that, based on parent questionnaires, parents of CWS were more likely to impose higher standards of behavior on their children compared to parents of CWNS. For example, they expected their children to walk and talk earlier. However, there was a great deal of overlap in the attitudes of both parental groups. More recent studies by Flugel (1979) and Zenner, Ritterman, Bowen, & Gronhovd, (1978) found that parents of CWS tended to be more critical or anxious compared to parents of CWNS. Others, however, have found no significant differences between the two groups of parents (Goodstein, 1956).
Other studies have found that the communicative interactions between parents and their children may be linked to fluency breakdown (Ratner, 2004). For instance, Meyers and Freeman (1985) found that parent’s fast speaking rates had a negative impact on the frequency of stuttering in young CWS. Guitar and Marchinkoski (2001) and Zebrowski, Weiss, Savelkoul, and Hammer (1996) noted that stuttering in young children may diminish when parents are recommended to adopt a slower rate of speech. Also, Winslow and Guitar (1994) found that teaching parents to lengthen their turn-taking latencies resulted in a decrease in stuttering in CWS.

Kloth, Kraaimaat, Janssen, and Brutten (1999) and Rommel, Hage, Kalebne, & Johanssen (2000) found the mother’s language of CWS was significantly longer and more complex than the mother’s language of CWNS. Starkweather (1987) proposed that the use of more complex language by the parents may place added self-imposed demands on the child to perform at a level that exceeds their capacity for speech and language formulation. In concordance, CWS have shown an increase in stuttering frequency when producing longer and more complex utterances (Gaines, Runyan and Myers, 1991; Logan & LaSalle, 1999; Yaruss, 1999). Other suspected parental stresses include the frequency at which a parent interrupts their child (Meyers & Freeman, 1985), and the extent to which parents ask questions (Langlois, Hanrahan & Inouye, 1986; Langlois & Long, 1988).

Importantly, Yairi (1997) noted that there is no direct link between environmental factors such as these and stuttering and that some of the negative traits observed in parents of CWS may reflect their own experiences with the disorder. Guitar (2004) also pointed out that certain personality and temperament traits (e.g. over sensitive, anxious, fearful) may render a child more vulnerable to environmental pressures.
The onset of stuttering has also been reported to occur during stressful periods in a child’s life such as a death in the family, moving to a new school, or birth of a sibling (Guitar, 200; Starkweather, 1987).

Conclusions

In summary, a wide variety of studies have been devoted to our understanding of stuttering. One of the most salient research areas has been in motor control, where differences in motor abilities at the group level in PWS compared to PNS have been consistently reported when performing both speech and nonspeech motor operations. The following chapter provides an overview of motor learning and some of the important components thought to be involved in the motor learning process. This overview, will allow me to discuss the data presented in chapter 3, within a framework of motor learning abilities in PWS.
Chapter II

MOTOR PRACTICE AND LEARNING

Introduction

Behavioral treatments for stuttering often aim for brain reorganization and plasticity for the establishment of new speech motor patterns that promote fluency, such as prolonging speech or forming light articulatory contact (e.g. Kroll & Scott-Sulsky, 2007; O’Brian, Packman & Onslow, 2007). Central to such approaches to treatment is the client’s ability to transition the newly learned speaking pattern to a sufficiently high level of automaticity so that it can be executed effortlessly in natural speaking situations. One of the main limitations to stuttering treatment outcome is the high incidence of relapse, ranging anywhere from 14% to 70% of participants within a year following treatment (Bloodstein & Bernstein-Ratner, 2008). Recent findings of reduced practice and learning abilities in PWS (Namasivayam and Van Lieshout, 2008; Smits-Bandstra, De Nil, & Rochon, 2006a), have allowed us to speculate that a deficiency in motor learning may be a contributing factor to the lack of long-term effectiveness of fluency intervention strategies.

A great deal of research has been devoted to our understanding of the behavioral and neurological processes associated with motor learning. The purpose of this chapter is to provide an overview of motor learning and some of the important components thought to be involved in the motor learning process. This is followed by a description of the stages of motor learning thought to occur as an individual transitions from the early to later stages of practice. Following this is a summary of the various measures used to assess the behavioral changes associated with the learning process. This chapter concludes with a brief description of the prominent theory of motor control and learning called Schema Theory (Schmidt, 1975; Schmidt & Lee, 2005). The Schema Theory is used in order to facilitate an understanding of some important principles of motor learning and is particularly useful when describing the processes associated with sequence skill learning.
Motor Skill Learning

Motor skill learning involves internal processes by which movements are produced effortlessly through practice or experience. Internal processes may include morphological changes in the central nervous system such as an increase in dendritic branching or an increase in synaptic connections between neurons (Rose, 1997). This is different than a motor ability that is genetically defined such as a person’s height or vision. A wide range of motor learning theories (Adams, 1971; Bernstein, 1967; Fitts & Posner, 1967; Kelso, 1995; Schmidt & Lee, 2005; Vereijken, Whiting, & Beek, 1992) agree that skill acquisition involves the interaction between the pre-existing capacities of an individual and the to-be-learned movement pattern. For instance, individual differences in the rate of learning a repetitive finger tapping task may reflect the number of hours they spend a week typing. It refers to the ability to acquire the temporal and spatial characteristics of a movement pattern so with practice the movement becomes smoother and is produced with less error, leading to a relatively permanent change in the feature of the behavior (Schmidt & Lee, 2005). This may be accompanied by a decrease in sensory and attentional demands (Schmidt & Lee, 2005).

Motor skill learning is dependent on either implicit (without awareness) or explicit (with awareness) knowledge, or both over the course of a learning experience (Grafton et al., 1995). Explicit learning involves the retrieval and processing of information necessary to perform a skill accompanied with awareness of the information being learned. In this case a person may use declarative strategies at the beginning of practice in order to make the most improvement gains (Fitts, 1964; Posner & Keele, 1968). A person does not need explicit knowledge of the skill, however, in order for learning to occur. For instance, a person may be unaware of a sequence hidden in a long movement yet make performance gains with practice. For the purpose of this dissertation, only studies employing explicit learning paradigms are included.
In summary, learning is a set of internal processes that occur with practice or experience. Learning results in permanent changes in the underlying capabilities for responding to a particular task. As a result, learning-related changes are not always obvious and must be inferred from other measures. While there are a large number of variables that can influence performance and learning, pertinent to this discussion are the processes of attention and working memory.

Attention and Automaticity

Attention is a complex theoretical construct that incorporates a wide range of cognitive functions including focused, sustained and divided attention; as well as speed of information processing (Sholberg & Mateer, 2001). These cognitive components involve a diffuse set of circuitries and structures that include but are not limited to the anterior frontal and temporal brain regions (Sholberg & Mateer, 2001).

Attention is essential to the early stages of performing a novel task as the learner attempts to understand what is required and how best to attempt the first few trials. Attention is required for the monitoring of feedback or reinforcement in order to determine success at performing a task as well as to integrate incoming sensory information with old memories (Baddeley, 2003). After all, following the first few years of life, learning a skill from scratch is rare. Instead the speed and efficiency of motor skill acquisition is largely a result of building from pre-existing skills and experiences (Fitts, 1967; Kelso, 1995). Studies have found individual differences in cognitive ability, particularly working memory, to be linked to performance differences during the early stages of learning a motor task (Sakai et al., 1998; Rypma et al., 2006; Vogal, McCollough, & Machizaway, 2005). A brief description of working memory and its role in the motor learning process is described in the following section.

Working Memory and Motor Learning

Pertinent to the studies described in this dissertation is the construct of divided attention which requires the individual to engage in more than one cognitive task simultaneously. Such a task requires a high level of working memory. Baddley (2003), whose model of working memory is considered the most
influential, states working memory constitutes a set of attention and regulation processes that help manage cognition by connecting the worker components (visuospatial sketchpad, phonological loop, and episodic buffer) to long term memory. Studies have reported working memory dependent activity in a network of regions including the dorsolateral prefrontal cortex (DLPFC), parietal cortices, and temporal lobes (Bor & Owen, 2006). Some studies report that the neural systems supporting working memory extend beyond these regions to include the pre-supplementary motor area (pre-SMA), premotor cortex (preMC), anterior cingulate cortex, Broca area, cerebellum and striatum (Cabeza & Nyberg, 2000; Glabus et al., 2003; Landau & D’Esposito, 2006; Sakai et al., 1998; Smith & Jonidas 1999). These areas show enhanced activity during the stage of motor learning when attentive processes are thought to dominate.

Working memory is essential during the initial stages of motor learning for the creation of new representations from the integration of incoming sensory information and old memories (Baddeley, 2003). Support for this claim stems from studies that have linked individual differences in behavior as well as neurological structures and functions mediating the processes for working memory to performance differences on motor learning tasks (Kennedy & Raz, 2005; Sakai et al., 1998). For instance, Kennedy and Raz (2005) showed that scores on a working memory test along with associated larger volumes of prefrontal cortex were associated with better performance during the early stages of a perceptual-motor task. In an fMRI study, Sakai et al. (1998) assessed individual differences in performance as subjects learned to press buttons in the correct order by trial and error. Subjects were grouped according to their performance level following practice. Results showed consistently high activity in the inferior learners in areas particularly important for working memory processing, such as the dorsolateral prefrontal cortex (DLPFC) and pre-supplementary motor area. In contrast, superior learners showed an earlier decline in these areas with practice.

Consistently high activity in these proposed working memory regions in the inferior learners following practice suggests that they had not yet internalized the sequence and as a result, required a
larger degree of cognitive control. Studies such as Sakai et al., (1998) suggest that working memory capacity may affect the speed and efficiency in which an internal model is developed.

Stages of Motor Learning

A learner is often thought to transition through relatively distinct phases of learning as they practice a motor skill. Fitts (1964; Fitts & Posner, 1967) proposed three phases that have proven useful for describing the motor learning process. These stages are called the cognitive phase, the associative phase and the autonomous phase. Adhering to these phases, the following section provides a brief description of the behavioral and neurological studies reporting learning–related changes associated with the learning process.

Initial Attempts at Performing a Task

The initial attempts at performing a task involve adjusting movement kinematics according to sensory feedback in order to make the first attempts at producing accurate movement (Doyon, Ungleider, et al., 2002). At the same time, task-specific components in memory are selected and used for solving the task at hand (Karni et al., 1998). Performance gains during this stage are typically very inconsistent as the learner is determining the most effective way to perform the task.

Cognitive processes such as working memory are also heavily engaged during this stage as the learner tries to understand the task and retrieve from memory aspects of the skill that have been previously learned (Baddeley, 2003). During these initial attempts at performing a task, increases in neural activity are shown in primary and higher visual cortices as well as superior, inferior and medial parietal lobes (Grafton et al., 1992). These sites are claimed to correspond to processes involved in attentive visual spatial processing (Kandall, Schwartz, & Jessel, 2000; Grafton et al., 1995) and
sensorimotor feedback monitoring (Colby & Duhamel, 1996; Colby & Goldberg, 1999) as the main goal of this stage is to link sensory representations of the environment into muscle control signals.

*Early Stage of Learning*

Usually after only a brief period of practice, the learner becomes less dependent on sensory input as the development of a new pattern begins to emerge from what was once, an initial repertoire of subroutines (Fitts, 1967). Dramatic performance gains can be seen at this stage, as the learner has begun to integrate the appropriate sensory cues in order to produce planned, goal-directed movement. Using a sequential, finger-thumb opposition task, Karni et al. (1998) observed significant declines in reaction time and performance accuracy in one 30 minute session of practice.

Several cortical and subcortical sites of activation have been found associated with this early stage of motor skill acquisition. Studies comparing new learning with simple, repetitive movements (e.g. tapping index finger) have observed increases in activation in the DLPFC, middle frontal cortex, preMC, primary motor cortex (M1), pre-SMA and caudate nucleus (Grafton, Woods, Tyszka, 1994; Jueptner et al., 1997; Karni et al., 1995, 1998), as well as the cerebellum (Doyon et al., 2002; Poldrack et al., 2005). Some studies also report strong functional interactions among the frontal and motor regions during early learning and may be due, in part, to the attentional demands required during the formation of a newly learned motor skill (Sanes & Donahue, 2000; Sun, Miller, Rao & D’Esposito, 2007; Tamas et al., 2008).

*Late Stage of Learning*

The late stage of learning involves more subtle adjustments in motor performance as the learner has determined the most effective strategy for carrying out the task. Performance becomes more consistent as practice continues across longer time periods until gradually performance levels off and asymptote is achieved.
Although a plateau is often referred to as a level in which maximum competence has been achieved, long term studies show that plateaus are not stagnant and gradual improvements in performance continue to be observed when practicing even the simplest motor skill across a long time period (Crossman, 1959; Fitts & Posner, 1967). Karni et al. (1998) stated that the behavioral changes associated with long term learning reflect the building of a discrete population of neurons that are recruited during practice and represent the appropriate connections between a specific stimulus and a response. This functional reorganization is thought to represent the development of an internal motor program (Schmidt, 1988) which results in self-initiated, automated movement (Hikosaka et al., 2002) that is guided internally by the learner and as a result is less reliant on sensory feedback (Schmidt & Lee, 2005).

Neuroimaging studies commonly report an overall decrease in the extent of activation in sensorimotor regions to occur later in learning (Doyon & Ungerleider, 2002; Jenkins et al. 1994; Poldrack et al., 2005; Rauch et al., 1997). Wu, Kanasaku, & Hallett (2004) found that practicing a finger tapping task daily for three weeks resulted in decreases in cortical activity in the bilateral cerebellum, bilateral preMC, posterior parietal cortex, pre-SMA and anterior cingulate cortex. Other studies report a shift in the site of activation later in learning so that rather than an overall decrease, decreased activity in some areas is offset by increased activity in other areas associated with continued practice. For instance, using fMRI, Duff, Xiong, & Wang (2007) found that following four consecutive weeks of practicing a finger tapping task, significant increases in activity in the thalamus and putamen were found, simultaneous to decreases in activity in the parietal, occipital and cingulate cortices as well as the cerebellum. Other studies have also shown the striatum, together with motor cortical regions, to increase with long term practice of a sequence skill (Doyon & Ungerleider, 2002; Grafton et al., 1994).

*Autonomous phase*
After many months or even years of practice, the learner may transition their ability to perform a motor skill to an automatic phase where the task can be performed without interference from many other simultaneous activities (Schmidt, 1988; Fitts & Posner, 1967). That is, when performing an automated task, the learner is capable of processing information concerning various aspects of a different task, including higher level cognitive functions such as strategy development.

In summary, as a skill transitions from the early to later stages of learning the motor act used to carry out the task is performed more smoothly and with greater efficiency. Some neuroimaging studies report learning to reflect a decrease in neuronal activity; while others report experience-dependent shifts in activity between and within the cortico-cerebellar and cortico-striatal circuitries.

Measuring Motor Skill Learning

A great deal of research has been devoted to assessing the behavioral determinants mediating the phenomenon of motor learning. From this research, has emerged an important distinction between practice effects and learning. Practice effects are commonly measured by tracking behavioral changes across time using performance curves; whereas motor learning involves changes in internal processes and therefore must be inferred using such measures as tests of retention and interference. The following sections provide a brief description of the measures used to assess the behavioral changes associated with practice effects and learning.

Measures of Practice Effects

Practice and repetition of a given movement pattern are essential components to motor learning. Practice effects are thought to represent momentary changes in performance (Schmidt, 2004) and may be used to predict learning (Schmidt & Lee, 2005). Practice effects are traditionally measured using performance curves by tracking the changes that occur in accuracy, reaction time and movement speed.
over the course of many practice trials. Reaction time is a measure of the time from the unanticipated signal to the beginning of the response to it (Schmidt, 1988). Movement time is typically measured as the interval from the initiation of the response to the completion of the response. In sequence skill learning experiments this variable is termed “sequence duration”.

*Measures of Motor Learning*

The relationship between motor practice and motor learning is complex because it cannot be assumed that learning has occurred based on observed practice effects alone. This is because many variables both internally driven and within the learning environment may influence the motor learning process but not become evident within a practice session. For instance, environmental variables that may have an effect on the learning process include differences in practice schedule (massed versus distributed practice), or the type of feedback (intrinsic versus extrinsic). Other variables such as memory, attention and effort are unobservable, internal states of an individual that also play an influential role in the learning process. For instance, practice leads to a decrease in the reliance on attentional recourses as a task is performed with less physical and mental effort. At the same time new memories are forming for that particular task and the learner is developing the capability to maintain the skill in memory. Measures that have sought to capture some of these internal processes associated with learning are discussed below.

*Tests of Retention*

Tests of retention are used in motor learning studies in order to assess the theoretical assumption that practicing a motor skill triggers a process of consolidation. Memory consolidation occurs during motor learning when a memory that is initially encoded into a fragile or unstable state (sensitive to interference) is transformed into a more ‘stable’ state (less sensitive to interference) with the passage of time (Robertson, 2004). Studies have shown that learning a motor skill initially occurs during practice; however the time between practice sessions also allows an opportunity for the memory to stabilize (Karni
et al., 1998; Robertson, 2004; Press Casement, Pascual-Leone, & Robertson, 2005). Consolidation of a motor skill is typically investigated by looking at performance after a retention interval. The most common way of measuring retention is by taking the difference score or “amount” of loss in a skill over a retention interval. It is calculated by measuring the difference in performance levels at the end of a practice period and beginning of the retention interval. Studies have observed retention intervals within time periods ranging from a minimum of five hours of wakefulness (Press et al., 2005) to a 24-hour period including sleep (Walker & Stickgold, 2004) to as long as four weeks (Duff et al., 2007). This formation and stabilization of motor memories has been proposed to be linked to the reshaping of neural responses reflecting a more stable and more effective representation of the movement plan that is resistant to degradation (Fisher, Hallschmid, Elsner & Born, 2002; Jog, Kubota, Connolly, & Graybiel, 1999; Stickgold & Walker, 2007).

*Tests of interference*

The amount of attention allocated to perform a given motor task is often used to determine the degree to which a task is learned in training (Logan & Etherton, 1994). It is assumed that a well-practiced task requires less attentional resources as the skill transitions to a more automatic state. Automaticity is therefore defined as the phenomenon of gradually achieving skilled performance during extended practice with less reliance on attention and other cognitive processes (Schmidt & Lee, 2004; Fitts, 1964). Shiffrin and Schneider (1977) suggested that the strengthening of stimulus-response mapping leading to automaticity of a given task could be achieved through simple, repetitive training. Others have suggested that the process leading to automaticity is more complex and involves task restructuring such as chunking (Graybiel, 1998) or strengthening of memory retrieval (Logan, 1988). Once a skill has become more automatic, attention can be directed to other aspects of performance or to a different task. For this reason, dual task experiments are used in experimental research in order to estimate the ‘amount’ of learning that has taken place (Curran & Keele, 1993; Hazeltine et al, 2002; Logan & Etherton, 1994).
In dual task experiments, a primary task is practiced repeatedly in order to allow automaticity levels to increase so attention can be directed to a secondary task. It is assumed that differences on the learned, primary task that emerge when a secondary task is introduced are a reflection of differences in the level of automaticity achieved on the primary task (Curran & Keele, 1993; Hazeltine et al., 2002; Schumacher et al., 2001). This type of experimental paradigm is especially useful when assessing between-group differences in performance on repetitive tasks where performance has reached a plateau across all participant groups.

One interpretation for why two tasks may interfere with each other when performed simultaneously is due to limitations in some central resource capacity (i.e. attention; Shiffrin & Schneider, 1997). Others claim that a decrement in performance during a dual task experiment is due to the demand from one task requiring processing from the same physical or neurological structure as the secondary task (Keele, 2003; Ahissar, Laiwand, Hechstein, 2001), resulting in a bottleneck phenomenon (Bourk, 1997).

**Effort and Motor Learning**

The amount of effort required to perform a given task will decline with practice. As a result, a skill can be thought of as being relatively “effortless” if it requires little cognitive preparation and a minimum amount of muscle execution (Starkweather, 1987; Ingham et al., 2009). While measures of heart rate or electromyographic activity may be used to track declines in physical effort during practice, cognitive effort is more elusive and must rely on self-judgments of perception rather than objective measures. Subjective measures of effort pose some limitations including the difficulty it is for an individual to differentiate between cognitive-based and physical-based effort. Nonetheless, subjective effort scales have proved useful for measuring performance gains in motor learning and treatment studies (Boberg & Kully, 1994; Oliveira & Kully, 1994). Similar to dual tasks, effort scales are particularly useful when measuring the “amount” of learning on simple, repetitive motor tasks where performance has approached a ceiling or floor over the course of a relatively short practice session. In this case, measures
of effort may be used as a tool for teasing apart individual differences in learning when performance scores show little change across subjects.

Schema Theory

To facilitate an understanding of motor learning, a brief outline of the Schema Theory (Schmidt, 1975; 2003) is presented here. The Schema Theory is unquestionably, one of the most well documented theories of motor learning. As described below, its theory provides a strong rationale for the changes in behavior we observe associated with the processes of motor learning. Although there are other theories of motor control and learning (e.g. dynamical systems theory; Kelso, 1995; Kelso, Saltzman, & Tuller, 1986), including more modern theories such as Bayesian decision theory (BDT; Wolpert, 2007; Wolpert & Flanagan, 2011), the Schema Theory is used because it has been instrumental in the development of the current studies.

Schema Theory assumes that the execution of coordinated movement involves units of action called motor programs. A motor program is an organized set of movement commands that can be organized prior to movement onset (Keele, 1968; Schmidt, 2003). To account for the uniqueness of any given movement, Schema Theory assumes that motor programs are abstract representations of a particular class of actions stored in memory and that specific parameters must be supplied to the program to define exactly how the movement should be executed according to task goals (Schmidt, 2003). For example, a finger tapping task involves basic musculature associated with finger flexion and extension. These combinations of actions are controlled by a general motor program (GMP; Schmidt, 2003). The force and timing of movement as well as the specific muscles to use are governed by the specific parameters chosen.

Following the first attempt at a novel task, an individual briefly stores initial conditions (e.g. current body position), the generated motor commands (e.g. timing and force of the muscles), sensory
consequences of these motor commands (e.g. proprioceptive feedback), and the outcome of the movement (e.g. whether the movement was correct or not). According to the Schema Theory, how this information interacts and the relationship it forms is captured in terms of schemas. Schemas are memory representations that capture the relationship between a given movement and past experiences or trials.

After each movement, the type of information is briefly stored in short term memory and used to update two different types of schemas: recall and recognition schema. The recall schema encodes information about the initial condition, the parameters that were used to execute the movement, and the desired environmental outcome of the movement. Based on the relationship established by past experience, the recall schema is used to select parameters that will be most appropriate at meeting the environmental goal. The recognition schema is important for response evaluation and encodes information about the initial conditions, the sensory consequences of the movement, and the environmental outcomes of the movement. The recognition schema compares the actual and desired sensory consequences and if a mismatch between these two signals occur than the recognition schema’s goal is to update the recall schema. In some cases, the outcome of the movement is not directly available to the individual. In this case, the individual must calibrate the expected sensory consequences with either external feedback (e.g. trainer) or rely on sensory consequences alone so that the recognition schema’s internal error signal can continue to make improvements in performance with future trials. Schema Theory assumes that repetition of a given task will result in a modified motor program that will best meet the task goals.

Schema Theory and Sequence Skill Learning

Schema Theory assumes that when practicing a pre-specified set of incremental units through repetition, they can be strung together and controlled as a single, larger GMP (Schmidt, 1988; Keele, 1968). In this case, it is possible to prepare a single “response” to a sequence involving many movements.
in a rapid succession. Schmidt (1988) described this response as having many parts that are not initiated separately, a process called chunking (Miller, 1956). The notion of “chunking” has been extensively researched and incorporated into several other models of motor programs and learning (Graybiel, 1998; Sakai, Hikosaka, & Nakamura, 2004). Learning of a sequential skill is then reflected by a decrease in the time it takes to recall, plan and execute a motor sequence (Ericsoon, Chase, & Faloun, 1980; Schmidt, 1975). Schmidt (1988) describes the changes in behavior from sequence skill learning using the principles of variability. In this case, with practice, variability within a sequence is considered smaller than the variability between a sequence. Neurological changes have also been reported to occur that are specific to sequence skill learning (Doyon et al., 1998; Doyon et al., 2002; Graybeil, 1999).

Sequencing of actions is used in various everyday tasks from sequencing movements in typing to playing a musical instrument to sequencing sounds in speech. In research, a commonly used sequence skill paradigm includes finger-tapping to a specified number sequence (Doyon et al., 2002; Doyon & Ungerleider, 2002; Karni et al., 1995). In this type of research setting, sequence skill learning can be considered a form of associative learning which involves the acquisition of connections between a stimulus and a response or response chain. It involves the building of new associations from smaller units.

Some examples of sequential skill learning are found in studies by Nissin and Bullemen (1987) and Cohen, Ivry, and Keele (1990) where they asked participants to press one of four keys corresponding to the location of a light displayed on a computer screen. They found significant declines in reaction time when performing a repeated versus nonrepeated pattern. Curran and Keele (1993) proposed the need to create a hierarchical rule set in order to learn a sequence of numbers. For example, “if 3 is after 2, then proceed with 1”; however others have found improvements in reaction time with implicit (i.e. without awareness) sequential learning tasks (Grafton et al., 1995; Krebs et al., 1998) as well.
Speech production in adults involves serial order processing of planned units (phonemes, syllables and words) that when strung together form meaningful sequences (Dell, Burger & Svec, 1997; Levelt, 2001). Therefore, sequence skill learning paradigms used in the laboratory are the closest representation to the motor processes involved in the act of speaking. As a result, the motor learning tasks presented in the following chapters are sequential in nature.

Conclusions

In summary, practice or repetition of a given movement pattern is an essential component to learning. Upon practicing a motor task, an individual’s performance is often characterized by shorter response times and sequence durations as well as more accurate responses. Learning involves a set of internal processes that occur with practice or experience. It results in permanent changes in the capability to respond to a particular task. While practice effects measure the momentary changes in performance and may be tracked using performance curves, learning is not directly observable and must be inferred from measured variables. Retention intervals are frequently used to measure the amount of loss in a skill over time. Measures of attention and effort are also used to measure learning and rely on the theoretical notion that learning results in less reliance on these variables. One prominent theory used to facilitate an understanding of motor learning is the Schema Theory. The Schema Theory assumes that sequential skill learning involves the stringing together of a pre-specified set of incremental units through repetition so that it can be controlled as a single, larger GMP.

The following section describes recent studies that have shown differences in practice and learning in PWS compared to PNS when performing both speech and nonspeech motor tasks. Results from these studies have provided the rationale for the research questions that this dissertation aims to answer.
CHAPTER III

MOTOR PRACTICE AND LEARNING IN PEOPLE WHO STUTTER

Introduction

A number of authors have proposed a motor learning limitation or deficit in people who stutter (e.g. Ludlow, Siren, & Zikria, 1997; Smits-Bandstra et al., 2006b; Namasivayam & Van Lieshout, 2008). This chapter discusses the converging evidence from both behavioral and neurological research that lends support for this assumption. The opening section summarizes evidence stemming from both speech and non-speech motor learning tasks where differences in performance between PWS and PNS are found following practice (Ludlow et al., 1997) and retention (Namasivayam & Van Lieshout, 2008). This is followed by indirect evidence stemming from dual task studies where PWS have showed larger interference effects when performing cognitive, linguistic and motoric tasks (Bernstein Ratner & Sih, 1987; De Nil & Bosshardt, 2001; Webster, 1988). This will lead into converging evidence from neuroimaging studies that have reported neurological differences in PWS compared to PNS in sites related to motor learning. Finally, motor learning as a factor to treatment outcome is briefly discussed. This chapter concludes with the general research questions this dissertation aims to answer.

Motor Practice and Developmental Stuttering

Nonspeech Performance

Using a sequential finger tapping task, Smits-Bandstra et al. (2006a) found that the finger tapping reaction times of PWS and PNS were similar during the initial stages of practice. However, as practice continued, results indicated significant differences in performance curves between groups. In this case, the PWS did not improve in finger tapping reaction times to the same extent as the PNS. Although not significant, a similar pattern for practice was observed between groups for the variable sequence duration. Webster (1986) found that PWS did not show improvements in accuracy compared to PNS when
practicing a 4-element finger tapping sequence task that did not include any repeated elements (e.g. 2-1-4-3).

In a study by Neilson and Neilson (1991), an auditory – motor tracking task elicited a longer delay (phase lag) between trigger stimulus and movement response in PWS for both control (jaw or hand) stimuli. Interestingly, when the experiment was replicated using only subjects who, after practicing for one hour, reached moderate performance criteria, a clear performance difference emerged between groups. The majority (the percentage was not provided) of subjects who were rejected because they failed to meet the performance criteria were PWS.

*Speech Performance*

Similar reduced performance gains in PWS compared to PNS have been observed when practicing speech motor tasks. Cross and Luper (1979) found PWS to be slower at initiating phonation when cued by a tone. Adams & Hayden (1976) found PWS to be slower at terminating phonation, a difference that continued following practice. A more recent study by Smits-Bandstra et al. (2006b) found that when practicing a 10-syllable, nonsense word sequence PWS showed a trend for slower performance gains compared to the PNS for the reaction time and sequence duration data.

Although not strictly a motor learning task, Ludlow et al. (1997) found that PWS were slower to learn the correct production of two, 4-syllable nonsense words and were overall less accurate compared to PNS. Cooper and Allen (1977) also found impairments in the rate of learning in PWS compared to PNS during a repetition task of reading aloud paragraphs and sentences. Children who stutter (CWS) have also shown slow performance gains when compared to fluent speaking children (CNS) when reproducing practiced nonsense syllable sequences that were three or more syllables in length (Bloodstein & Bernstein- Ratner, 2008).
In summary, evidence has suggested that PWS do not benefit to the same extent from practicing speech and nonspeech tasks as PNS. One of the main limitations to the studies described above is that performance gains were observed during a single practice session. Although practice effects can be observed in as little as ten repetitions (Schmidt, 1988), learning cannot be assumed to occur unless more permanent changes in the behavior take place. The following section summarizes the few studies that have directly investigated performance differences between PWS and PNS using tests of retention and interference.

**Motor Learning and Developmental Stuttering**

*Tests of Retention*

Tests of retention are often used to measure whether relatively permanent gains in performance are made following practice. The most common way to measure retention is by calculating the difference score or the “amount” of loss in a skill over a retention interval. There is some evidence suggesting PWS have a reduced ability to retain a novel motor task following a retention period. In a study by Smits-Bandstra et al. (2006a), PWS showed a significant loss in retention for the variable sequence duration when performing a sequential finger tapping task. No significant differences in retention were found when practicing a syllable reading task.

One limitation to the Smits-Bandstra et al. studies described above is that learning related measures were taken within the same day. Although practice effects can be observed in as little as ten repetitions (Schmidt, 1988), sufficient time may not have been provided to allow temporary influences on performance (e.g. fatigue, mood) to dissipate (Schmidt & Lee, 2005).

Using kinematic measures, Namasivayam and Van Lieshout (2008) investigated the differences in PWS versus PNS in their ability to learn and retain bi-syllabic, novel nonword sequences (e.g. “bapi”)
under both habitual and fast speaking rates. The target sequences were practiced during two practice sessions that were divided by a 10 minute break. A third practice session took place following a one week retention period. Results showed less stability and strength in coordination patterns in PWS compared to PNS as well as significant decreases in the strength of inter-gestural frequency coupling between closure and tongue body gestures in PWS at normal, habitual speaking rates following a one week retention period. According to Namasivayam and Van Lieshout (2008), an increase in strength of inter-gestural frequency coupling, which was observed in the PNS, is thought to represent a more stable relationship between speech gestures and is thus indicative of a learned movement pattern, a characteristic not present to the same extent in PWS.

*Speech and Nonspeech Tests of Interference*

Studies assessing the performance of PWS under concurrent task conditions have reported larger interference effects compared to PNS under both speech and nonspeech conditions. Fitzgerald, Cooke and Greiner (1984) asked a group of PWS and PNS to write the numbers one through 12 with both hands simultaneously and as quickly as possible as they performed a spontaneous speaking and reading task. Results showed that PWS had larger differences in organization skills between the dominant and non-dominant hand compared to controls; as well as more reversed numbers and poor organization in non-dominant hand writing. Similarly, during a bimanual handwriting task, Webster (1988) reported poor letter formation quality, slower task execution, and more letter reversals in PWS compared to PNS. Webster interpreted the results to suggest that PWS have fewer processing resources available to perform the dual task to the same extent as PNS.

Webster (1989) assessed PWS’ and PNS’ ability to concurrently tap a number sequence with one hand and turn a knob back and forth 30 degrees with the other hand. Results showed more errors in PWS compared to controls on both tasks when performing under dual task conditions. In a subsequent study,
Webster (1990) compared the performance between PWS and PNS during a bimanual coordination task where they were asked to tap a key twice with one hand for every single tap of a key with the other hand. Results showed significantly slower performance in PWS compared to PNS. Sussman (1982) also found greater disruption in PWS compared to PNS when performing a finger tapping task concurrently with a verbal task. Similar interference effects have been reported in school-age children who stutter (Brutten & Troten, 1986).

In a more recent experiment by Smits-Bandstra et al. (2006b), dual task abilities were assessed between PWS’ and PNS’ as they practiced the same ten number finger tapping task alone and simultaneously with a color recognition task. Results showed that the performance of PWS on the single, finger tapping task was as slow and inaccurate as the performance of the PNS on the dual task. Under dual task conditions, the PNS showed a decrease in response time and accuracy rate due to the added complexity of the task; while the response times remained consistently slow for the stuttering speakers under both the single and dual task conditions. The results of these dual task studies demonstrate a relatively non-progressing performance pattern in stuttering speakers and an impaired ability to reach a level of asymptote.

**Cognitive and Linguistic Tests of Interference**

PWS require more processing capacity when performing dual tasks that include a cognitive and/or linguistic component. Bosshardt, Ballmer and De Nil (2002) asked PWS and PNS to generate sentences from two unrelated nouns while simultaneously performing a rhyming and category decision task. PWS significantly reduced the number of propositions under dual task conditions.

De Nil and Bosshardt (2001) assessed behavioral and neurological differences between PWS and PNS as they performed a simultaneous sentence formulation and rhyming or category decision-making task. Under dual task conditions, PWS showed significantly more errors in rhyming and category decision
making compared to PNS. On the sentence formulation task, PWS produced sentences that contained fewer syllables and were less grammatically complex compared to controls; however there was no difference between groups on the number of words used. Neurological analysis showed an increase in activity in brain regions associated with the early stages of motor learning, suggesting less automatized processing of the speech and language task or perhaps within the motor control system in PWS compared to PNS.

Stuttering Frequency and Tests of Interference

Studies have commonly used stuttering frequency as a measure of the level of difficulty a particular task is for a PWS. This is due to the findings that an increase in stuttering frequency correlates with an increase in task difficulty (Bernstein Ratner & Sih, 1987). Bosshardt (1999) found a significant increase in the frequency of stuttering in PWS when asked to repeat random three-word sequences containing three-syllable nouns (e.g. coconut) concurrently with a mental calculation task of adding three addends (e.g. $23 + 12 + 5$). Greiner, Fitzgerald, and Cooke (1986) found similar results when comparing the performance of PWS and PNS under four conditions including single tapping, or tapping while performing a spontaneous speaking, reading or singing task. Group analysis of PWS showed poor performance as well as an increase in stuttering frequency on the dual finger tapping and spontaneous speaking task; whereas PNS showed no task effects.

Neurological Analysis of Learning Related Differences in Developmental Stuttering

Using fMRI, De Nil and Bosshardt (2001) found a more widespread activation pattern in PWS compared to controls during both a single, sentence generation task as well as a dual, word rhyming and word categorization task. They suggested PWS may have an inability to automatize speech-motor processes effectively as these results are similar to the activation pattern observed during the early practice stages in PNS (Poldrack et al., 2005; Rauch et al., 1997).
Studies assessing the short and long term effects of treatment on changes in neural activity have highlighted potential differences in the motor learning abilities in PWS. In an fMRI study by Giraud et al. (2008), activity in the caudate nucleus correlated with stuttering severity during a speaking task at pre-treatment. That is, those who stuttered more severely showed more activity in the caudate nucleus. The caudate nucleus is observed to play a role in the later stages of sequence skill learning, particularly when maintenance of speed is required (Lehericy et al., 2005). This correlation was absent following participation in a three-week intensive fluency therapy program where they learned techniques such as syllable prolongation and soft voice onset. However, there was no significant correlation between fluency gains due to therapy and an increase in activity in the caudate nucleus, as would be expected considering the role the caudate nucleus plays in sequential motor learning (Gafton et al., 1995; Jueptner et al., 2004; Karni et al., 1995).

In PET studies by De Nil (1998) and De Nil et al. (2003), post-treatment analysis revealed an overall increase in neural activation with a tendency for greater activation in the left hemisphere, compared to the right hemisphere activation observed during pre-treatment analysis. In addition, when subtracting an oral reading task from a verb generation task, similar activations were found between PWS and PNS. In other words, the neurological activity responsible for higher order learning processes was similar between groups, lending support for impairment at the motor planning or execution level. De Nil et al. (2003) also observed an increase in activation in the pre- and post central gyrus, superior temporal gyrus, insula and cerebellum bilaterally, with right hemisphere activations found in the putamen, frontal gyrus and anterior cingulate during a reading and spontaneous speaking task before treatment. Post-treatment scanning revealed a decrease in overall activity with a shift in activity from the right to the left hemisphere. Although Neumann et al. (2003) also found a shift from the right to the left hemisphere following fluency treatment, the hyperactivation prior to treatment became even more widespread after
treatment. At a two year follow-up scan, neurological activity was shown to shift back to the right hemisphere and still remained more widespread than before therapy.

These results suggest that some of the neurological differences that set PWS apart from PNS disappear when PWS gain more control over their fluent speech (De Nil, Kroll, LaFaille & Houle, 2003). However, PWS’ overactivation in cerebral activity compared to controls (De Nil et al., 2003; De Nil & Bosshardt, 2001; Neumann et al., 2003), along with an increase in cerebellar activity (De Nil et al., 2003) at post-treatment scans may reflect a failure to learn a fluency skill to a level in which automatization is achieved. This explanation is plausible considering the learning related activation patterns generally observed in PNS in which a larger extent of activity is observed as the skill is introduced following by an overall decrease in activity as the skill becomes learned (Poldrack et al., 2005; Rauch et al., 1997).

Treatment Effects

Differences in practice effects and learning in PWS compared to PNS may have potential clinical implications regarding the long – term effectiveness of fluency intervention strategies. PWS show a high incidence of relapse, ranging anywhere from 14% to 70% of participants within a year following the participation of a fluency treatment program (Bloodstein & Bernstein Ratner, 2008). Although relapse following treatment has been identified as a crucial area in need of further research (Craig, 1998), studies in this area are sparse. Some research has investigated factors that may predict the long term fluency success following treatment using such variables as stuttering severity, speech attitudes, or locus of control (Craig, 1998; De Nil & Kroll, 1995). A more recent study by Howell and Davis (2011) reported stuttering severity, as measured by the SSI-3, was a significant predictor for the recovery of stuttering when the first assessment was taken at around 8 years of age, a much older age than what has been used in previous studies. However, the treatment program used was relatively short in duration, consisting of only one week of intensive therapy. As a result, it is difficult to predict whether stuttering severity is a potential factor to treatment success or to predicting persistent versus spontaneous recovery. Overall, the
majority of studies have found no single cause for a persons’ failure to maintain a fluency skill (Bloodstein & Bernstein-Ratner, 2008). The previous review of motor and neural characteristics of stuttering in chapter 1, combined with the principles of motor learning and skill maintenance, as well as the evidence of a potential motor learning deficit in people who stutter discussed in this chapter, suggest that the study of motor learning abilities in PWS and the relationship of these abilities to stuttering treatment outcome is a much needed area of research.

Conclusions

Results from behavioral and neuroimaging studies provide converging evidence that PWS possess a limitation or deficiency in their motor learning ability. One limitation to the studies reviewed above is that very few of them were specifically investigating motor learning in PWS. Rather, the primary area of interest was in the allocation of attentional resources, linguistic ability or motor control and evidence of deficient motor learning abilities compared to PNS was indirect. The extent to which such differences relate specifically to motor learning capacities is unclear. Therefore, studies specifically designed to assesses practice and learning – related differences in motor performance between PWS and PNS are warranted.

A second limitation to the studies reviewed is that learning is almost exclusively measured during a single practice session. Whether these differences in practice effects are related to a deficiency in skill learning remains to be seen.

The first objective of this proposal is to investigate whether the reported differences in practice between PWS and PNS during a speech-motor task are representative of a deficiency in motor learning by assessing performance following a retention period. The second objective of this proposal is to assess whether these differences reflect a general deficit in motor learning or if they are specific to the speech-motor system. To do this, a subsequent study will investigate practice effects and learning using a nonspeech task. It is hypothesized that differences in practice effects on both the speech and nonspeech
task will increase following extended practice and a retention period. This will provide evidence for a generalized motor learning deficit. A third objective is to determine whether the proposed deficiency in motor learning may be used as a predictive factor to long term treatment outcome. The relationship between motor learning ability and relapse following treatment is an important issue that has not yet been addressed in the literature.

Therefore, the purpose of this dissertation is to address the following general research questions:

(i) Do PWS differ from PNS in their ability to learn a novel speech sequence skill task given extended practice and a retention period?

(ii) Do PWS differ from PNS in their ability to learn a novel nonspeech sequence skill task when given extended practice and a retention period?

(iii) Is the suspected deficiency in motor learning a predictor to long-term treatment outcome?
CHAPTER IV

SPEECH SEQUENCE SKILL LEARNING IN ADULTS WHO STUTTER

This chapter has been previously published.


Abstract

The present study compared the ability of 12 people who stutter (PWS) and 12 people who do not stutter (PNS) to consolidate a novel sequential speech task. Participants practiced 100 repetitions of a single, monosyllabic, nonsense word sequence during an initial practice session and returned 24-hours later to perform an additional 50 repetitions. Results showed significantly slower sequence durations in the PWS compared to PNS following extensive practice and consolidation. However, the hypothesis that reduced performance gains in PWS compared to PNS during practice would be maintained following a 24-hour consolidation period was not supported. Further descriptive analysis revealed large within group differences in PWS which to some extent were attributed to a subgroup of PWS who failed to show any improvements in performance following practice or consolidation. The results and the possible presence of subgroups of PWS are discussed with regard to their limitations in motor learning abilities.

Introduction

Learning of complex motor skills such as speaking may be affected in people who stutter (PWS; De Nil, 1999b) as evidenced by studies showing that PWS do not benefit to the same extent from practicing speech and nonspeech sequence skill tasks as people who do not stutter (PNS; Ludlow et al., 1997; Neilson & Neilson, 1991; Smits-Bandstra et al., 2006a; 2006b). Based on recent findings of poor motor practice effects in PWS (Smits-Bandstra et al., 2006b), it has been suggested that these findings
may have potential clinical implications regarding the long-term effectiveness of fluency intervention strategies that involve acquiring a novel speech movement pattern such as forming light articulatory contacts or prolonging speech with a high degree of automaticity (Bloodstein & Bernstein Ratner, 2008). One of the main limitations to stuttering treatment programs in general is the high incidence of relapse, ranging anywhere from 14% to 70% of participants within a year following treatment (Bloodstein & Bernstein-Ratner, 2008). Although there is now some evidence to suggest that a deficiency in motor learning may play a role (Smits-Bandstra et al., 2006a) almost all behavioral studies with people who stutter have measured learning—related changes exclusively during single practice sessions. Little is known whether the observed group differences continue following a period of rest or consolidation. If they do, this could point to a deficit in learning rather than just practice-related effects.

*Sequence Skill Learning*

Motor learning involves the interaction between the pre-existing capacities of an individual and the to-be-learned movement pattern (Kelso, 1995). It refers to the ability to acquire the temporal and spatial characteristics of a movement pattern in order that, with practice, muscle execution becomes increasingly dependent on an internal representation rather than external sensory feedback (Schmidt, 2004). Such motor learning is accompanied by a decrease in sensory and attentional demands (Schmidt & Lee, 2005).

Practice or repetition of a given movement pattern is an essential component of learning. Practice effects are traditionally measured using such variables as accuracy, reaction time and sequence duration. Upon practicing a motor task, an individual’s performance is often characterized by shorter response times and sequence durations as well as more accurate responses. Practice effects are thought to represent the momentary changes in performance (Schmidt, 2004) and may be used to predict the relatively permanent consequences of practice (Schmidt & Lee, 2005). Learning, however, cannot be assumed to occur based on practice effects alone as variables in the environment such as fatigue may affect
performance during a single practice session. As a result, learning is not directly observable and must be inferred from measured variables such as whether the improvements from practice transfer to a similar but novel task or whether the performance improvement is retained following a period of rest (Magill, 1998).

*The role of consolidation in motor learning*

Memory consolidation refers to processes by which a motor memory that is initially encoded into a ‘fragile’ state (sensitive to interference) is transformed into a more stable state with the passage of time (Fischer et al., 2002; Robertson, 2004). Memory consolidation does not stop when practice ends but has been shown to continue across hours, days and weeks following the termination of practice (Fischer et al., 2002; Press et al., 2005). For instance, Karni et al. (1995b) found that speed and accuracy of a sequential finger tapping task continued to improve after training had ended and that only a small number of repetitions on the following day were required to initiate further gains in performance. Although the time it takes a skill to stabilize is dependent on many factors (e.g. task difficulty, length of practice), several studies using simple, repetitive motor tasks have shown the stabilization of a motor memory following a relatively short 24-hour rest period (Walker & Stickgold, 2004; Press et al., 2005).

*Motor practice effects in PWS*

Several studies have shown PWS to be slower and less accurate compared to PNS when performing speech-motor tasks. Adam and Hayden (1976) reported that PWS were slower at initiating and terminating phonation when cued by a tone and that this trend continued following practice. Cooper and Allen (1977) found that PWS required more repetitions than control subjects to increase their rate of speech when practicing a repetitive reading task. Similarly, in a study by Ludlow, Siren and Zikira (1997), PWS were slower to learn the correct productions of two, 4-syllable nonsense words and were overall less accurate compared to PNS.
Similar trends in performance have been observed in studies employing nonspeech tasks (Neilson & Neilson, 1991; Smits Bandstra et al., 2006b; Webster, 1986; Weinstein et al., 1989), suggesting that group differences are not limited to the sensorimotor processes involved in speech production. For instance, Webster (1986) found that PWS were slower and less accurate than control participants when practicing a bimanual finger tapping task. Others have shown that group differences remain when stuttering speakers are given time to practice a motor skill (Neilson & Neilson, 1991; Smits-Bandstra et al., 2006a).

In a series of studies conducted by Smits-Bandstra and her colleagues (2006a, 2006b, 2009), PWS’ inability to improve with practice to the same extent as PNS on both a syllable reading and finger tapping task were shown to have an effect on their ability to transition the skill to a more automatic level. Smits-Bandstra et al. (2006a) found that PWS and PNS performed similarly during the initial sets of practice; however as practice continued results indicated a trend for slower reaction times and longer sequence durations in the PWS. In addition, the PWS demonstrated reduced transfer and retention abilities. Although suggestive, these results should be taken with caution as the behavioural measures in this study were taken during a single practice session. This may not have provided sufficient time to allow the temporary influences on performance (e.g. fatigue) to dissipate (Schmidt & Lee, 2005), and the results may have reflected practice rather than learning effects.

Dual task paradigms are commonly used in motor learning research in order to measure the level of automaticity achieved following practice (Magill, 1998; Schmidt, 2004). It is assumed that repeated practice leads to a reduction in cognitive demands, leaving attentional resources available for a secondary task. Smits-Bandstra and De Nil (2009) found that the performance of PWS during a single speech and nonspeech task was as slow and inaccurate as the performance of the PNS during a dual task condition. Under such task conditions, the PNS showed a decrease in response time and accuracy rate on the primary task compared to the single task condition due to the added task complexity of the dual task. However, the
response times remained consistently slow for the PWS regardless of whether they performed under either a single or dual task condition. These results suggest a relatively non-progressing performance pattern in stuttering speakers and may point to an impaired ability to reach automaticity.

*Motor learning abilities in PWS*

One limitation to the studies described above is that performance gains were measured during a single practice session. Although practice effects can be observed in as little as ten repetitions (Schmidt, 1988), learning cannot be assumed to occur unless more permanent changes in the behavior take place. One of the few studies to date that sheds some light on the learning abilities of PWS has been reported by Namasivayam and van Lieshout (2008). In this study, the speed and coordination of lip movements were assessed as participants repeated a set of nonsense words at two different rates (normal and fast) across three test sessions, two on the same day and one at least a week later. Results were similar between PWS and PNS for movement amplitude and duration; however, during same day trials PWS showed less stability and strength in coordination patterns compared to PNS, a difference that remained a week later. PWS but not PNS also showed significant decreases in the strength of inter-gestural frequency coupling following retention at normal, habitual speaking rates.

**Present Investigation and Objectives**

The studies reviewed so far suggest that PWS may have a limited ability to acquire a novel movement pattern as observed in same day practice performance. However, as discussed, such practice effects cannot be considered reliable indicators of learning. Therefore, the present study aimed to investigate directly whether differences in motor practice between stuttering and nonstuttering adults reflect practice effects or point to differences in motor learning capacity. Specifically, it was hypothesized that poor performance gains in PWS compared to PNS during practice would be maintained following a 24-hour consolidation period.

**Methods**
Subjects

Twelve English speaking males who stutter, ranging in age from 23.1 to 40.1 (M = 33.0, S.D. = 6.3) were matched with twelve English speaking males who do not stutter, ranging in age from 22.2 to 39.5 (M = 32.2, S.D. = 5.0). All participants were right handed as measured on the Edinburgh Handedness Inventory (Oldfield, 1971). Only male participants were used in this study because of the predominance of male PWS who stutter and to avoid confounding variables of sex-related differences in performance measures (Fitzgerald, Cooke, & Greiner, 1984). All participants reported a negative history of neurologic, psychiatric, motor or speech and language disorders (other than stuttering in the PWS), or of medications that would impair their motor functioning.

Stuttering participants reported their onset of stuttering in childhood. Based on the SSI-3 (Riley, 1994) stuttering severity of the participants was in the very mild (6), mild (4), moderate (1), or severe (1) range (Table 1). Interjudge reliability measured for 25% of PWS’s reading and speaking samples, and calculated using Cohen’s kappa coefficient, was .98 and .96 respectively. None of the stuttering participants had received fluency treatment in the year prior to participation in this study. All participants provided written informed consent according to procedures provided by the University of Toronto Health Science Research Ethics Committee.

Table 4-1

PWS’ stuttering severity scores using the SSI-4 (Riley, 1994).

<table>
<thead>
<tr>
<th>PWS</th>
<th>Reading (%)</th>
<th>Speaking (%)</th>
<th>Total Overall Scores(severity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>14</td>
<td>20 (mild)</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>10</td>
<td>16 (very mild)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>5</td>
<td>9 (very mild)</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>2</td>
<td>5 (very mild)</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>8</td>
<td>11 (very mild)</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>2</td>
<td>4 (very mild)</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>14</td>
<td>18 (mild)</td>
</tr>
<tr>
<td>8</td>
<td>22</td>
<td>17</td>
<td>32 (severe)</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>4</td>
<td>18 (mild)</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>23</td>
<td>19 (mild)</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>14</td>
<td>12 (very mild)</td>
</tr>
<tr>
<td>12</td>
<td>5</td>
<td>32</td>
<td>25 (moderate)</td>
</tr>
</tbody>
</table>

*Speech sequence task*

A single, monosyllabic, nonsense word sequence, 10 syllables in length, was used as the speech sequence (“baz dob jeb zot gak vud daf bup jeg tup”). Nonsense words were used to minimize the risk of confounding variables from higher order linguistic processing, and also because a meaningful sentence would likely reduce the memory demands placed on motor learning. A consonant-vowel-consonant structure, varying in consonants and vowels, was used in order to provide a closer representation to the complexities of natural speech. Stimuli were derived from the English Lexicon Project (Balota et al., 2007) using a random word generator. The syllables were selected based on the following criteria: (1) the words were orthographically legal and pronounceable but not derived from the root of real words, (2) the
words consisted of a low bi-gram frequency which entail syllables that are the most infrequently used and as a result, must be assembled from smaller units (Levelt & Wheeldon, 1994) and (3) the initial and final position of each word consisted of non liquid consonants (to aid in acoustic analysis).

Procedures

Each participant was tested over two consecutive days. The first day assessed performance effects from practice. Participants were seated comfortably in front of a computer screen. Participants performed 100 repetitions of the speech sequence. They were instructed to “speak as quickly as you can without making mistakes”, and “to begin when the sequence appears on the screen”. In addition, in order to discourage an increase in errors under faster speaking rates, participants were also instructed to “pronounce the beginning and ending of each word”. The 100 repetitions were divided into blocks of 10, each separated by 2 seconds. Each block was preceded by a visual “ready” stimulus presented for 500ms. A five minute rest period was given between block 5 and block 6 during which time an unrelated video was shown.

Participants returned approximately 24 hours after completion of testing on the first day. A 24-hour retention period is frequently used in the motor learning literature as it is considered enough time for a new memory to be consolidated into a stable state and thus become more resistant to further interference (Walker & Stickgold, 2004). Participants in our study were instructed to not practice the sequence in between the testing periods. When returning after the 24-hour rest period, participants performed 50 more repetitions of the same speech task practiced on day one. Again, the repetitions were divided into blocks of 10, with a two second interval between each block. Because only 50 repetitions were used, no extended rest period was provided.

Dependent Variables

The variables used to measure performance gains included accuracy, response preparation time and sequence duration as well as the slope of the line for the variables response preparation time and
sequence duration across blocks. In addition, measures of retention were obtained for the variables accuracy, response preparation time, and sequence duration. These variables are considered strong indicators of motor learning (Schmidt & Lee, 2005). All the participants’ speech sequence productions were video and audio recorded. Accuracy was calculated off-line by the first author based on the audio recordings. It was measured by the number of distortions (e.g. inappropriate devoicing or voicing of phonemes), incorrect substitutions, or missing words for all sequences in day one and day two. For both groups, sequences that contained dysfluencies such as repetitions, prolongations and blocks were excluded from both the total error count and temporal measures as their inclusion would artificially increase the movement duration time for the completed sequences. The percentage of sequences containing dysfluencies for both the PWS and PNS were low, 4.7% (85/1800) and 2.3% (41/1800), respectively. More specifically, out of the 1800 sequences produced by each group, only 85 of the PWS’ sequences and 41 of the PNS’ sequences were excluded due to dysfluencies. A second rater, blind to the conditions of the study, performed a separate error and dysfluency count on the entire sample. Errors and dysfluencies that were not in agreement received a second review by both raters at which time the agreements were resolved.

Response preparation time and sequence durations (to the nearest millisecond) were calculated off-line using the wave form acoustic analysis software PRAAT (Boersma & Weenink, 2001). Response preparation time measurements were taken as the time from the onset of the visual stimulus presentation to the onset of acoustical energy associated with the word-initial stop consonant /b/. Measurements were taken for sequences in blocks 1,2,5,6,9,10 on day 1 and blocks 11, 13, 15 on day 2. Measuring the first, middle, and last sequences of day 1 and day 2 was considered sufficient to gauge the pattern of learning within and between groups.

Sequence duration was measured as the time difference between the onset of acoustical energy associated with the first and final word, respectively. Similar to measuring response preparation time,
measurements were taken for sequences in blocks 1, 2, 5, 6, 9, 10 on day 1 and blocks 11, 13, 15 on day 2. A second rater reanalyzed 10% of the participants’ acoustic waveforms for both response preparation time and sequence duration. Inter-rater reliability for cursor placement within 10ms of the first rater was .96 and .99 for initiation time and sequence duration, respectively.

The slope of the line was measured by the rate of change for sequence duration and response time (Y axis) across blocks (X axis) for day one and day two separately. In regression analysis, this term is the regression coefficient (Portney & Watkins, 2000). Measures of retention were calculated separately for the variables accuracy, response preparation time and sequence duration using the mean performance for PWS and PNS on the final block of practice on day one and the first block of practice on day two.

Statistical Analysis

Practice effects: Two-factor mixed factorial ANOVA

The effects of practice on the variables accuracy, response preparation time, and sequence duration, were assessed for day one (practice) using a 2x6 two mixed factorial ANOVA, and day two (consolidation), using a 2x3 two-factor mixed factorial ANOVA, with Block as the within-group factor and Group as the between-group factor. Similarly, variability measures (SD) for response preparation time and sequence duration on day one and two were assessed using 2 x 6 (day one) and 2 x 3 (day two) two-factor mixed factorial ANOVAs.

Practice effects: Slope comparisons

Slope comparisons were conducted in order to compare the PWS versus PNS with respect to the amount of performance improvement that occurred on day one and day two. Independent sample t-tests were calculated to determine whether the regression coefficients (slopes) were significantly different between the PWS and PNS for the dependent variables sequence duration and response preparation time on day one and day two separately. Accuracy was not compared statistically due to the small number of errors across practice blocks.
Test of retention

Measures of retention were obtained by calculating paired sample t tests for PWS and PNS separately to determine if the mean performance on the final block of practice on day one was significantly different from the first block of practice on day two. Separate analyses, corrected for multiple comparisons, were done for the variables accuracy, response preparation time and sequence duration.

Results

Practice effects

Accuracy

The results for accuracy of the syllable sequence task are shown in Figure 1. The number of errors exhibited by PWS (M = .102, S.D. = .06) was not significantly different from PNS (M = .149, S.D. = .05). Both groups showed a consistently small number of errors across practice blocks. For day one, no significant main effect for Block, F (5, 110) = .228, p = .95 or Group, F (1, 22) = .181, p = .67, was found. Similarly, the Group x Block interaction, F (5, 110) = .455, p = .84, was not significant. On day two neither the main effects for Block, F (2, 44) = 1.95, p = .15 or Group, F (1, 22) = .540, p = .470, nor the Group x Block interaction, F (2, 44) = .54, p = .588, were significant.
Figure 4-1. Mean number of errors for PWS and PNS across day 1 (Blocks 1-10) and day 2 (Blocks 11-15) of practice.

Response preparation time

The mean response preparation times for the variable Block did not differ significantly, $F (5, 110) = .455, p = .711$, nor was there a significant difference between Groups, $F (1, 22) = 2.26, p = .146$. Similarly, the Practice x Block interaction did not reach statistical significance $F (5, 110) = .482, p = .789$. The same was found for day two. Neither the main effects for Block: $F (2, 44) = 1.269, p = .291$, Group: $F (1, 22) = 1.123, p = .302$, nor the Group x Block interaction, $F (2, 44) = .020, p = .980$, reached significance (see Figure 2).

Table 4-2. Mean and standard deviations (in brackets) for accuracy, response preparation time and sequence duration for PWS compared to PNS during the first and last block on day 1 (Block 1 and 10) and day 2 (Block 11 and 15). Total values for both PWS and PNS are also included.
<table>
<thead>
<tr>
<th>Group</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Block 1</td>
<td>Block 10</td>
</tr>
<tr>
<td>PNS</td>
<td>.05 (.112)</td>
<td>.15 (.234)</td>
</tr>
<tr>
<td>PWS</td>
<td>.15 (.162)</td>
<td>.15 (.370)</td>
</tr>
<tr>
<td>Total</td>
<td>.10 (.147)</td>
<td>.15 (.305)</td>
</tr>
</tbody>
</table>

### Response Preparation Time (s)

<table>
<thead>
<tr>
<th>Group</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Block 1</td>
<td>Block 10</td>
</tr>
<tr>
<td>PNS</td>
<td>.305 (.103)</td>
<td>.301 (.150)</td>
</tr>
<tr>
<td>PWS</td>
<td>.401 (.212)</td>
<td>.378 (.217)</td>
</tr>
<tr>
<td>Total</td>
<td>.353 (.170)</td>
<td>.340 (.187)</td>
</tr>
</tbody>
</table>

### Sequence Duration Time (s)

<table>
<thead>
<tr>
<th>Group</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Block 1</td>
<td>Block 10</td>
</tr>
<tr>
<td>PNS</td>
<td>5.31 (1.34)</td>
<td>4.11 (.877)</td>
</tr>
</tbody>
</table>
Sequence Duration

Significant reductions in sequence duration across practice trials for both groups were found on day one, Block: $F(5,110) = 30.845, p < .001, \eta^2 = .584$ and day two, Block: $F(2, 44) = 17.042, p < .001, \eta^2 = .437$ (Table 2). Although both groups benefited from practice, PWS demonstrated significantly slower sequence durations compared to PNS during the initial practice session on day one, Group: $F(1,22) = 4.167, p = 0.05, \eta^2 = .159$ and on day two following the consolidation period, Group: $F(1, 22)$
= 4.373, \( p < 0.05 \), \( \eta^2 = .166 \) (Figure 3). No significant Group x Practice interaction was found for day one, \( F(5, 110) = .808, p = .546 \) or day two, \( F(2, 44) = 1.450, p = .246 \).

Figure 4.3. Mean sequence durations (s) for PWS compared to PNS during Day 1 (Block 1-10) and Day 2 (Block 11-15) of practice.

*Individual differences in sequence duration*

Although similar learning curves were demonstrated between groups, descriptive graphic analysis of individual measures of sequence duration (Figure 4) revealed higher variability in the PWS than PNS. As a result, a k-mean clustering (Portney & Watkins, 2000) was performed in order to identify subgroups with similar sequence durations. Results showed 8 PNS and 4 PWS who performed faster than the overall mean sequence duration while 4 PNS and 8 PWS performed slower than the overall mean sequence
duration. In addition, it appeared visually that performance gains (the difference from the first block on day one to the last block on day two) were associated with participants’ initial performance level on day one. In other words, among the PNS, those who performed more slowly during the initial practice trials on day one showed the most performance gains. Alternatively, those who performed relatively fast during the initial practice trials appeared to have less room for improvement and thus showed the least performance gains. This trend, however, was not evident in a subgroup of PWS. Instead, four out of the 12 PWS demonstrated very little improvement in performance (< 1s), despite showing an average to slow performance (between 5-7 s) during the initial practice session. There was no obvious relationship between the participants in this subgroup for either age or stuttering. In addition, this particular subgroup of PWS did not show poor practice effects and learning in either response preparation time or accuracy.
Figure 4.4. Individual differences in practice for sequence duration (s) for PWS compared to PNS. Individuals’ mean sequence duration (ms) for the first block of practice (x axis) is compared to the difference between the first and last block (y axis) of practice. Weighted points represent a subgroup of PWS who failed to show any improvement in performance.

Variability

Response preparation time

A significant Group main effect (Table 3) indicated more variability in PWS compared to PNS, Group: $F(1, 22) = 4.244, p = .05, \eta^2 = .162$ (Figure 5) on day one of practice. However, this trend did not continue on day two, Group: $F(1, 22) = 2.683, p = .116$, where both groups maintained a consistent degree of variability across practice trials. As a result, no significant Block ($F(5, 110) = 1.302, p = .268$) or Group x Block ($F(5, 110) = 1.338, p = .254$) interaction was found for day one. The same was true for day two, for Block, $F(5, 110) = 1.765, p = .183$ and Group x Block, $F(5, 110) = .292, p = .748$.

Sequence Duration
Both groups showed a decrease in variability in sequence duration during the first day of practice, Block: $F(5, 110) = 10.336, p < .001, \eta^2 = .320$; however this trend did not continue following the 24-hour consolidation period, Block: $F(5, 110) = 2.429, p = .100$ (Figure 6). No significant Group main effect (day one: $F(1, 22) = .006, p = .938$; day two: $F(1, 22) = 2.884, p = .104$) or Group x Block interaction (day one: $F(5, 110) = .549, p = .738$; day two: $F(5, 110) = .045, p = .957$) was found for either of the two testing days.
Figure 4.5. Variability (S.D.) for response preparation time (s) for PWS compared to PNS across practice trials on day 1 (Blocks 1-10) and day 2 (Blocks 11-15).
Figure 4.6. Variability (S.D.) for sequence duration (s) for PWS compared to PNS across practice trials on Day 1 (Blocks 1-10) and Day 2 (Blocks 11-15).

Table 4.3. Standard deviations (s) for response preparation time and sequence duration for PWS and PNS during the first and last block on day 1 (Block 1 and 10) and day 2 (Block 11 and 15). Total values for both PWS and PNS are also included.
### Sequence Duration

<table>
<thead>
<tr>
<th>Group</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block 1</td>
<td>Block 10</td>
<td>Block 11</td>
</tr>
<tr>
<td>PNS</td>
<td>.176 (.097)</td>
<td>.136 (.052)</td>
</tr>
<tr>
<td>PWS</td>
<td>.191 (.115)</td>
<td>.193 (.118)</td>
</tr>
<tr>
<td>Total</td>
<td>.184 (.105)</td>
<td>.165 (.094)</td>
</tr>
</tbody>
</table>

### Practice effects: Slope comparisons

Because the statistics used to evaluate group differences may have obscured trends in continuous data, the slopes of the performance curves in both groups were compared statistically. The slopes for response preparation time on day one for PWS (\(M = -.052, \text{S.D.} = .30\)) did not significantly differ from those for the PNS (\(M = -.005, \text{S.D.} = .28\), \(t(22) = .388, p = .702\)). Similarly, no differences were found for day two (PWS: \(M = -.022, \text{S.D.}=31\); PNS: \(M = -.124, \text{S.D.} = 257\), \(t (22) = -.877, p = .39\)). For sequence duration, the performance slopes also did not differ significantly between groups. In this case, the mean slope of PWS on day one (\(M = -.582, \text{S.D.} = .27\)) did not significantly differ from that of PNS (\(M= -.564, \text{S.D.} = .27\)).
S.D. 34), t(22) = .147, \( p = .884 \). Neither did the slopes on day two (PWS: \( M = -.404 \), S.D. = 43, PNS: \( M = -.378 \), S.D. = .46 (t(22) = .143, \( p = .88 \)).

Test of retention

Errors did not change across the 24-hour consolidation period for PWS, t (11) = .364, \( p = .723 \), or PNS, t (11) = 2.31, \( p = .032 \). Improvements in response preparation time were maintained across the 24-hour consolidation period as differences were insignificant for both PWS, t (11) = -.582, \( p = .572 \) and PNS, t (11) = -.883, \( p = .392 \). Both PWS and PNS showed the ability to maintain their improvements in sequence duration from day one to day two as differences were not statistically significant for either group, t (11) = -.461, \( p = .654 \), t (11) = 1.38, \( p = .194 \), respectively (Table 2).

Discussion

Motor learning differences

The current findings do not support our main hypothesis that poor practice effects and learning occur in PWS compared to PNS as there were no statistically significant interactions between group and practice for accuracy, response anticipation time or sequence duration on day one or day two. Despite slower sequence durations compared to the PNS, PWS did show an improvement in performance with practice and after consolidation. Also similar to PNS, PWS showed the ability to retain what they had learned for all measured variables on day one and following a 24-hour consolidation period. In this case, both groups essentially “picked up” where they left off on day one. PWS have been shown to demonstrate performance gains with practice (Cooper & Allen, 1977; Smits-Bandstra & De Nil, 2009). There is even evidence to suggest that improved fluency as well as an increase in speech rate from repeated readings, a process referred to as the adaptation effect, is a result of practicing articulatory and phonatory motor processes (Max, Caruso, & Vandevenne, 1997; Max et al., 2003; Max & Baldwin, 2010; Wingate, 1986). For example, Max & Caruso (1998) found that as participants continually read a passage, a decrease in stuttering was observed, along with an increase in articulation rate as well as a decrease in word duration,
vowel duration and CV transition extent. A more recent study by Max and Baldwin (2010) found that fluency improvements with repeated readings were retained following a 24-hour consolidation period in 6 out of the 10 participants.

However, our findings indicated that even following a relatively large number of practice trials on day one and retention on day two, PWS did not reach the speed in sequence duration observed in PNS. Also, descriptive analysis showed that PWS’ performance was similar to PNS during the initial trials, with group differences emerging as practice continued (see Figure 3). Smits-Bandstra et al. (2006a) found similar results using a finger tapping task where group differences in sequence duration became apparent with practice. These results, along with several other studies employing speech (Ludlow et al., 1997; Smits-Bandstra & De Nil, 2009) and nonspeech (Neilson & Neilson, 1991; Smits-Bandstra et al., 2006a) tasks have suggested possible limitations in PWS’ motor learning abilities. A more complex paradigm involving a second, interfering task may help in teasing apart motor learning differences among groups.

Motor skill limitations

Our findings of significantly slower sequence duration between PWS and PNS support the observation that group differences not only occur in nonspeech movement tasks (Smits-Bandstra et al., 2006b; Webster, 1986), but extend into the speech-motor system as well (Smits-Bandstra et al. 2006b). While Smits-Bandstra, et al. (2006b) only found a non-significant trend, group main effect differences in our study were statistically significant, which most likely resulted from using a somewhat more complex speaking task.

More importantly, findings from the present investigation demonstrated that sequence duration differences between groups continued following a relatively large number of practice trials as well as after a consolidation period. One explanation for such findings may be that slower sequence durations in PWS reflect a motor skill limitation (De Nil, 1999a; Van Lieshout et al., 1995). According to Schmidt & Lee (2005), a skill is considered a learned movement that requires practice in order to master. Like any
motor skill, speaking falls along a skill continuum and the motor skill abilities of PWS may be posited to fall at the lower end of this continuum (Van Lieshout, 2004). It is possible that the relatively high task demands of speaking “as quickly as you can without making mistakes”, allowed for these limitations in their speech motor skill to surface. However, this remains speculative as the current study did not compare performance on tasks varying in complexity nor did it demand the speakers to produce the speaking task at varying speaking rates (slow versus fast).

Namasivayam and van Lieshout (2008) conducted a study in which tasks varied in complexity. In this study, significantly larger movement amplitudes of upper lip movement in PWS compared to controls were reported following the practice and consolidation of a set of non-words at both slow and fast speaking rates. An alternative explanation provided by these authors was that performance differences may reflect a motor control strategy used to maintain stability. In this case, the speaker is likely to exhibit fluent speech with fewer errors when the demands placed on the speech-motor system do not exceed the individuals’ capacities. In this case maintaining a relatively slower speed of movement (sequence duration) may have been a mechanism used to optimize processing of sensory information (De Nil & Abbs, 1991; De Nil, 1999a; Loucks & De Nil, 2001; Van Lieshout et al., 2004). Support for this assumption can be found in the present study by the fact that even the PWS who scored in the severe range on the SSI remained relatively fluent (only 4.7% of sequences containing dysfluencies) across practice trials.

However, this interpretation seems less likely based on a number of observations. First, in previous research using almost identical but nonspeech motor tasks (finger tapping), very similar differences in practice effects between stuttering and nonstuttering adults have been observed. Unless one assumes that people who stutter use the same cautious strategy during speech as well as nonspeech tasks, it would seem that the most parsimonious explanation for the observed changes in behaviour is that they are related to practice and learning rather than a voluntary strategy in one but not the other task. Secondly,
the reading adaptation effect in stuttering, which is a result of practice (Max & Baldwin, 2010), would lead one to expect that the frequency of stuttering will reduce following repeated readings of the syllable sequence, thereby decreasing the duration of the sequence readings. Nevertheless, the question whether difference in task performance in people who stutter compared to their fluent controls are reflective to some extent of underlying sensorimotor processes is a very intriguing one that deserves further investigation.

*Individual differences in sequence duration*

When individual differences in sequence duration were analyzed descriptively, it became apparent that large within group differences in PWS, to some extent, could be attributed to a subgroup of PWS who failed to benefit from practice or consolidation. More specifically, 33% of PWS showed a lack of improvement in speech sequence duration following practice and consolidation (Figure 4), despite exhibiting relatively average – to – slow performance on the initial practice trials. Only one PNS showed a similar lack of improvement following practice and consolidation. The remaining group of PNS improved in their performance from block one to block 15. It is important to note that three out of the 12 PWS showed the largest amount of improvement out of all the participants following practice (Figure 4). This may explain why there was no statistically significant interaction between group and practice for the variable sequence duration. These findings suggest, however, that some but not all PWS show an inability to improve their performance when given practice and consolidation. While this descriptive finding raises some interesting questions, for instance with respect to treatment outcome variability, further research using larger sample sizes is needed to investigate whether or not these identified subgroups represent a true differentiation among adults who stutter or are an incidental observation in the current study.

Some indirect support that the present observations may point toward a true subgroup difference comes from a number of studies in which similar subgroups of PWS have been identified (Ludlow et al., 1997; Neilson & Neilson, 1991; Smits-Bandstra, De Nil, & Saint-Cyr, 2006b). For instance, Smits-
Bandstra et al. (2006b) reported that a third of the PWS showed a performance pattern similar to PNS while the others varied in performance. Ludlow et al. (1997) found that two out of the five PWS were unable to learn the correct production of the target nonsense words, even when given extended practice.

Conclusions

The results from the current study provide partial support for previous findings of performance differences between PWS and PNS when practicing a novel speech-motor task (Cooper & Allen, 1977; Ludlow et al., 1997; Smits-Bandstra et al., 2006b). The present investigation extended these findings by demonstrating that some group differences remain following more extensive practice and after a 24-hour consolidation period. Other hypotheses that motivated the present study, particularly the hypothesis that poor performance gains observed during practice for the PWS group would be maintained following a 24-hour consolidation period, were not supported. While the findings of the present study need to be confirmed in future studies, preferably using larger sample sizes to confirm the presence of potential subgroups among adults who stutter, results may be indicative of the presence of difficulties in motor learning, at least in a subgroup of the stuttering population. Future research is also needed to determine whether the current findings are linked to age of onset, stuttering severity, or other factors. The conclusions from such research could have important clinical implications as it may contribute to the identification of potential risk factors or predictors of stuttering development. It also may shed further light on which factors affect relapse following fluency treatment.
CHAPTER V

NONSPEECH SEQUENCE SKILL LEARNING UNDER SINGLE AND DUAL TASK CONDITIONS IN ADULTS WHO STUTTER

This chapter has been submitted for publication.


Abstract

The present study compared practice effects and learning abilities in 11 persons who stutter (PWS) and 12 persons who do not stutter (PNS) using a finger-tapping task under single and dual task conditions. Sequence skill learning was measured by comparing PWS’ and PNS’ performance curves of accuracy, reaction time, and sequence duration. In addition, measures were obtained for retention of skill as well as interference effects during dual task conditions. For reaction time and sequence duration data, results showed that PNS’ performance reached a relative plateau in performance while PWS’ continued to show improvements well into practice on day two. Tests of retention showed that PWS were able to retain the practiced task following a retention period for the variables accuracy and sequence duration but not reaction time. Although no significant interactions were found for tests of condition, additional assessment showed significantly larger differences in finger tapping performance in PWS compared to PNS when transitioning from the single to dual task condition. The implications of the observed learning differences for our understanding of stuttering as well as intervention are discussed.
Introduction

Many stuttering treatment programs involve acquiring novel speech motor patterns such as prolonging speech or forming light articulatory contacts. Clinical strategies such as these emphasize the importance of practice with the goal of reducing the attentional demands required to monitor the new fluency technique. Central to such approaches to treatment is the clients’ ability to transition the newly learned speaking pattern to a sufficiently high level of automaticity so that they can be executed effortlessly in natural speaking situations. A number of studies have suggested however that people who stutter (PWS) may perform poorer on tasks of motor learning compared to people who do not stutter (PNS). In particular, these studies have demonstrated lower performance gains in PWS compared to PNS when practicing speech or nonspeech tasks (Ludlow et al., 1997; Neilson & Neilson, 1991; Smits-Bandstra, De Nil & Saint-Cyr, 2006a; Smits-Bandstra, De Nil, Rochon, 2006b). Using a speech task, Bauerly & De Nil (2011) and Namasivayam & van Lieshout (2008) have shown that these group discrepancies appear to be maintained even following extended practice and retention, which may suggest impaired motor learning abilities among PWS (Bauerly & De Nil, 2011). Little is known, however, about the ability of PWS to automatize a nonspeech motor pattern when given time to practice and consolidate the new skill. Exploring such motor learning abilities in PWS may lend important contributions to our understanding of stuttering as a general motor control deficit.

Motor practice and motor learning

Practice and repetition of a given movement pattern is an essential component of motor learning. Motor practice effects are thought to represent the momentary changes in performance (Schmidt, 2004) and may be used to predict learning (Schmidt & Lee, 2005). Practice effects are traditionally measured using such variables as accuracy, reaction time and sequence duration (Magill, 1998; Schmidt & Lee, 2004). Studies
have shown that practicing a repetitive, sequence skill results in an initial, steep learning curve followed by a plateau where little improvement in performance takes place (Karni et al., 1998; Quesada & Schmidt, 1970).

Motor learning, on the other hand, involves internal processes associated with acquiring a novel motor skill through practice or experience. Internal processes may include morphological changes in the central nervous system such as an increase in dendritic branching or an increase in synaptic connections between neurons (Rose, 1997). Motor learning involves the interaction between the pre-existing capacities of an individual and the characteristics associated with the to-be-learned movement pattern. For example, variability among individuals in the rate of learning a repetitive finger tapping task may reflect the number of hours they spend a week typing or playing a musical instrument such as the piano. In this scenario, each person brings their previous experiences into the learning paradigm. When practicing a novel movement pattern, muscle execution is thought to rely less on attention and sensory feedback as the development of an internal memory representation of the acquired skill if formed. The movement is then executed with less variability and greater accuracy (Schmidt & Lee, 2005).

The relationship between motor learning and motor practice is complex because it cannot be assumed automatically that learning has occurred based on observed practice effects alone. Indeed, the latter may be influenced also by variables in the environment such as fluctuations in attention, fatigue or mood (Magill, 1998; Schmidt, 2004). Although motor learning occurs as a result of motor practice, the learning process itself is internal and cannot be directly observed (Schmidt, 2004). Instead, learning is assumed to have occurred if the following two conditions apply: (1) performance improvements are retained following a retention (consolidation) period and (2) performance is resistant to interference by a secondary (dual) task (Schmidt & Lee, 2005). These two conditions will be discussed in more detail in the following sections.
The role of consolidation in motor learning

Memory consolidation occurs during motor learning when a memory that is initially encoded into a fragile or unstable state (sensitive to interference) is transformed into a more ‘stable’ state (less sensitive to interference) with the passage of time (Robertson, 2004). Studies have shown that learning a motor skill initially occurs during practice; however, the time between practice sessions also allows an opportunity for the memory to stabilize (Karni et al., 1998; Robertson, 2004; Press Casement, Pascual-Leone & Robertson, 2005). Consolidation of a motor skill is typically investigated by looking at performance after a retention interval. Studies have observed this time period to range from a minimum of five hours of wakefulness (Press et al., 2005) to a 24-hour period including sleep (Walker & Stickgold, 2004). This formation and stabilization of motor memories has been proposed to be linked to the reshaping of neural responses reflecting a more stable and more effective representation of the movement plan that is resistant to degradation (Fisher, Hallschmid, Elsner & Born, 2002; Jog, Kubota, Connolly & Graybiel, 1999; Stickgold & Walker, 2007).

Attentional resources and automaticity

The initial attempts at performing a motor task involve adjusting movement parameters based on information provided by sensory feedback in order to produce accurate movements (Doyon & Ungerlieder, 2002). At the same time, relevant task-specific components previously learned and stored in memory are selected and used for solving the task (Karni et al., 1998). These early motor learning processes require a high degree of attention as the main goal at this stage is to link sensory representations of the environment to muscle control signals (Baddely, 2003; Fitts, 1967).
With practice, the learner becomes less dependent on sensory input as the development of a new pattern begins to emerge from what was once an initial repertoire of subroutines (Fitts & Posner, 1967). The learner has begun to integrate the appropriate sensory cues in order to produce planned, goal-directed movement. At this stage of learning, less attention is needed for that task and attentional resources can be directed toward other operations (Fitts & Posner, 1967).

Automaticity is a measure of the amount of attention required for a particular task. It is assumed that a well-practiced task requires less attention and thus allows the freeing up of attentional resources for other tasks. As a result, such tasks are less likely to show interference from other, competing tasks. For this reason, dual task experiments are commonly used to estimate the ‘amount’ of learning that has taken place (Curran & Keele, 1993; Hazeltine, Teague & Ivry, 2002; Logan & Etherton, 1994). This type of experimental paradigm is especially useful when assessing between-group differences in performance on repetitive tasks where performance has reached a plateau across all participant groups. It is assumed that changes in between-group differences on the learned, primary task, that emerge when a competing secondary task is introduced, are a reflection of differences in the level of automaticity achieved by each group for the primary task (Curran & Keele, 1993; Hazeltine, Teague, and Ivry, 2002; Schumacher et al., 2001).

*Motor practice effects in PWS*

Results from several previous studies have suggested that PWS are slower and less accurate compared to PNS when practicing a speech (Ludlow, Siren and Zikira, 1997; Smits-Bandstra et al., 2006b) and nonspeech (Namasivayam and van Lieshout, 2008; Smits-Bandstra et al., 2006a) motor task. Bauerly and De Nil (2011) tracked performance between PWS and PNS as they performed 100 repetitions of a nonsense syllable sequence. Although there were no significant differences between groups on any of the measured variables, descriptive analysis showed that PWS’ performance was similar to PNS’ during the
initial practice trials with group differences in the speed of movement emerging as practice continued. Similarly, Smits-Bandstra et al. (2006b) observed that PNS perform a repetitive syllable reading and finger tapping task more quickly with practice compared to PWS. Ludlow (1997) also showed that PWS were slower to learn the correct productions of two, 4-syllable nonsense words and were overall less accurate compared to controls.

In a study by Neilson and Neilson (1991), an auditory-motor tracking task elicited a longer delay (phase lag) between trigger stimulus and movement response in PWS for both control (jaw or hand) stimuli. Interestingly, when the experiment was replicated using only subjects who, after practicing for one hour, reached a moderate performance criterion, a clear performance difference emerged between groups. The majority (a percentage was not provided) of subjects who were rejected because they failed to meet the performance criteria were PWS.

Motor learning abilities in PWS: Tests of retention

One limitation to the studies described so far is that learning related measures were obtained during a single practice session. Although practice effects can be observed in as little as ten repetitions (Schmidt, 1988), it may not provide sufficient time to allow the temporary influences on performance (e.g. fatigue) to dissipate (Schmidt & Lee, 2005). As a result, these studies only demonstrated group differences in practice effects while leaving motor learning abilities largely unexplored.

Some studies have demonstrated that PWS show a reduced ability to retain a novel motor task following a rest period (Namasivayam and van Lieshout, 2008; Smits-Bandstra et al., 2006b). In the study by Smits-Bandstra et al. (2006b) differences in motor learning of a novel finger tapping and syllable reading task were assessed by observing difference in group performance following a 40 minute rest period. Response time data for the finger tapping and syllable reading data showed that PWS were not able to retain what they had learned to the same extent as controls. On the contrary, using a similar sequential
syllable reading task, Bauerly and De Nil (2011) found that PWS and PNS were able to retain what they had learned for all measured variables (accuracy, reaction time, and sequence duration) following a 24-hour consolidation period. Results from this study suggest that PWS may benefit from extended practice as 100 repetitions of the speech task were required, as opposed to the 30 repetitions in Smits-Bandstra et al. (2006b).

Using kinematic measures, Namasivayam and Van Lieshout (2008) reported differences in retaining a set of nonsense words that were practiced at two different rates (normal and fast) across three test sessions; two on the same day and one at least a week later. Results showed less stability and strength in coordination patterns in PWS compared to controls as well as significant decreases in the strength of inter-gestural frequency coupling (between closure and tongue body gestures) in PWS at normal, habitual speaking rates following a one week retention period. According to Namasivayam and Van Lieshout (2008), an increase in the strength of inter-gestural frequency coupling, which was observed in the PNS, is thought to represent a more stable relationship between speech gestures and thus indicative of a learned movement pattern, a characteristic not present to the same extent in PWS.

Motor learning in PWS: Interference effects

Studies assessing the performance of PWS under concurrent task conditions have reported larger interference effects compared to PNS. When performing a simultaneous finger-tapping and spontaneous speaking task, Greiner, Fitzgerald and Cooke (1986) reported that PWS were slower and made more errors on the primary, finger-tapping task. The PWS also demonstrated an increase in stuttered speech on the competing speaking task. Sussman (1982) also found greater disruption in PWS compared to PNS when performing a finger tapping task concurrently with a verbal task. Similar interference effects have been reported in school-age children who stutter (Brutten & Trotter, 1986).
Other studies have found that PWS require more processing capacity when performing dual tasks that involve the speech-planning system (Caruso, Chodzko-Zajko, Bidinger & Sommers, 1994; Bosshardt, Ballmer & De Nil, 2002). In a study by Bosshardt (2002), participants were required to generate sentences from two unrelated nouns while simultaneously performing a rhyming and category decision task. PWS significantly reduced the number of prepositions under dual task conditions, whereas PNS did not show a difference between single and dual task conditions. The influence of secondary tasks has also been shown to have an effect on the frequency of stuttering (Arends, Povel & Kolk, 1988; Bosshardt, 1999, 2002; Caruso et al., 1994; Greiner et al., 1986). For instance, Bosshardt (2002) found a significant increase in stuttering frequency during a word repetition task when similar words were read concurrently. Results such as these suggest that PWS exhibit greater sensitivity to interference when performing dual tasks.

As previously discussed, dual task paradigms are commonly used in motor learning research in order to measure the level of automaticity achieved following practice (Magill, 1998; Schmidt, 2004). Smits-Bandstra et al. (2006a) compared 12 PWS and 12 PNS when practicing a repetitive, finger-tapping sequence either alone or simultaneously with a color recognition distracter task. They reported that PWS showed a slower and more variable performance in both the single and dual task conditions compared to PNS. In addition, PWS showed significantly more errors on the color recognition distracter task, which according to the authors, suggested that PWS showed difficulties in transitioning a newly practiced motor skill to the same level of automaticity as PNS.

Present Investigation and Research Questions

All dual task experiments discussed above were based on observation of task performance during a single practice session, and little is known about PWS’ ability to learn and automatize a motor task when given more time to practice and consolidate the skill. A nonspeech task was employed in the present study because previous studies (Smits-Bandstra et al., 2006b) have shown similar practice effects for speech and
non-speech task. A non-speech task would allow us to determine if differences in PWS reflect a more generalized deficit in motor learning.

Therefore, the present investigation aimed to assess the abilities of PWS and PNS to practice and learn a sequential finger-tapping task during a practice session and following a 24-hour consolidation period. As discussed earlier, for the purpose of the present study, motor learning was defined as (1) the ability to consolidate (retain) improvements in performance following a 24-hour period and (2) the ability to perform the finger-tapping task more automatically in the presence of a concurrent competing task (interference). The following three research questions were addressed:

1. Do PWS demonstrate poor performance compared to PNS following practice under single and dual task conditions?

2. Do PWS, compared to PNS, demonstrate a reduced ability to retain the sequential, nonspeech task following a 24-hour rest period?

3. Do PWS show a reduced ability to automatize the sequential, nonspeech task compared to PNS by demonstrating greater interference when performing under dual task conditions?

Methods

Subjects

Eleven right-handed English speaking males who stutter, ranging in age from 23.1 to 40.1 years \((M = 33.4, \text{S.D.} = 6.4)\) and 12 English speaking males who do not stutter ranging in age from 22.2 to 41.1 years \((M = 33.2, \text{S.D.} = 5.2)\) participated in this study. The age between the two groups was not significantly different, \(t(21) = .635, p = .917\). One PWS failed to perform the experimental task correctly.
due to hand cramping and his data was excluded from the analysis, leaving 11 PWS. All participants were right handed as measured by a minimum score of 9/10 ($M = 9.25$, S.D. = .25) on the Edinburgh Handedness Inventory (Oldfield, 1971). Only male participants were asked to participate in this study because of the predominance of males who stutter and to avoid confounding variables of sex-related differences in motor performance measures (Fitzgerald, 1984). Based on their self-rated typing skills, groups’ speed of typing was comparable and ranged from slow (3), average (6), fast (10) to very fast (4). No participants self-reported to play a musical instrument or were professional typists. Ten PWS and 11 PNS earned a college education and one PWS and one PNS reported a high-school education. All participants indicated a negative history of neurologic, psychiatric, motor or speech and language disorders (other than stuttering), and were not taking medications that could impair their motor functioning at the time of testing. All participants passed a pure tone hearing screening at 250, 500, 1000, 2000, and 4000Hz frequencies. In order to test for possible group differences in working memory, all subjects completed the Letter-Number Sequencing test of working memory from the Wechsler Adult Intelligence Scale (WAIS-III; Weschler, 1997). No significant between-group difference were found (PWS: $M = 14.82$, S.D.= 2.6; PNS: $M=13.42$, S.D. = 2.5), $t (21) = .093$, $p = .156$.

All stuttering participants reported an onset of stuttering in childhood. Based on the SSI-3 (Riley, 1994), stuttering severity of the subjects in this study varied from very mild to severe (Table 1). Interjudge reliability measured for 25% of PWS’ conversation and reading samples, calculated using Cohen’s kappa coefficient, was .92 and .90, respectively. Intrajudge reliability (Kappa coefficient), calculated for 10% of participants conversation and reading samples, was .97 and .96, respectively. Participants had not received treatment for their stuttering for at least one year prior to participation in this study.

Participants provided written informed consent according to the protocol approved by the University of Toronto Health Services Research Ethics Committee.
Table 5.1

PWS’ stuttering severity and overall scores using the SSI-4 (Riley, 2004).

<table>
<thead>
<tr>
<th>PWS</th>
<th>Reading (%)</th>
<th>Speaking (%)</th>
<th>Total Overall Scores(Severity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>2</td>
<td>10 (very mild)</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>10</td>
<td>18 (mild)</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>9</td>
<td>11 (very mild)</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>5</td>
<td>10 (very mild)</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>8</td>
<td>11 (very mild)</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>14</td>
<td>18 (mild)</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>5</td>
<td>9 (very mild)</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>4</td>
<td>18 (mild)</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>23</td>
<td>19 (moderate)</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>14</td>
<td>12 (mild)</td>
</tr>
<tr>
<td>11</td>
<td>14</td>
<td>25</td>
<td>32 (severe)</td>
</tr>
</tbody>
</table>
Tasks and procedures

Participants performed a finger-tapping task either as a single task or simultaneously with a tone monitoring task. The single (finger-tapping) and dual (finger-tapping and tone monitoring) task conditions were administered in a fixed interleaved design for all participants, similar to Smits-Bandstra et al. (2006a).

Finger tapping sequence task

A ten-number sequence (1 3 2 4 1 4 2 3 1 2), derived from a random number generator in Excel (Microsoft, Inc.), was visually displayed on a computer monitor and repeated across practice trials on day one and day two. The numbers in the sequence ranged from one to four and each corresponded with one of four horizontally arranged buttons on a response box (Cedrus 610, Superlab Inc.). The motor sequence typing task was designed similar to the one used in Smits-Bandstra et al. (2006a). No number triplet was used more than once, no number pair was used consecutively (e.g. 1 4 1 4), and every number was used two or three times per sequence.

Subjects were asked to reproduce the visually presented number sequence by pressing the four buttons on the response box in the correct order using the fingers of their dominant right hand. Participants placed their index finger on the left most button (button 1), middle finger on button 2, etc. The response box was shielded from view for the subjects in order to prevent visual feedback. Participants were instructed to “type as fast as you can without making mistakes” and to “begin as soon as the sequence appears on the screen”.

During the finger tapping single task, subjects were presented with a visual signal (“ready”) followed by an interstimulus interval (ISI) (randomly varying between 1.0, 2.0, or 3.0 seconds) to minimize anticipation effects on reaction time. Next, participants were presented with the number
sequence displayed horizontally in the middle of a computer screen and printed in black. The numbers remained on the screen for as long as it took the participants to complete the sequence. Completion of the last number in the sequence triggered a new “ready” signal and a new ISI interval, after which the sequence was displayed again.

*Tone monitoring task*

For the dual task, participants were presented with the same finger tapping task described above but with a tone monitoring task presented simultaneously with the onset of the number sequence. Because the focus of the present study was on the interference effects of the tone task when performed simultaneously with the finger tapping task, the tone task was not presented as a single task. The task involved a sequence of four different tones (250Hz, 500Hz, 1000Hz, 2000Hz), each being presented for 250 ms through a headset, for a total sequence duration of 1 second. The tone sequences were presented at the same time that the number sequence appeared on the screen. The tone sequences were presented as either a repeating or non-repeating sequence. For the repeating sequence, one of the four tones was repeated (e.g. 250Hz, 1000Hz, 250Hz, 2000Hz). For the non-repeating sequence, all four tones were presented and in random order. The order was randomized while maintaining an equal number of repeating and non-repeating tone sequences across all dual tasks.

In the dual task condition, subjects listened to the tone sequence while simultaneously performing the finger tapping sequence task. Following each sequence, a visual question mark was shown following an ISI of one of three random durations (1.0, 2.0, and 3.0 seconds). Participants were instructed to press a ‘yes’ or ‘no’ button, corresponding to button one and two on the response box, as quickly as they could to indicate whether or not the same tone was presented twice. Participants were instructed to be as accurate as possible when completing the tone monitoring distracter task. Following the participant’s tone response, the next finger sequence trial started following a random ISI interval.
Procedures

The single and dual task conditions were repeated in a fixed interleaved design. Each participant was tested over two days. On the first day, when performance effects from practice were assessed, they performed 30 single, 30 dual, 30 single, 30 dual, and 15 single, totaling 135 trials. The final 15 single finger tapping trials were not included in the analysis but were added following the last dual task condition in order to avoid the tone-monitoring competing task from being performed last and thereby interfering with the consolidation process.

Participants returned approximately 24 hours later for a second performance testing session. They were asked not to practice the finger tapping sequence during the time between the two test sessions. Although motor skill consolidation can easily continue over a very long period, a 24-hour period is consistent with the motor learning literature as it is considered sufficient time for a new memory to be consolidated into a stable state and thus more resistant to further interference (Walker & Stickgold, 2004). On day two, the number and sequence of single and dual task trials were the same as on day one, except for the final 15 single trials, which were no longer presented.

Familiarization

Immediately prior to the experiment on day one, participants were provided with the opportunity to become familiar with the tasks. First, participants practiced five repetitions of a finger-tapping task, similar to the one used in the experiment. They were instructed to concentrate on becoming familiar with the button press box rather than trying to respond as quickly as possible. All participants reached the criterion of four out of five correct responses. Second, participants practiced five repetitions of the tone monitoring task using the same pure tones as in the experimental task. Again, all participants reached the criterion of four out of five correct responses.
Dependent variables and statistical analysis

Each participant’s performance was recorded automatically using Superlab pro 4.0 software. The variables used to measure performance gains included accuracy, reaction time, and sequence duration, which are considered strong indicators of motor learning (Schmidt & Lee, 2005). Accuracy was measured based on errors for both the finger-tapping task and tone-monitoring task. Finger-tapping errors were measured as the number of sequences containing one or more incorrect taps. Tone-monitoring errors were measured as the number of incorrect ‘yes’ or ‘no’ button presses.

Reaction time was measured as the time (in milliseconds, ms) from the onset of the visual stimulus (number sequence for the finger–tapping task and “?” for the tone-monitoring task) to the first button press in both the finger-tapping and tone-monitoring task. Finger-tapping and tone-monitoring button press reaction times that fell outside three standard deviations from an individual’s mean were considered extreme outliers and excluded from analysis (Portney & Watkins, 2000). As a result, on day one, 19 out of the combined 1320 trials for PWS (1.4%) and 18 out of the 1440 trials for PNS (1.2%) were excluded. On day two, 15 out of 1320 trials for PWS (1.1%) and 21 out of 1440 trials for PNS (1.4%) were excluded. No tone-monitoring button presses fell outside three standard deviations from an individual’s mean.

Sequence duration was measured as the time interval (ms) between the first and the final button press for the finger-tapping sequence. Sequence durations that fell outside three standard deviations of an individuals’ average were considered outliers and were excluded from analysis. Consequently, on day one, 12 out of the combined 1320 trials for PWS (.9%) and 7 out of 1440 trials for PNS (.4%) were excluded. On day two, 5 out of the 1320 trials for PWS (.3%) and 5 out of 1440 trials for PNS (.3%) were excluded. In addition, trials that were invalid due to behaviors such as sneezing, yawning, or distraction
were also excluded. This resulted in the exclusion of one additional trial for both PWS and PNS on day one, and the exclusion of two additional trials for PWS and one additional trial for PNS on day two.

In order to minimize the effect of transient fluctuations in performance from trial to trial, the 60 trials for the single task condition on each of the two days were averaged into 12 equal blocks of five (trial 1-5, 6-10, 11-15, etc.). A similar procedure was used for the 60 dual task trials. This resulted in 12 single blocks (2x6) and 12 dual blocks (2x6) on day one and day two.

The variables accuracy, reaction time, and sequence duration were assessed using separate 2 x 2 x 2 x 4 multifactor repeated ANOVAs (Portney & Watkins, 2000) with two levels of Group (PWS versus PNS), two levels of Day (day 1 and day 2), two levels of Condition (single task versus dual task) and four levels of Trial (first block of 5 finger tapping trials versus last block of 5 finger tapping trials for each single and dual practice session).

Accuracy and reaction time for the tone monitoring task were assessed using two additional 2 x 2 x 4 multifactor repeated ANOVAs (Portney & Watkins, 2000) with two levels of Group (PWS versus PNS), two levels of Day (day 1 versus day 2) and four levels of Trial (first block of 5 tone monitoring trials versus last block of 5 tone monitoring trials for each dual practice session).

Similar to the procedure followed in Smits-Bandstra, et al (2006b), the ability to retain improvements in performance following a 24-hour retention period was assessed for PWS and PNS by calculating paired sample t tests between the means of the final block of five finger tapping trials on day one and the first block of five finger tapping trials on day two. Separate analyses, corrected for multiple comparisons, were carried out for accuracy, reaction time and sequence duration.

**Results**
Levene’s Test of Equality of Error Variance was not significant for measures of accuracy, reaction time or sequence duration data at alpha .05, indicating equal error variance between groups. Mauchly’s Tests of Sphericity was performed to determine if the adjustment to the value of \( p \) was needed.

The sphericity tests were not significant for accuracy, reaction time, or sequence duration comparisons at alpha .05 and therefore no correction was used (Portney & Walkins, 2000).

**Accuracy**

The results for accuracy are shown in Table 5.2. Finger tapping errors under single and dual task conditions for PWS did not significantly differ from PNS on day one or day two. No significant main effects for Day, Condition, or Trial were found, nor was there a significant interaction.

Table 5.2

The finger tapping errors for PWS and PNS in block 1 (average of trials 1-5), block 6 (average of trials 26-30), and block 12 (average of trials 56-60) in the single and dual task conditions for day one and day two.
The results for reaction time are shown in Table 5.3. Both groups showed significant improvements in performance across trials, $F(3,63) = 80.71$, $p < .001$, $\eta^2_{p} = .794$ and days, $F(1, 21) = 89.86$, $p < .001$, $\eta^2_{p} = .811$. A significant Day x Trial interaction, $F(3, 63) = 5.87$, $p < .05$, $\eta^2_{p} = .219$ occurred because the performance curves differed from day one to day two. Descriptive analyses showed that this was because both groups showed large performance gains on day one; whereas on day two, their performances began to level off (Figure 5.1). Despite the similarities in performance gains between groups, a Group x Trial interaction $F(3, 63) = 2.97$, $p < .05$, $\eta^2_{p} = 1.24$ occurred because in contrast to the PNS, PWS’ performance continued to show some improvements in performance on day two. A 2-way interaction for Condition x Trial, $F(3, 63) = 6.99$, $p < .05$, $\eta^2_{p} = .250$ was also found. No other interactions were found, nor was there a main effect for Group.

Table 5.3

<table>
<thead>
<tr>
<th>Group</th>
<th>Day</th>
<th>Single</th>
<th></th>
<th>Dual</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Block 1</td>
<td>Block 6</td>
<td>Block 12</td>
<td>Block 1</td>
<td>Block 6</td>
</tr>
<tr>
<td>PWS</td>
<td>1</td>
<td>.36 (.35)</td>
<td>.90 (.32)</td>
<td>.455 (.25)</td>
<td>1.1 (.25)</td>
<td>.81 (.25)</td>
</tr>
<tr>
<td>PNS</td>
<td></td>
<td>1.25 (.33)</td>
<td>.50 (.35)</td>
<td>.91 (.37)</td>
<td>1.0 (.4)</td>
<td>.58 (.34)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>.09 (.15)</td>
<td>.63 (.36)</td>
<td>.62 (.39)</td>
<td>.63 (.41)</td>
<td>.81 (.36)</td>
</tr>
<tr>
<td>PWS</td>
<td></td>
<td>.41 (.15)</td>
<td>.91 (.35)</td>
<td>.91 (.37)</td>
<td>1.0 (.4)</td>
<td>.58 (.34)</td>
</tr>
<tr>
<td>PNS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Reaction time

The results for reaction time are shown in Table 5.3. Both groups showed significant improvements in performance across trials, $F(3,63) = 80.71$, $p < .001$, $\eta^2_{p} = .794$ and days, $F(1, 21) = 89.86$, $p < .001$, $\eta^2_{p} = .811$. A significant Day x Trial interaction, $F(3, 63) = 5.87$, $p < .05$, $\eta^2_{p} = .219$ occurred because the performance curves differed from day one to day two. Descriptive analyses showed that this was because both groups showed large performance gains on day one; whereas on day two, their performances began to level off (Figure 5.1). Despite the similarities in performance gains between groups, a Group x Trial interaction $F(3, 63) = 2.97$, $p < .05$, $\eta^2_{p} = 1.24$ occurred because in contrast to the PNS, PWS’ performance continued to show some improvements in performance on day two. A 2-way interaction for Condition x Trial, $F(3, 63) = 6.99$, $p < .05$, $\eta^2_{p} = .250$ was also found. No other interactions were found, nor was there a main effect for Group.

Table 5.3
The finger tapping reaction time (ms) of PWS and PNS in block 1 (average of trials 1-5), block 6 (average of trials 26-30), and block 12 (average of trials 56-60) in the single and dual task conditions for day one and day two.

<table>
<thead>
<tr>
<th>Group</th>
<th>Day</th>
<th>Single</th>
<th>Dual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Block 1</td>
<td>Block 6</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>966(46)</td>
<td>744(48)</td>
</tr>
<tr>
<td>PWS</td>
<td></td>
<td>827(44)</td>
<td>627(46)</td>
</tr>
<tr>
<td>PNS</td>
<td></td>
<td>790(45)</td>
<td>555(53)</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>604(43)</td>
<td>496(51)</td>
</tr>
<tr>
<td>PWS</td>
<td></td>
<td>827(44)</td>
<td>627(46)</td>
</tr>
<tr>
<td>PNS</td>
<td></td>
<td>790(45)</td>
<td>555(53)</td>
</tr>
</tbody>
</table>
Figure 5.1. Mean finger tapping reaction times (ms) for single and dual task conditions on day 1 and day 2 for PWS and PNS.

Sequence Duration

The duration data are shown in Table 5.4. PWS showed significantly slower sequence durations compared to PNS across trials, Group $F(1,21) = 9.63, p < .05, \eta_p^2 = .314$. A significant Group x Trial interaction $F(3,63) = 5.64, p < .05, \eta_p^2 = .212$ and Group x Day interaction $(1, 21) = 5.53, p < .05, \eta_p^2 =$
.209 indicated that, with practice, sequence durations of PNS reached a relative plateau while PWS continued to show improvement. A Day x Condition x Trial interaction $F(3, 63) = 3.08, p < .05, \eta_p^2 = 1.28$ indicated that both groups showed significant improvements in sequence duration across trials and conditions on day one and two (Figure 5.2). No significant main effect for Condition or significant 4-way interaction was found.

Table 5.4

Finger tapping sequence durations (ms) of PWS and PNS in block 1 (average of trials 1-5), block 6 (average of trials 26-30), and block 12 (average of trials 56-60) in the single and dual task conditions for day one and day two.

<table>
<thead>
<tr>
<th>Group</th>
<th>Day</th>
<th>Single</th>
<th></th>
<th></th>
<th>Dual</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Block 1</td>
<td>Block 6</td>
<td>Block 12</td>
<td>Block 1</td>
<td>Block 6</td>
<td>Block 12</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Block 1</td>
<td>Block 6</td>
<td>Block 12</td>
<td>Block 1</td>
<td>Block 6</td>
<td>Block 12</td>
</tr>
<tr>
<td>PWS</td>
<td>5166(381)</td>
<td>3528(256)</td>
<td>2800(189)</td>
<td>4623(331)</td>
<td>3606(239)</td>
<td>3213(184)</td>
<td></td>
</tr>
<tr>
<td>PNS</td>
<td>3968(365)</td>
<td>2620(245)</td>
<td>2370(181)</td>
<td>3140(317)</td>
<td>2585(229)</td>
<td>2418(176)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Block 1</td>
<td>Block 6</td>
<td>Block 12</td>
<td>Block 1</td>
<td>Block 6</td>
<td>Block 12</td>
</tr>
<tr>
<td>PWS</td>
<td>3018(201)</td>
<td>2526(161)</td>
<td>2403(170)</td>
<td>2941(173)</td>
<td>2710(162)</td>
<td>2602(176)</td>
<td></td>
</tr>
<tr>
<td>PNS</td>
<td>2275(193)</td>
<td>2040(154)</td>
<td>2104(163)</td>
<td>2080(165)</td>
<td>2060(155)</td>
<td>2115(169)</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5.2. Mean finger tapping sequence duration (ms) for single and dual task conditions on day 1 and day 2 for PWS and PNS

_Tone monitoring task_

The Levene’s Test of Equality of Error Variance was not significant for accuracy or reaction time data at alpha .05, indicating equal error variance between groups. Mauchly’s Tests of Sphericity was performed to determine if the adjustment to the value of $p$ was needed. The sphericity tests were not
significant for accuracy, reaction time, or sequence duration comparisons at alpha .05 and therefore no correction was used (Portney & Walkins, 2000).

A Group main effect showed significantly more tone monitoring errors for the PWS compared to the PNS, Group $F (1, 21) = 6.59, p < .05, \eta_p^2 = .239$ (Figure 5.3). A Day x Group interaction was also found due to PNS’ tone monitoring errors improving from the first trial block on day one ($M = .91, S.D. = .9$) to the last trial block on day two ($M = .41, S.D. = .66$), whereas PWS’ slightly worsened from the first trial block on day one ($M = 1.18, S.D. = 1.2$) to the last trial block on day two ($M = 1.27, S.D. = 1.10$). No main effect for Trial or a 3-way interaction for Group x Day x Trial was found.

Both groups showed significant improvements in tone monitoring reaction times across Trials, $F (3, 63) = 8.04, p < .001, \eta_p^2 = .277$. A Day x Trial interaction occurred because most of the performance gains were made on day one; whereas performance started to plateau on day two, $F (3,63) = 4.38, p < .05, \eta_p^2 = .173$. No main effect for Group was found, nor was there a 3-way Group x Day x Trial interaction.
Tests of retention

The results for retention are shown in Table 5.3 for reaction time and Table 5.4 for sequence duration. Both the PNS and the PWS showed an ability to retain what they had learned on day one following an approximate 24-hour retention period for accuracy and sequence duration but not reaction time. While PNS’ errors showed some decline from day one (M= 1.08, S.D. = 1.3) to day two (M= .416,
S.D. = .668), this difference was not significant. Similarly, PWS showed some decline in errors from day one (M= 1.09, S.D. = 1.13) to day two (M= .091, S.D. = .301), which also was not significant. While PNS’ mean response times were maintained across the 24-hour retention period; the PWS’ mean response times from the last five trials on day one to the first five trials on day two in contrast showed a significant decline, t(10) = -6.03, p<.01, two-tailed. No significant differences were found for either group between the mean sequence duration for the last five trials on day one and the first five trials on day two.

Analysis of single to dual task transition

In order to further assess automaticity levels, PWS were compared to PNS in their ability to transition from the single to the dual task conditions. For the variables accuracy, reaction time, and sequence duration the difference between the mean of the final five trials (last block of each 30 single task session) of each single task session and the corresponding first five trials of each subsequent dual task session (first block of each 30 dual task session) were obtained. This yielded four Condition scores (four single tasks versus four dual tasks) from both day one and day two. The variables accuracy, reaction time and sequence duration were assessed using separate 2 x 4 multifactor repeated ANOVAs (Portney & Watkins, 2000) with 2 levels of Group (PWS vs. PNS) and 4 levels of Condition scores.

The Levene’s Test of Equality of Error Variance was not significant for accuracy, reaction time or sequence duration data at alpha .05, indicating equal error variance between groups. Mauchly’s Tests of Sphericity was performed first to determine if the adjustment to the value of p was needed. The sphericity tests were significant for reaction time and sequence duration comparisons at alpha .05 and therefore a Greenhouse-Geisser correction was used. The Mauchly’s Test of Sphericity was not significant for the accuracy data (Portney & Watkins, 2000).

For interference effects, the difference between the mean of the last five single task trials in a block and the corresponding mean of the first five dual task trials in the subsequent block was obtained
for accuracy, reaction time, and sequence duration. PWS’ scores for finger tapping accuracy between the single versus dual task conditions did not differ significantly from those of PNS. Likewise, no significant Group main effect or Group x Condition interaction was found. For finger tapping reaction time, no main effect for Group or Condition was found, nor was there an interaction (Figure 5.5). Although both groups improved on their finger tapping sequence duration as they transitioned from the single to the dual task conditions, Condition: F(3,63)= 7.86, p< .001, ſ² = .272, PWS showed significantly larger dual task interference effects on day one and day two compared to controls, Group: F (1, 21) = 14.25, p < .001, ſ² = .404 (see Figure 5.6). No Group x Condition interaction was found.
Figure 5.4. Mean difference in reaction time and variability (S.D.) between the last 5 trials in each single, finger tapping session and the first 5 trials in each subsequent dual session (condition effects) for day one and day two.
Figure 5.6. Mean difference in sequence duration and variability (S.D.) between the last 5 trials in each single, finger tapping session and the first 5 trials in each subsequent dual session (condition effects) for day one and day two.

Discussion

The specific aim of this study was to assess the ability of PWS to practice and learn a sequential finger tapping task following practice and a 24-hour consolidation period. Our first objective was to address whether PWS demonstrate slower performance gains, compared to PNS, following practice under single and dual task conditions. Our findings partly support the presence of differences in performance as group differences emerged for reaction time and sequence duration but not accuracy. Although both groups improved in reaction time under the single and dual task conditions on day one and day two, a significant group x trial interaction emerged due to PNS reaching a relative plateau in performance under both conditions while PWS’ performance continued to improve. Findings for sequence duration showed significantly slower movement speeds in PWS compared to PNS under both the single and dual task conditions on day one and day two. A significant group x trial interaction revealed that PNS’ sequence durations reached a relative plateau under both conditions while PWS’ performance continued to show improvement.

We also aimed to assess whether PWS show poor motor learning abilities as evidenced in a reduced ability to consolidate a practiced, sequential finger tapping task compared to controls following a 24-hour consolidation period and by showing greater interference when performing under dual task conditions. Similar to PNS, PWS showed the ability to retain the practiced task following a retention period for the variables accuracy and sequence duration but not reaction time. Both groups showed the ability to learn to perform the finger-tapping task more automatically even when interference was created.
by a concurrent competing task as there was no group x condition interactions for any of the measured variables. Additional analysis of PWS’ and PNS’ ability to perform the finger tapping task under dual task conditions revealed significantly larger interference effects for PWS compared to controls for sequence duration data only. That is, PWS showed a significantly larger difference in finger tapping performance between the last five trials of the single task and the first five trials of the dual task compared to PNS. While poor retention abilities (reaction time data only) and larger group interference effects (sequence duration only) lends partial support for the hypotheses of reduced motor learning in PWS, our insignificant findings from the multifactor repeated ANOVAs for any of the measured variables do not provide such support and further research is needed.

Practice effects

As discussed in the introduction section, practice effects are considered to represent momentary improvements in performance (Schmidt, 2004) that are traditionally observed as an increase in speed and accuracy, resulting from a decreased reliance on sensory mechanisms to guide performance (Fitts, 1967).

Both groups showed significant improvements in reaction time and sequence duration across conditions for day one and day two. Visual inspection of the graphed data for reaction time (Figure 1) and sequence duration (Figure 2) showed similar log-linear performance slopes (Newell & Rosenbloom, 1981). That is, PWS benefited from practice and consolidation, although their sequence durations were significantly slower than the PNS.

These group differences, however, were not homogeneous across practice trials as shown by a significant group x trial interaction for reaction time and sequence duration. Visual inspection of the data showed an initial, rapid decrease in reaction time and sequence duration with practice for both groups, although slower in the PWS compared to controls. With practice, however, PNS’ performance reached a
relative plateau whereas PWS’ performance remained relatively variable with improvements in performance still occurring well into practice on day two.

The finger tapping task was used in the current study in order to assess whether differences between PWS and PNS observed in previous studies are limited to the movements involved in speech production (Bauerly & De Nil, 2010; Smits-Bandstra et al., 2006b; Namasivayam & van Lieshout, 2008) or represent a general motor deficit affecting the control and organization of nonspeech movement. Several studies have found PWS to differ from PNS when performing tasks involving unrelated effector systems (Max, Caruso & Gracco, 2003; Forster & Webster, 2001). In addition, studies specifically designed to assess practice related differences have found slower performance in PWS when practicing nonspeech tasks (Smits-Bandstra et al., 2006a, 2006b). For instance, Smits-Bandstra et al. (2006a) reported significantly slower and more variable performance when practicing a finger-tapping task singly and concurrently with a color recognition task. Results from the current study support this theoretical viewpoint of a motor control deficit in PWS that extends beyond the organizational principles specific to speech production.

Motor learning

One condition that needs to be met in order to assume learning has occurred is that improvements in performance following practice must be maintained following a retention period. This is based on the theoretical assumption that practicing a motor skill triggers a process of consolidation whereby an initial, unstable memory representation is transitioned into a more stable state with the passage of time. The ‘amount’ of skill lost over the 24-hour consolidation interval was significant for reaction time measures among the PWS but not among PNS. Such differences were not found for accuracy or sequence duration. Descriptive data showed that PWS made improvements in reaction time across trials on day one, although significantly slower than the PNS. Results conform with several motor control studies that have found
poor reaction time skills in PWS using nonspeech tasks (Cross, 1978; Jones et al., 2002; Weinstein, Caruso, Severing & Verhoeve, 1989. This significant loss in retention of the skill on day two suggests a reduced ability to acquire permanent gains in performance. These results, however, are contrary to what was found in a previous study by Bauerly and De Nil (2011) where both PWS and PNS showed the ability to retain their improvements in reaction time following the practicing and consolidating of a sequential speech task. The reason for this discrepancy is most likely due to an increase in task complexity as the previous study by Bauerly and De Nil (2011) used a single, repetitive speech task without a secondary, interfering task. Smits-Bandstra et al. (2006a) also found retention differences in PWS for reaction time but not for sequence duration and suggest this is due to less effective manual skill learning.

As discussed earlier, another condition that needs to be met in order to assume learning has occurred is that after considerable practice, two tasks can be performed simultaneously with little cost to either (Hazeltine et al., 2002; Schumacher et al., 2001). Any discrepancy in performance can be assumed to reflect the level of automaticity (or lack thereof) achieved on the first, primary task (Hazeltine et al., 2002; Schmidt, 1988; Smits-Bandstra et al., 2006a).

Groups did not show any 2, 3, or 4-way interactions for condition indicating that PWS did not differ from PNS in their ability to perform the finger tapping task under dual task conditions. However, additional analysis of PWS’ and PNS’ abilities to transition from the last five single finger tapping trials to the subsequent first five dual finger tapping trials showed significantly larger interference effects in the PWS compared to PNS for the variable sequence duration. That is, the PWS showed significantly slower finger tapping speeds during the first five dual task trials. In addition, they made significantly more tone monitoring errors. Visual inspection of the graphed data suggested with practice that PNS’ finger tapping sequence duration remained relatively the same across the single and dual task conditions and as a result showed very little interference by the time they reached the last dual block on day one (Figure 2). In
contrast, PWS’ finger tapping sequence duration under the dual task condition remained slower compared to their performance under the single task condition across practice on day one and day two. Smits-Bandstra et al. (2006a) found similar results using a finger tapping task concurrently with a color monitoring task. In her study, PNS showed quick, accurate and an increasingly automatic performance with practice while PWS remained slow and variable under both conditions. Greater interference effects in PWS have been found in other studies using finger-tapping tasks concurrently with verbal tasks (Greiner et al., 1986; Sussman, 1982; Bruten & Trotter, 1985). Although interference effects for sequence duration in PWS remained following a relatively large number of practice trial, descriptive analysis showed that these group differences lessened with practice, suggesting that PWS did have the potential to automatize the task to the same degree observed in PNS, but at a slower rate (Figure 5).

One explanation for PWS’ greater difficulty learning a novel sequential motor skill compared to controls may be a result of having limited motor abilities (De Nil, 1998; Van Lieshout, Hulstijn, & Peters, 1996; Van Lieshout, 2004). Schmidt (1988) describes motor abilities as an underlying trait, not modified by practice, which plays a key role to the success on a particular motor task. Motor abilities can be considered to fall along a continuum where individuals possess various levels of ability. Therefore, abilities can define a person’s potential for success and may also represent limitations on performance (Schmidt, 1988). Although a motor skill consists of a learned movement that requires practice in order to master; its level of success will ultimately depend on an individual’s underlying abilities required for carrying out the task at hand (Schmidt, 1988; Magill, 1998).

In regards to individual differences in motor skill, the PWS’ poor motor abilities demonstrated in the current study may be an explanation for their difficulty in reaching the reaction time and sequence durations observed in the PNS following practice and consolidation. Supporting evidence comes from a study by Namasivayam and van Lieshout (2008) where PWS showed significantly larger movement amplitudes of upper lip movement following practice and learning of a nonword speech task. They
posited that this difference may reflect a motor control strategy used to maintain stability. This is likely the case in the current study as it appeared that maintaining a relatively slower speed of movement may have been a mechanism used to optimize processing of sensory information (De Nil & Abbs, 1991; De Nil, 1999a; Loucks & De Nil, 2001; Van Lieshout et al., 2004). In this case, PWS’ slower movements for both reaction time and sequence duration may have been a strategy used to keep speed and accuracy in balance. This strategy would have been consistent with the instructions they received to “type as fast as you can without making mistakes”. This could explain why PWS failed to reach the speed of performance observed in PNS, even when given a relatively large number of practice trials. Instead, their limited motor abilities led them to continuously require a relative high degree of attention across extended practice and consolidation, as they continued to use a “controlled” movement strategy that required the monitoring of feedback (van Lieshout et al., 1996). As a result, processes required to perform the secondary, tone-monitoring task interfered with performance on the finger tapping task. This was shown by significantly larger interference effects for sequence duration as well as greater tone monitoring errors in PWS compared to PNS. However, as stated earlier, differences in interference effects between groups for sequence duration decreased with practice, suggesting the ability to automatize the skill, albeit at a slower rate.

Earlier research has demonstrated that the skills required to perform a particular motor task will change with practice (see Fleishman & Bartlett, 1969 for a review). More specifically, Fleishman and Rich (1963) found that early in practice, performance is more reliant on cognitive functioning such as working memory and reasoning; while later in practice as the task becomes more routine, motor abilities such as movement speed, reaction time, and strength become more important. In line with this, results from the current study lend support for PWS’ limitations in motor ability, as opposed to differences in cognition, as poor performance in PWS remained as practice continued into the later stages of practice.
where motor abilities are thought to dominate. Also, scores on the WAIS-III, Letter-Numbering Subtest for working memory showed no significant difference between groups.

As an alternative explanation, it could be hypothesized that the poor dual task performance observed in PWS may have been a result of difficulty detecting and monitoring the pure tones. PWS showed significantly greater tone-monitoring errors compared to PNS on day two. This may have caused slower sequence durations and stronger interference effects as they would require greater attentional resources when performing the dual task compared to controls. However, during the familiarization task, PWS reached the criteria of four out of five correct. An increase in tone-monitoring errors became apparent in PWS only when performing the tone-monitoring task under dual task conditions. Therefore, results do not lend support for difficulties in PWS in monitoring the pure-tones in isolation. Also, an increase in tone monitoring errors did not emerge until day two, suggesting practice related differences. Supporting evidence stems from a study by Sasisekaran, De Nil, Smyth and Johnson (2006) where no differences in speed or accuracy were found between PWS and PNS when performing a pure tone monitoring task similar to the one used in the current study. Corbera, Corral, Escera and Idiazabal (2005) also did not find differences in cognitive evoked potential (ERP) activity in PWS compared to controls in response to pure tone stimuli. Although PWS have shown to take longer detecting changes in a tracking signal (Nudelman, Herbrick, Hess, Hoyt, Rosenfield, 1992) or when responding to pure tones (Hampton & Weber-Fox, 2008), these studies required immediate responses as opposed to the present study which required a response following completion of the finger tapping task and a 1-3 second ISI. As a result, participants were given ample time to process the tones and thus prepare for a response.

Possible implications for stuttering treatment

It may be reasonable to assume that one factor limiting the effectiveness of treatment may be the difficulty PWS have in using their newly learned fluency techniques in naturalistic settings, when an
increase in cognitive demands are more likely to occur, for example when speaking under communicative pressure. Support for this assumption stems from the current study where larger differences between the single to dual task transitions for sequence duration were found for PWS compared to PNS. Other studies have also reported greater dual task interference in PWS compared to controls (De Nil & Bosshardt, 2001; Fitzgerald, Cooke & Greiner, 1984; Greiner, Fitzgerald & Cook, 1986) as well as an increase in stuttering frequency under cognitive demanding tasks (Bosshardt, 1999; 2002; Caruso et al., 1994).

Clearly, much more research is needed in investigating the practice and learning abilities in PWS using some of the same fluency enhancing techniques used in the clinic within a controlled laboratory setting.

Conclusion

Our main findings partially support previous research of poor performance gains in PWS compared to PNS when practicing nonspeech tasks. Our main findings do not lend strong support for differences in motor learning; however based on additional measurements of retention and single to dual task transition, PWS did differ from PNS on a number of important variables that relate to practice effects and learning. One question that remains is whether task complexity would influence results. While the dual task used in the present study was relatively demanding, it may not have sufficiently taxed the participants’ resources to yield very strong effects in a relatively short period of time. Also, the interleaved design used in the current study, whereby the single and dual tasks order was kept constant across participants, may have resulted in an order effect. This however would only affect our interpretation significantly if one assumes that the order effect would be different between the PWS and PNS, which remains a question for follow-up studies. In conclusion, while the current study provides some partial support for a motor learning deficit in PWS, it fails to provide unequivocal support and future research in this area is clearly needed, especially given the potential implications for clinical intervention.
CHAPTER VI

MOTOR LEARNING ABILITIES IN ADULTS WHO STUTTER: PREDICTIVE FACTORS TO LONG TERM TREATMENT OUTCOME

Abstract

The present study investigated the extent to which individual differences in motor learning are associated with differences in stuttering treatment outcome. Twenty-one adults who stutter participating in the intensive, three-week, Fluency Plus Program (Kroll & Scott-Sulsky, 2010) were assessed for their working memory ability and motor learning performance on a sequential syllable reading and finger tapping task. Treatment success was measured at pre-treatment, post-treatment and six months following the termination of treatment using a comprehensive battery of tests that included stuttering severity, introspective clinical characteristics (OASES; Yaruss, 2010) and fluency effort. The relationship between motor learning and treatment outcome was examined using multiple regression analyses. Results suggested that there is no simple relationship between motor learning ability and treatment outcome as no significant relationships were found for measures of treatment success (e.g. % syllable stuttered) and measures of motor learning. Nor did results show that working memory ability is linearly related to treatment outcome.

Although treatment proved successful as evidenced by percent syllable stuttered and scores on the OASES, scores on a self-reported effort scale indicated that participants still required a high degree of effort when using their newly learned fluency skills in everyday conversation. Treatment outcome measures are discussed with regard to the relevance of increased automaticity of a learned speech pattern and its role in understanding the effectiveness of treatment therapies.
Introduction

Many traditional stuttering treatment programs involve acquiring a novel speech motor skill during speaking such as forming light articulatory contacts or vowel prolongations (Guitar, 2004; Kroll & Scott-Sulsky, 2010). Some of these treatment programs involve intensive, daily practice where participants are explicitly taught fluency techniques in order to prevent or manage moments of stuttering. In these treatment settings, extensive practice of a fluency skill across multiple days is essential for long-term retention and maintenance of a skill. The development of these intensive programs is founded on a well-established concept of motor learning in which extensive practice across multiple days is thought to lead to more automatic performance and thus allow the client to perform the skill within everyday speaking contexts.

Recent findings of reduced practice and learning abilities in PWS compared to PNS (Bauerly & De Nil, 2011; Namasivayam & Van Lieshout, 2008; Smits-Bandstra, et al., 2006a) have allowed us to postulate the effectiveness of clinically used fluency intervention strategies that involve acquiring a novel speech pattern. Furthermore, Bauerly and De Nil (2011) found that the significantly slower sequence durations in people who stutter (PWS) compared to people who do not stutter (PNS) during the practice of a nonspeech sequence task could be attributed to a subgroup of PWS who failed to show any improvements in performance following practice and retention.

Although research has investigated many factors that may predict the long term fluency success from treatment (Craig et al., 1998), motor learning abilities have not yet been explored. Motor learning abilities are a particularly important factor to consider when evaluating an individual’s success with a treatment program that focuses heavily on learning “a new way of speaking”. Due to the presence of subgroups in PWS who are reported to benefit less from motor learning (Bauerly & De Nil, 2011), the current study investigated the implications for client variability to treatment outcome.

Treatment outcome
One of the main limitations to stuttering treatment programs is the high incidence of relapse (Bloodstein & Bernstein-Ratner, 2008), ranging anywhere from 14% to 70%. Unfortunately, little is known as to why stuttering therapy is not always effective. It is clear, however, that some individuals are not able to maintain their fluency skills on either a short or long term basis. Several studies have investigated whether individual stuttering profiles at pre-treatment may be used as predictive factors to short and long term fluency success. Such factors have included etiology (Blood, 1985; Poulos & Webster, 1991), pre-treatment severity (Howell & Davis, 2011; Huinck et al., 2006), type of speech behaviors (prolongations, repetitions; Borden, 1990), as well as personality factors such as speech attitudes and locus of control (Craig, 1998: De Nil & Kroll, 1995; Guitar & Bass, 1978). Some research has used such factors to identify subgroups of PWS based on treatment gains (Huinck et al., 2006). Although a combination of factors (Craig, 1998) have been identified that may have the potential to predict relapse following treatment, there are other factors that have not yet been explored, such as the motor learning abilities in PWS.

It is somewhat surprising that no studies have systematically investigated differences in motor learning abilities as a possible contributor to relapse considering that many treatment programs involve acquiring complex speech motor patterns (Kroll & Scott-Sulsky, 2010). Clinician strategies such as light articulatory contacts or stretched syllable emphasize the importance of practice with the goal of reducing the attentional demands required to monitor the new fluency technique so that the new way of speaking can be accomplished in a more effortless, automatic way. Reduced practice effects and learning have been found in some PWS (Bauerly & De Nil, 2011; Ludlow et al., 1997; Smits-Bandstra et al., 2006b); perhaps these same individuals are also those more likely to have difficulty transitioning the newly learned skills to a level at which to prevent relapse.

Measuring treatment outcome

Treatment outcome measures commonly used in research include objective measures of speech and nonspeech behaviors such as frequency and type of stuttering (Riley, 1994). Covert aspects of the
disorder are also considered when measuring treatment outcome and may include the assessment of the fears, the anticipations, and the persons’ self-concept associated with the disorder (Yaruss, 2010). While there are a number of other measures that test the success of a particular treatment program, one criterion that is particularly relevant to the current study and described by Bloodstein and Bernstein – Ratner (2008) is that the “client must be free from the necessity to monitor their speech” (p.342). Fluency should not be considered normal unless the speaker is free from cognitive and physical effort of using their new fluency skills. Despite the importance, speech effort remains an elusive concept (Ingham & Cordes, 1997; Ingham, Bothe, Jang, Yates, Cotton, & Seybold, 2009) that has often been excluded from treatment outcome measures. Starkweaher (1987) described “effortless” speech in two ways: (a) it requires little cognitive effort, and (b) it requires only a small amount of muscular exertion. As a subjective measure, these two characteristics may be difficult to tease apart. In a treatment study by Boberg and Kully (1994), 29 out of 30 participants felt, one and two years following therapy, that they could “almost always” or “sometimes” speak fluently without thinking about controlling their speech. Whether “thinking about controlling their speech” is a rating of cognitive effort or physical activity remains to be seen. Recent studies have used speech effort as a subjective measure when assessing the effects of fluency enhancing conditions (e.g. auditory masking, chorus reading) and have reported that self-ratings of speech effort offer an independent and reliable measure of fluency that may be useful for the assessment of stuttering treatment programs (Bothe et al., 2009; Ingham, Warner, Byrd & Cotton, 2006).

**Motor practice**

To facilitate the understanding of learning a new fluency skill in treatment, a brief introduction to the principles of practice and learning are presented below. For a more complete description of motor practice and learning refer to Schmidt and Lee (2004). Because treatment programs rely on the individual’s ability to maintain a skill on a long term basis as well as the ability to perform the skill within a variety of communicative contexts, the focus of motor learning in this review is on PWS’ performance under tests of
retention and interference. Also included is a description of some of the more relevant variables that may enhance the learning process, including variables that have been reported to have an effect on individual differences in motor learning.

The two most important factors that promote learning are practice and experience (Rose, 1997; Schmidt & Lee, 2005). The main goal during the initial attempts at performing a novel task is to link sensory representations of the environment into muscle control signals (Kendall et al., 2000). The effects from practice are thought to represent the momentary changes in performance (Schmidt, 2004) and may be used to predict the relatively permanent consequences of practice (Schmidt & Lee, 2005). Performance gains are often characterized by shorter reaction times and sequence durations, more accurate responses as well as a decrease in sensory and attentional demands (Magill, 1998; Schmidt & Lee, 2004).

Cognitive processes (i.e. working memory) are most active during this stage as the learner tries to understand the task, and retrieve from memory aspects of the skill that have been previously learned (Baddeley, 2003). There are other variables that also help in determining the effectiveness of practice such as fluctuations in attention, fatigue, or motivation (Schmidt, 2004). In regards to motivation, the learner must perceive the task as meaningful in order for them to be motivated to practice. If not, no learning will occur (Magill, 1998).

The capacity to acquire a skill is also largely dependent on individual characteristics. Learning curves show large intersubject variability in the speed and accuracy at which a skill is learned (Ackerman, 1988). Studies suggest that these individual differences may be due in part to the individual strategy used to approach a given task (Ackermann, 1988; Fleishman, 1978). Cognitive abilities such as working memory are also reported as predictor factors to individual differences in motor learning (Bor & Owen, 2006; Raz et al., 2000; Kennedy & Raz, 2005; Sakai et al., 1998).

Motor learning
Motor learning refers to the ability to acquire the temporal and spatial characteristics of a movement pattern in order that, with practice, muscle execution becomes increasingly dependent on an internal representation rather than external feedback (Schmidt, 2004).

Learning, however, cannot be assumed to occur based on practice effects alone as variables in the environment such as fatigue and motivation may affect performance during a single practice session. As a result, learning is not directly observable and must be inferred from measured variables such as whether the improvements from practice are retained following a retention (consolidation) period or whether performance is resistant to interference by a secondary, dual task (Magill, 1998; Schmidt & Lee, 2005).

**Practice effects in PWS**

Several studies have shown slower and less accurate performance in PWS compared to PNS when performing speech-motor tasks. For instance, Adams and Hayden (1976) and Cross and Luper (1979) have found PWS compared to PNS to be slower at initiating and terminating phonation when cued by a tone, a difference that continued following practice.

Similar trends in performance have been observed when practicing nonspeech motor tasks (Neilson & Neilson, 1991; Smits-Bandstra et al., 2006b; Webster, 1986; Wienstein et al., 1989), suggesting that group differences are not limited to the sensorimotor processes involved in speech production. For instance, Webster (1986) found that PWS were slower and less accurate than PNS when practicing a bimanual finger tapping task.

**Motor learning in PWS**

As described earlier, learning cannot be assumed to occur based on practice effects alone. Although practice effects can be observed in as little as ten repetitions (Schmidt, 1988), it may not provide sufficient time to allow the temporary influences on performance (e.g. fatigue) to dissipate (Schmidt & Lee, 2005). Several more recent studies have investigated whether these earlier reported differences in practice
effects in PWS indeed reflect differences in motor learning by observing performance following a retention period and under competing, dual-task conditions.

Tests of retention

One method used to measure motor learning is to assess whether the practiced task is retained following a retention period (Magill, 1998). Studies have shown that learning a motor skill initially occurs during practice; however the time between practice sessions also allows an opportunity for the memory to stabilize (Karni et al., 1998; Robertson, 2004; Press et al., 2005).

Studies have found differences in retention in PWS compared to PNS using both speech and nonspeech tasks (Namasivayam & Van Lieshout, 2008; Smits-Bandstra et al., 2006). In a study by Smits-Bandstra et al. (2006), PWS showed a reduced ability to retain a finger-tapping and syllable reading task following practice and a 40 minute retention period compared to controls. Similarly, Namasivayam and Van Lieshout (2008) reported differences in retaining a practiced set of nonsense words at two different rates (normal and fast) across three test sessions; two on the same day and one at least a week apart. In this study, results showed less stability and strength in coordination patterns in PWS compared to controls as well as significant decreases in the strength of inter-gestural frequency coupling at normal, habitual speaking rates. Although Bauerly and De Nil (2011) did not find group differences in retention when assessing performance on a sequential speech task following a 24-hour period PWS’ performance remained significantly slower compared to the PNS’.

Tests of Working Memory

As discussed previously, many motor skills require the use of higher level cognitive resources, such as working memory, in order for gains in performance to be made. Working memory processes are thought to dominate during the early stages of learning. Working memory defines a person’s information processing capacity (Daneman and Carpenter, 1980; Newell, 1973). It refers to the cognitive processes involved in the calculations and manipulations of incoming information as well as the storage of this
information (Baddeley & Hitch, 1974) and is an important component to the early stages of learning. Studies investigating performance as a participant engages in two tasks simultaneously are often used to assess working memory abilities (Curran & Keele, 1993; Dominey, 1998; Hazeltine et al., 2002; Logan & Etherton, 1994).

Studies have found that PWS require more processing capacity when performing dual tasks that involve the speech - planning system (Caruso et al., 1994; Bosshardt et al., 2002). In a study by Bosshardt (2002), participants were required to generate sentences from two unrelated nouns while simultaneously performing a rhyming and category decision task. PWS significantly reduced the number of propositions under dual task conditions, whereas PNS did not show a difference between single and dual task conditions. The influence of secondary tasks has also been shown to have an effect on the frequency of stuttering (Arends et al., 1988; Bosshardt, 1999, 2002, Caruso et al., 1994). Greiner et al. (1986) reported PWS were slower and made more errors on the primary, finger-tapping task and demonstrated an increase in stuttered speech on the competing speaking task. Sussman (1982) also found greater disruption in PWS compared to PNS when performing a finger tapping task concurrently with a verbal task. Results such as these suggest that PWS exhibit greater sensitivity to interference when performing dual, cognitive processing tasks.

**Tests of Interference**

As a skill becomes learned, performance relies less on attention and other cognitive processing activities. As a result, dual task paradigms are often used in motor learning research in order to measure the level of automaticity achieved following practice (Magill, 1998; Schmidt, 2004). Any discrepancy in performance can be assumed to reflect the level of automaticity achieved on the first, primary task (Hazeltine et al., 2002; Schmidt, 1988).

Several studies using speech and nonspeech motor tasks have reported slower reaction times (Smits-Bandstra et al., 2006a, 2006b) slower sequence durations (Bauerly & De Nil, 2011; Smits-Bandstra et al., 2006a; Fitzgerald et al., 1984; Webster, 1990) and less accurate responses (Bauerly & De Nil,
Nonspeech sequence skill learning in adults who stutter under single and dual task conditions. Manuscript under review; Fitzgerald et al., 1984; Smits-Bandstra et al., 2006) in PWS compared to controls under concurrent conditions. In a study by Bauerly & De Nil (Nonspeech sequence skill learning in adults who stutter under single and dual task conditions. Manuscript under review), larger interference effects were found in PWS when practicing a finger tapping task simultaneously with a tone monitoring task. In this study, descriptive analysis showed PNS became more consistent in their performance on a finger tapping task with practice and showed very little interference from the dual task during the final stages of practice on the first day and following a 24-hour retention period. On the contrary, PWS continued to show a large interference effect when performing the dual task across practice on day one and day two. In addition, PWS showed significantly more tone monitoring errors compared to PNS on day one and day two of practice. Results suggested an impaired ability to transition a novel motor sequence to the same level of automaticity as PNS.

Larger interference effects in PWS when performing under dual task situations may help explain relapse with a particular treatment program. While some PWS have reported the ability to speak fluently with little to no effort following treatment, others have reported difficulty in using their fluency skills in more stressful situations such as when speaking with their employer (Guitar, 2006). The later may be due to a difficulty in using their new skills within more attention demanding situations, suggesting that their fluency skills had not been automatized to level in which they can be performed under such dual task situations.

*Individual differences in motor learning*

In the study by Bauerly & De Nil (2011), descriptive analysis showed large within group differences in PWS which to some extent, are suggestive of a subgroup (four out of 12) who failed to benefit from practice or consolidation. These findings suggest that some, but not all, PWS show an inability to improve their performance when given practice and consolidation. Other studies have identified similar
subgroups of PWS who have shown to not benefit from practice (Ludlow et al., 1997; Neilson & Neilson, 1991; Smits-Bandstra et al., 2006b). For instance, Smits-Bandstra et al. (2006b) reported that a third of the PWS showed a performance pattern similar to PNS while the others varied in performance. Although not a motor learning task, Kleinow and Smith (2000) also found that approximately a third of the PWS showed large spatiotemporal variability compared to the remaining group of PWS and controls when repeating a phrase at habitual and slow speaking rates. Clearly, the presence and nature of this subgroup of PWS who appear to benefit less from motor learning opportunities may have implications for client variability in treatment outcome and therefore deserve further study.

Present investigation and Research Questions

The purpose of the present study was to investigate the extent to which individual differences in motor learning are associated with differences in stuttering treatment outcome. This objective was accomplished using a longitudinal paradigm in which PWS participating in an intensive fluency enhancing program were assessed for their working memory ability and their motor learning performance on a syllable reading and finger tapping task. It was hypothesized that within group differences in working memory as well as in speech and nonspeech sequence skill acquisition in stuttering speakers would predict performance on treatment outcome measures.

Research Questions

• Are the within group differences in speech sequence skill acquisition in stuttering speakers predictors of successful learning of a new fluency skill?

• Are the within group differences in nonspeech sequence skill acquisition in PWS predictors of successful learning of a new fluency skill?

• Are the within group differences in working memory abilities in stuttering speakers predictors of successful learning of a new fluency skill?
Methods

Participants

Twenty-two English speaking PWS, ranging in age from 16.0 to 45.2 ($M = 28.3$, S.D. = 8.8) participated in this study. PWS were rated for severity using the Stuttering Severity Instrument-3 (SSI: Riley, 1994). Based on the SSI-3, stuttering severity ratings of the participants were in the very mild (8), mild (6), moderate (4), and severe (3) range. Profiles of the participants with respect to gender, age, stuttering severity and introspective clinical characteristics from the Overall Assessment of the Speakers Experience with Stuttering (OASES) are shown in Table 1. OASES scores represent the introspective clinical characteristics of stuttering such as the feelings, behaviors, attitudes, as well as social anxiety that may accompany the disorder. It is a norm referenced tool frequently administered before and after therapy in order to gauge the impact of therapy on cognitive and affective components of stuttering (Silverman, 1980; Yaruss & Quesal, 2006). Interjudge reliability measured for 25% of PWS’ reading and speaking samples, and calculated using Cohen’s kappa coefficient, was .98 and .99 respectively. None of the participants reported receiving fluency treatment within the two years prior to participation in this study. All participants were right handed as they all scored 10/10 on the Edinburgh Handedness Inventory (Oldfield, 1971). All participants reported a negative history of neurologic, psychiatric, motor or speech and language disorders (other than stuttering), or of taking any medications that would impair their motor functioning. For the purpose of the nonspeech task, no participant self-reported to be a professional typist or musician. Approval from the Human Ethics Review Committee at the University of Toronto was obtained for the study. All participants provided written informed consent before participating in the study. Table 6.1. Individual subject information with regard to age, gender, overall score on the Stuttering Severity Instrument 3rd edition (SSI-3: Riley, 1994), corresponding stuttering severity classification according to the SSI-3, overall score on the OASES, and scores on the Letter-Number Sequencing Subtest by the WAIS-III (Weschler, 1997; see section 2.4.1).
<table>
<thead>
<tr>
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<th>Age</th>
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<th>OASES</th>
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<td>22</td>
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<td>2.14</td>
<td></td>
</tr>
</tbody>
</table>

*Fluency Plus Program*

All participants participated in a three-week intensive treatment program at the Speech and Stuttering Institute in Toronto, Canada called the Fluency Plus Program (Kroll & Scott-Sulsky, 2010). The program is based on Precision Fluency Shaping (Webster, 1974) and views stuttering as a speech-motor disorder that can be improved by gaining control over speech muscles through the use of the following eight fluency enhancing techniques: stretched syllable, full breadth, gentle onset, reduced air pressure, reduced articulatory pressure, full articulatory movement, and stretched syllable target. Clients gain the ability to use their newly learned fluency skills in all relevant speech contexts through transfer tasks and cognitive restructuring tasks focused on addressing individual’s attitudes, beliefs, and feelings. The program requires four and a half hours of treatment daily for three consecutive weeks. For a complete description, refer to *The Fluency Plus Program: An Integration of Fluency Shaping and Cognitive Restructuring Procedures for Adolescents and Adults who Stutter* (Guitar and McCauley, 2010). Several studies have confirmed treatment success by reporting decreases in stuttering immediately after treatment with regression rates ranging from
5% to 20% at 1 or 2 year follow-up sessions but still well above pretreatment levels (De Nil and Kroll, 1995; De Nil et al., 2003; Kroll et al., 1997).

**Measures of treatment success**

Treatment success in the current study was measured using a comprehensive battery of tests that included stuttering severity, introspective clinical characteristics (stuttering-related feelings, behaviors and attitudes, and social anxiety; OASES) and fluency effort (SEFE). These different measures will be discussed separately in the following sections.

**Percentage of stuttered syllables.** A conversation and reading sample was taken from each participant in order to measure changes in the observable characteristics of stuttering. The primary investigator counted the number of stutters and number of syllables in an approximate 300 syllable conversational sample taken from a videotaped within clinic interview. The Rainbow Passage, a reading sample of 452 syllables in length, was also taken from each participant. For reliability, twenty percent of the speech samples were randomly chosen, stratified for participant (i.e. one rater rated a participant’s samples from all three measurement occasions, but did so without identifying information) and assigned to a trained rater who was blind to the conditions of the study. Rating procedures are similar to Huinck et al. (2006). Using Cohen’s kappa coefficient, inter-rater reliability for both speaking and reading samples were .93 and .98 respectively. For intra-rater reliability, fifteen percent of the samples were randomly selected, rated by the primary investigator and then re-rated 6 months later. Intra-rater reliability, using Cohen’s kappa coefficient was .99.

**Overall Assessment of the Speakers Experience with Stuttering (OASES).** This is a test that when combined with percent syllable stuttered, enables the measurement of the broader consequences of the disorder and includes the perspective of the person who stutters (Yaruss, 2010; Prins & Ingam, 2009). This tool is particularly useful when measuring treatment outcome because when combined with percent syllable stuttered, it provides a more comprehensive measurement of treatment success, including both
covert and overt behaviors of the disorder. The OASES contains four sections, each of which can be linked to a component of the World Health Organization’s (WHO, 2001) International Classification of Functional Disability and Health (ICF). These sections include: (a) general perspectives about stuttering, (b) affective, behavioral, and cognitive reactions to stuttering, (c) functional communication difficulties, and (d) impact of stuttering on the speaker’s quality of life (Yaruss, 2006). Overall scores from all four subtests were used for analysis.

**Self-evaluation of fluency effort (SEFE).** The SEFE is a questionnaire that was designed for the purpose of this study in order to assess participant’s effort required to use their newly learned fluency skills in everyday situations. Its purpose was to measure the extent to which the speaker transitioned their newly learned fluency skills to a more automatic state. The questionnaire uses 25 speaking situations taken from the Self-Efficacy Scale for Adults Stutterers (SESAS; Manning, 2001). Participants are required to rate their fluency effort on a 7 point scale with 1 indicating *no effort* and 7 indicating *extreme effort* (see Appendix A). Average scores were calculated for each participant. It is assumed that if the speaker requires very little effort to use their fluency skills in everyday situations then they have achieved a relatively high degree of automaticity. This test was administered on the final day of treatment and then again at the six month follow-up session. Test-retest reliability was conducted for 25% of the questionnaires. For this, participants were randomly selected and administered the questionnaire again three days after the first or second administration. Test-retest reliability was .90. This scale is similar to a scale used in Ingham, Warner, Byrd & Cotton (2006) and Ingham, Bothe, Jang, Yates, Cotton & Seybold (2009) where participants self-reported their physical effort using a 9-point scale as they performed several different fluency enhancing conditions such as chorus reading.

*Predictors to treatment outcome*
The predictive value of motor learning for treatment outcome was assessed by using a test of working memory and measures of motor learning (performance on a speech and nonspeech task). These measures will be discussed separately in the following sections.

*Weschler Adult Intelligence Scale-III, letter – number sequencing subtest (WAIS-III: Weschler, 1997).* As discussed in the introduction section, stuttering speakers have shown reduced performance on tests that require a high degree of verbal working memory such as on tasks of nonword repetition (Hakim & Ratner, 2004) and silent reading (Bosshardt, 1990). Due to these findings combined with reports that verbal working memory has been shown to be a strong predictor of performance during the early and later stages of motor skill learning (Ackerman, 1998), a test of working memory was included as a potential predictor to treatment outcome. The WAIS-III requires the individual to listen to a set of mixed letters and numbers and recite back first the numbers and then the letters. It not only requires an individual to engage in more than one cognitive task simultaneously but also to manipulate objects in memory and as a result, requires a high level of working memory (Sohlberg & Mateer, 2001). This subtest was administered by the first author. The test consists of seven items with three trials each. The test is discontinued once a participant fails on all three trials within an item. The number of correct items were totaled and used as the raw score for each participant. Normative data from The Psychological Corporation reported a mean of 10.79 and standard deviation of 3.28 (The Psychological Corporation, 1997; Tulsky & Zhu, 2000).

*Speech task.* A single, monosyllable, nonsense word sequence, 10 syllables in length, was used as the speech sequence (“buz dob jeb zot gak vud daf bup jeg tup”). The same speech sequence was used by the authors in a previous study (Bauerly & De Nil, 2011). Stimuli were derived from the English Lexicon Project (Balota et al, 2007) using a random word generator. The syllables were selected based on the following criteria: (1) the words were orthographically legal and pronounceable but not derived from the root of real words, (2) the words consisted of a low bi-gram frequency which entail syllables that are most infrequently used and as a result, must be assembled from small units (Levelt & Wheeldon, 1994) and (3)
the initial and final position of each word consisted of non liquid consonants (to aid in acoustic analysis). All participants’ speech productions were video and audio recorded.

_Nonspeech task._ A ten-number sequence (1 3 2 4 1 4 2 3 1 2), derived from a random number generator in Excel (Microsoft, Inc.), was visually displayed on a computer monitor and repeated across trials. The numbers ranged from one to four and each corresponded with one of four horizontally arranged buttons on a response box (Cedrus 610, Superlab Inc.). The numbers were arranged so no number triplets were used more than once, no number pair was used consecutively (e.g. 1 4 1 4) and every number was used between two and four times per sequence. Participants used their dominant hand to press four buttons that were arranged horizontally on a response box (Cedrus 610, Superlab Inc.) in order to reproduce the visually presented number sequence. Participants placed their index finger on the left most button (button 1), middle finger on button 2, etc. The response box was shielded from view for the subjects in order to prevent visual feedback. The finger tapping stimulus and instructions are identical to the one used in Bauerly and De Nil (Nonspeech sequence skill learning under single and dual task conditions. Manuscript under review). Participants’ performance was recorded automatically using Superlab pro 4.0 software.

_Motor practice task procedures._ Participants performed 50 repetitions of both a speech and nonspeech sequence. The order at which the sequences were presented was randomized across participants. Participants sat in front of a computer screen and were presented with a visual “ready” word followed with an random interstimulus (ISI) of one of three durations (1.0, 2.0, 3.0 seconds) to minimize anticipation effects on reaction time. Participants were then presented with the sequence displayed horizontally and printed in black. Participants read the speech and nonspeech sequence from the computer screen. They were instructed to “speak/type (depending on task) as quickly as you can without making mistakes” and to “begin as soon as the sequence appears on the screen”. In addition, for the speaking task, in order to discourage an increase in errors under faster speaking rates, participants were also instructed to “pronounce the beginning and ending of each word”. The speech sequence remained on the screen for
eight seconds before disappearing. This was followed by a randomized ISI and a new “ready” signal. The nonspeech sequence remained on the screen for as long as it took the participants to complete the sequence. Similar to the speech task, this was followed by an ISI of one of three randomized durations and a new “ready” signal.

**Motor practice variables.** The variables accuracy, reaction time and sequence duration were used to measure performance gains for both the speech and nonspeech tasks. These variables are frequently used in motor control research in order to measure practice-related changes in performance (Schmidt & Lee, 2005). For the speech task, accuracy was calculated off-line by the first author based on the audio recordings. It was measured by the number of distortions (e.g. inappropriate devoicing or voicing of phonemes), incorrect substitutions, or missing words for all sequences. Sequences that contained dysfluencies such as repetitions, prolongations, and blocks were excluded from both the total error count and temporal measures. The percentage of sequences containing dysfluencies for all participants was 9.7%. As a result, out of the 1050 sequences produced by the participants, 101 were excluded due to errors. A second rater, blind to the condition of the study, performed a separate error and dysfluency count on the entire sample. Errors and dysfluencies that were not in agreement received a second review by both raters at which time the disagreements were resolved. For the nonspeech task, accuracy was measured as the number of sequences containing one or more incorrect taps.

For the speech task, response time and sequence durations (to the nearest millisecond) were calculated off-line using the wave form acoustic analysis software PRAAT (Boersma & Weenink, 2001). Response time measurements were taken from the onset of the visual stimulus presentation to the onset of acoustical energy associated with the word-initial stop consonant /b/. Sequence duration was measured as the time difference between the onset of acoustical energy associated with the first and final word, respectively. A second rater, blind to the conditions of the study, reanalyzed 10% of the participants’ acoustic waveforms for both reaction time and sequence duration. Using Cohen kappa coefficient, inter-
rater reliability for curser placement within 10 ms of the first rater was .94 and .91 for reaction time and sequence duration, respectively. For the nonspeech task, participants performance was recorded automatically using Super pro 4.0 software. Reaction time was measured as the time (ms) from the onset of visual stimulus presentation to the first button press. Sequence duration was measured as the time difference between the first and final button press.

**Qualitative Measures**

Two qualitative measures were included in order to assess additional factors that have the potential to contribute to treatment success. These include a practice log and strategy questions. These measures are described in more detail below.

*Practice log.* It is important that participants are motivated to learn a new task for the most effective learning to occur (Schmidt and Lee, 2004). One way to measure an individual’s level of motivation is to record the amount of time they spend practicing their new skills. For this reason, a practice log was administered by email with SurveyMonkey (surveymonkey.com) every month in order to assess the amount of time a subject spends practicing their newly learned fluency skills. The first multiple choice question was, “On average, how many times a week did you practice?”. Participants reported their answer by choosing from eight options ranging from “0” to “>7”. The second multiple choice question was “On average, how long were your practice sessions?”. Participants reported their answers in increments of five minutes from “5” to “> 40”.

Also, for an individual to be motivated to learn a new skill they must perceive the task as meaningful and useful. As a result, the following question was incorporated into the practice log and used as an indicator of motivational level: “How useful do you feel your fluency skills are in speaking situations?” Participants reported their answer on a 7-point scale from 1 being “not useful” to 7 being “extremely useful”. A general comment section was also included.
Strategy questions. Studies assessing individual differences in motor learning have correlated performance with individualistic strategies used to approach the task (Schlaug, Knorr & Seitz, 1994). For this reason, the following two questions regarding strategies were incorporated into the six month follow-up session conversation: (1) “Other than what you learned here, in the 3-week intensive program, did any other strategies help you when using your newly learned fluency skills in situations outside the clinic?” (2) “Was there a fluency technique that you found you used more than others?”

Procedures

This study consisted of three measurement periods: pre-treatment, post-treatment, and six month follow-up. These sessions are discussed separately in the following sections.

Pre-treatment. In the morning of the first day of the treatment program, participants who agreed to participate in the study were pulled from the treatment group in order to complete the following tasks: a speaking sample for a percentage of syllables stuttered, WAIS – III Letter Number Sequencing subtest, OASES, syllable reading task and finger tapping task. The percentage of syllables stuttered and OASES are routine measures for the Fluency Plus Program and therefore were conducted by a certified speech-language pathologist. Following this session, participants met with the primary investigator in order to complete the WAIS-III and perform the syllable reading and finger tapping tasks. Administration of the tasks was counterbalanced among participants in order to ensure that half of the subjects performed the speech task and half of the subjects performed the nonspeech task first. Randomization was used when assigning a participant to a task order. For these tasks, participants were seated in front of a computer screen in a quiet room with the primary investigator.

Post-treatment. This session assessed participants’ treatment outcome. It took place on the last day of treatment in the same environment as the pre-treatment session. The following measures of treatment outcome were taken: percentage of syllables stuttered, Self Evaluation of Fluency Effort (SEFE), and (c) OASES.
Practice log. For six months following the termination of treatment, a request to complete the internet-based practice log was emailed to the participants at the end of each month. If a participant failed to complete the survey within seven days of the first reminder, a second request was emailed to the participant.

Six month follow-up. Six months following the termination of treatment, participants’ either returned to the Speech and Stuttering Institute or met with the primary investigator at the Speech Fluency Lab at the University of Toronto. At this time, their fluency skills and overall treatment outcome were measured. At this time, the following measures were taken: percentage of syllables stuttered, OASES, and SEFE. The strategy questions were also administered at this time.

Statistical Analysis

The first level of analysis aimed at determining whether treatment was successful. As described above, measures of treatment success were determined using percent syllables stuttered, OASES scores, and SEFE scores taken at pre-treatment, post-treatment and six month follow-up sessions. Three paired sample $t$–tests were conducted (pre-treatment versus post-treatment, pre-treatment versus follow-up and post treatment versus follow-up) for each measure of treatment success (% syllable stuttered, OASES and SEFE). Alpha was set at .016 (.05/3) to control for Type I error.

To examine the relationship between motor learning and treatment outcome, three multiple regressions were performed, with % syllable stuttered, OASES scores, and SEFE scores as the dependent variables. For these dependent variables, only the differences from pre-treatment to six month follow-up were used in the analysis as it was determined to be the most relevant to the purpose of the study and values were very similar to the differences from pre-treatment to post-treatment (see Table 2). The independent variables used for all three multiple regressions were WAIS-III, Letter- Number Sequencing subtest scores, speech error, speech reaction time, speech sequence duration, nonspeech error, nonspeech reaction time, and nonspeech sequence duration. Because of the overall exploratory nature of this study
and the potential implications each of these independent variables may have for treatment outcome (see Methods section), it was decided to include all variables in the multiple regression analyses. For each measure of motor learning, the average of the last five trials (trial 45-50) was subtracted from the first five trials (trials 1-5). This difference score was then used as the measure of motor learning for both the speech and nonspeech task.

Results

Treatment success

Percent syllables stuttered

Results demonstrated a significant reduction in percent syllable stuttered in conversation from pre-treatment ($M=9.69, \text{ S.D.} = 7.14$) to post-treatment ($M = 2.11, \text{ S.D.} = 2.12$), $t(20) = 5.216, p < .01$. Six month follow-up data reported some regression ($M = 4.16, \text{ S.D.} = 4.68$); however levels were still significantly below pre-treatment levels, $t(20) = 4.92, p < .01$ (see Figure 1).
A significant reduction in OASES scores were also shown from pre-treatment ($M = 3.17$, S.D. = .882) to post-treatment ($M = 2.38$, S.D. = .650), $t (20) = 4.607$, $p < .01$. Similar to percent syllable stuttered, some regression occurred at six months follow-up ($M = 2.54$, S.D. = .667); however levels were still significantly below pre-treatment levels, $t (20) = 3.52$, $p < .01$ (see Figure 2). These scores provide an indication of the impact of stuttering on various aspects of the speaker’s life. The impact rating represents differing degrees of stuttering impact (mild, mild-moderate, moderate, moderate-severe, severe). Pre-treatment results were mod-severe, reducing to moderate post-treatment and remaining at this level at the six month follow up session.
Figure 6.2. PWS’ mean scores for each of the four sections of the Overall Assessment of the Speakers Experience with Stuttering (OASES) at pre-treatment, post-treatment and six month follow-up

**SEFE**

PWS did not show significant reductions in self-reported amount of effort required to use the newly learned fluency skills from post-treatment \((M = 3.45, \text{S.D.} = 1.4)\) to six months follow-up \((M = 3.08, \text{S.D.} = .947)\), \(t(20) = 1.264, p = .221\) (see Figure 3).
Figure 6.3. PWS’ mean scores on the Self Evaluation of Fluency Effort (SEFE) at post-treatment and six month follow-up

Table 6.2. Means and standard deviations for treatment measure differences from pre-treatment to post-treatment, pre-treatment to six months follow-up and post-treatment to six month follow-up for percent syllable stuttered, OASES scores, and SEFE scores.

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<th>Post-treatment versus Six Month Follow-up</th>
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<td>5.53 (5.14)</td>
<td>-2.05 (3.73)</td>
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<td>.625 (.812)</td>
<td>-.64 (.53)</td>
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<tr>
<td><strong>SEFE Scores</strong></td>
<td>n/a</td>
<td>n/a</td>
<td>.370 (1.34)</td>
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</table>

*Measures of motor learning*

*Finger tapping task*

PWS demonstrated a relatively low number of finger tapping errors ($M = 9.0$, S.D. = 8.3) across the 50 trials of practice. PWS’ reaction times declined from the first five trials ($M = 1030.8$ ms, S.D. = 354.6) to the last five trials ($M = 695.9$ ms, S.D. = 71.7; see Figure 4). Likewise, PWS’ sequence durations declined from the first five trials ($M = 4836.8$ ms, S.D. = 386.3) to the last five trials ($M = 3750.7$ms, S.D. = 157.3; see Figure 5).
Figure 6.4. Finger tapping reaction time (ms) obtained by PWS across 50 trials of practice
Syllable reading task

PWS’ mean errors (number of distortions, incorrect substitutions, or missing words) on the syllable reading task was 8.14 (S.D. = 7.74). PWS’ reaction times decreased from the first five trials ($M = 619.4 \text{ ms}, \text{ S.D.} = .432.2$) to the last five trials ($M = .557.8 \text{ ms}, \text{ S.D.} = 211.1$) (see Figure 6); whereas PWS’ sequence durations declined from the first five trials ($M = 5413.6 \text{ ms}, \text{ S.D.} = 1456.5$) to the last five trials ($M = 4580.8 \text{ ms}, \text{ S.D.} = 1632.4$; see Figure 7).
Figure 6.6. Syllable reading reaction time obtained by PWS across 50 trials of practice.
Predictors of treatment success

Correlation analyses

For exploratory purposes, a matrix of intercorrelations for all pairs of variables was obtained. No mathematical corrections were made for the multiple comparisons (Rothman, 1990). There was a
significant negative correlation between syllable reading reaction time and percent syllable stuttered for the pre-treatment to post-treatment measurement period. There was also a significantly positive correlation between finger tapping sequence duration and OASES scores for the pre-treatment to post-treatment measurement period. For all other correlations, none of the measures or predictors of treatment success (percent syllable stuttered, OASES, SEFE, WAIS score, speech error, speech reaction time, speech sequence duration, nonspeech error, nonspeech reaction time, and nonspeech sequence duration) obtained from pre to post treatment, pre to follow-up treatment, and post to follow-up treatment differences revealed any significant relationships. See Table 3 and Table 4 for the Pearson correlations between the measures of treatment success and predictors of treatment success.

Table 6.3. Correlation matrix for predictors of treatment success on the syllable reading task (speech errors, speech reaction times (RT), and speech sequence duration from the first five trials to the last five trials) and treatment outcome (difference between pre-post treatment, pre-follow up treatment and post-follow up treatment for % syllable stuttered, OASES scores, and SEFE scores). Scores on the WAIS are also included as a predictor of treatment success.

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<th>% Syllable Stuttered</th>
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<th>Speech Duration</th>
<th>WAIS Score</th>
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<th>Speech RT</th>
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Table 6.4. Correlation matrix for predictors of treatment success on the finger tapping task (finger tapping errors, finger tapping reaction times (RT), and finger tapping sequence durations from the first five trials to the last five trials) and treatment outcome (difference between pre-post treatment, pre-follow up treatment and post-follow up treatment for % syllable stuttered, OASES scores, and SEFE scores).
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<tr>
<th></th>
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<td>.297</td>
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</tbody>
</table>

Multiple regression analysis
Results showed that WAIS-III score, speech error, speech reaction time, speech sequence duration, nonspeech error, nonspeech reaction time, and nonspeech sequence duration were not significant predictors of percent syllable stuttered, $R^2 = .11$, $F (7, 20) = .277, p = .93$. That is, only 10% of the variability in treatment outcome can be explained by the measures of motor learning. Similarly, these same predictors of treatment success were not significant predictors of OASES scores from pre-treatment to six month follow up, $R^2 = .52$, $F (7, 20) = 2.02, p = .13$, or SEFE scores from pre-treatment to six month follow-up, $R^2 = .16$, $F (7, 20) = .359, p = .91$.

Qualitative measures

Practice log

Although the number of self-reported times per week participants practiced declined from the first ($M = 4.73$, S.D. = 3.55) to the second ($M = 3.61$, S.D. = 2.62) month; there were insignificant changes in practice across the six month period (see Figure 8). Similarly, the length of practice time declined from the first ($M = 24.81$, S.D. = 13.04) to the second month ($M = 19.7$, S.D. = 13.33); however differences were insignificant across the six month period (see Figure 9). Average monthly data for question three indicated that participants’ continued to feel that their fluency skills were useful in everyday speaking situations (see Figure 10). Ten participants responded at least once to the general comments section in which two general themes emerged. First, four participants expressed difficulty transferring their newly learned fluency skills to everyday speaking situations. For example, “I start off using my new fluency skills but quickly start speaking in my old pattern” or “I have the most difficulty with transferring my fluency skills”. Second, three participants reported a general discomfort in using ‘New Normal’ in conversation. For example, “I’m not comfortable with the rate of new normal” or “Speaking in new normal feels alien to me”.
Figure 6.8. Monthly averages of the number of times per week PWS practiced their new fluency skills.

Figure 6.9. Average length (minutes) of PWS’ practice sessions from the first to sixth month following treatment.
Strategy questions

All but one participant reported that they did not use any additional strategies to help them when using their fluency targets in everyday speaking situations. One participant reported that relaxation techniques helped him such as deep breathing and meditation. Participants varied in the type of fluency technique they used more than others. The following fluency techniques were reported to be used more than others: full articulatory movement (7 participants), stretching syllables (5 participants), gentle onset (6 participants), and reducing air and articulatory pressure (3 participants).

Discussion

Treatment outcome measures

Treatment was shown to be successful as evidenced by significant decreases in percent syllable stuttered and scores on the OASES from pre-treatment to post-treatment and post-treatment to six month follow-up. These results are in agreement with previous treatment studies assessing effectiveness of the program, which reported significant decreases in stuttering immediately following the intensive treatment
program with regression rates ranging from 5% to 20% at one and two year follow-up sessions (De Nil & Kroll, 1995; De Nil et al., 2003; Kroll et al., 1997). Scores on the OASES showed significant declines that may be at least partly due to the program’s inclusion of cognitive restructuring (e.g. coping with anxiety).

Although treatment proved successful on two out of the three measures used in this study, scores on the SEFE indicated that participants continued to require a high degree of effort after six months when using their newly learned fluency skills in everyday situations. One reason for this difficulty may be due to the strain and vigilance required to keep the new pattern of speaking going during conversation (Sheehan, 1984). This is consistent with some of the comments made by participants that it was difficult transferring their newly learned fluency skills to everyday conversations with some reporting that they would shift back to their old way of speaking as the conversation continued.

The bivariate correlations described in section 3.3 did not show a significant correlation between SEFE scores and percent syllable stuttered or OASES, indicating that those who made the most fluency gains from treatment, according to their percent syllable stuttered and OASES, are not necessarily the ones who reported greater automaticity when using their new fluency skills in everyday speaking situations. These results indicate that it may be misleading to measure long term treatment success based on percent syllable stuttered and self-reported perceptions and attitudes (OASES) alone and that there are other components to treatment outcome that need to be addressed when considering success of a particular program. Bloodstein and Bernstein-Ratner (2008) listed a number of criteria that should be met in order for treatment to be considered successful that not only include the reduction of stuttering frequency and the subjective feelings associated with one’s own speech behavior but also a decrease in the “the necessity to monitor their speech” (p.342). Fluency can hardly be thought of as normal to the speaker if it requires constant effort to maintain.
Scores on the SEFE bring to light an important aspect of treatment outcome besides fluency that has been largely ignored in research. Attention has rarely been given to the part of increased automaticity of a learned speech pattern and its role in understanding the effectiveness of treatment therapies. Although normative values of self rated effort measures in normal, baseline or treatment conditions have not been established, in a study by Bothe et al. (2009), it was suggested a reliable and useful tool for the measurement and treatment of stuttering. Although the purpose of their study was to assess self-reported physical effort across four fluency enhancing conditions (auditory masking, chorus reading, whispering, rhythmic speech), results also suggested the use of a speech effort scale for measuring treatment outcome for a number of reasons. First, self-reported effort ratings were relatively stable across similar fluency enhancing conditions, suggesting this rating to be generally reliable. Second, speech effort ratings were statistically independent from other treatment outcome measures including percent syllables stuttered and speech naturalness, suggesting a validly interpretable measure of fluency that is independent from other objective measures perceived by the listener.

Alternatively, one must consider whether the automaticity of a fluency enhancing skill is a reasonable treatment goal. As Bloodstein & Bernstein-Ratner (2008) report, treatment techniques that incorporate the use of artificial speech patterns to improve fluency seldom result in an individual reaching spontaneous and automatic fluency. Andrews (1984b) stated “Stuttering is a chronic disorder and many adults can only remain fluent by dint of constant effort”. As a result, some researchers suggest that fluency enhancing and stuttering modification techniques be taught as an option for the PWS to use on occasion, for example during high stress situations, rather than as a standard manner of speaking to avoid stuttering altogether (Andrew, 1984; Bloodstein & Bernstein-Ratner, 2008; Yaruss, 2002). On the contrary, some PWS in our study reported the ability to use their newly learned fluency skills to a level in which their speech approximated normally fluent, effortless speech, possibly pointing to the presence of subgroups of PWS in the ability to learn new skills efficiently. Unfortunately, we know very little about
the long term processes of learning such complex skills due to limited research. Some motor learning studies show that individuals performing simple repetitive tasks such as finger tapping can reach a level of asymptote in three weeks given daily practice (e.g. Karni et al., 1998). Other studies using slightly more complex tasks (i.e. walking speed) have shown that automaticity as measured using dual task paradigms in disordered populations (i.e. Parkinsons Disease; Nieuwboer, Rochester, Muncks, & Swimmen, 2009; Rochester et al., 2010) can be achieved within an approximately five week time period when given daily practice. The learning of new fluency skills combined with the “unlearning” of old habits, however, is a very challenging task, particularly when having to transfer the skills to everyday situations. Nonetheless, results suggest that a subgroup of PWS in the current study may have been able to automatize their fluency skills to some degree and based on previous motor learning research (Karni et al., 1998), it can be assumed that this same subgroup may have benefited from longer practice period.

4.2 Performance curves

Individual differences in sequence duration for both the finger tapping and syllable reading (see Figure 11 for an example of individual differences in finger tapping) data revealed large within group variability with some individuals showing no improvement with practice.

Correlations between measures of treatment success (percent syllable stuttered, OASES, SEFE) and predictors of treatment success (errors, reaction time, sequence duration for both speech and nonspeech task and WAIS-III scores) revealed a significant negative relationship between syllable reading reaction time and percent syllable stuttered from pre-treatment to post-treatment. In other words, those individuals who showed the shortest reaction times when performing the syllable reading task were the ones who showed the least gains in treatment, with respect to stuttering frequency. In this case, poor treatment gains may be due to an individual's inability to allocate sufficient time to create and prepare abstract motor plans for their newly learned fluency targets. However, this is only speculative and future research investigating the reaction time abilities in PWS when performing their fluency targets would
help in answering this question. A significant relationship was also found between OASES scores and finger tapping reaction time, a finding that is difficult to interpret.

Multiple regression analysis showed that error, reaction time and sequence duration on a simple, sequential speech and nonspeech task are not linearly related to percent syllable stuttered as measured from pre-treatment to six month follow-up. As a result, the data did not support the hypotheses that within group differences in speech and nonspeech sequence skill acquisition are predictive factors to successful learning of a new fluency skill.
It is possible that the performance observed in this particular study was restricted to this particular group of individuals thereby limiting the generality of our findings. Due to this concern, comparisons were made between this study groups’ performance and PWS’ performances from previous studies by the same authors using identical speech (Bauerly & De Nil, 2011) and nonspeech tasks (Bauerly & De Nil, Nonspeech sequence skill learning under single and dual task conditions. Manuscript under review.). As shown in Figure 12 and Figure 13, differences in performance between groups for sequence duration on both the speech and nonspeech task were statistically insignificant.
Figure 6.12. Comparisons between the study described in Chapter 5 (Bauerly & De Nil, Nonspeech sequence skill learning under single and dual task conditions. Manuscript under review) and the current study for finger tapping sequence durations in PWS.
Therefore, one conclusion could be that there is no simple relationship between motor learning ability, as measured in this study, and treatment outcome. In other words, those who show learning on the speech and nonspeech tasks are not necessarily the ones who show good treatment outcome. In a previous adaptation study by Max and Baldwin (2010), three out of eight subjects who showed the ability to adapt to a reading passage experienced no fluency benefit of repeated versus novel sentences at the beginning of a second, retention test. Max and Baldwin (2010) proposed that there may not be a simple relationship between motor learning and the ability to generalize those learning effects to previously unpracticed movement sequences. We found a similar discrepancy between learning and treatment outcome that
warrants further investigation with future studies that perhaps include motor learning tests of transfer and retention.

Working memory ability

During the early stages of practicing a motor task, performance is more reliant on cognitive functioning such as working memory (Fleishman & Rich, 1963; Fleishman & Bartlett, 1969). Results from the current study suggest that individual differences in working memory ability are not a contributing factor to treatment outcome. That is, those who performed well on the WAIS-III, Letter-Number sequencing subtest were not necessarily the ones who showed the most treatment gains. Although previous studies show that PWS require more processing capacity when performing dual tasks involving the speech-planning system (Caruso, Chodzko-Zajko, Biingr & Sommers, 1994; Bosshardt, Ballmer & De Nil, 2002), results from the current study suggest that these limitations do not have an effect on their motor learning abilities. Using the same working memory task as in the current study, Bauerly and De Nil (Nonspeech sequence skill learning under single and dual task conditions. Manuscript under review.) found no significant difference in working memory ability between PWS and PNS. They interpreted their findings to suggest that PWS’ difficulty in automatizing a finger tapping skill is instead a result of motor skill limitations.

Limitations

Some caveats to this study are warranted. First, it is possible that the motor tasks were too simple. As shown in sequence duration for both the finger tapping and syllable reading tasks, performances quickly reached a relative plateau. In this case all subjects performed nearly maximally in only a few practice trials, making it difficult to tease out individual differences in motor learning. One way to have avoided this limitation is through the use of a dual task condition. In this case, any decrements in performance under dual task conditions would be observed as a function of an individual’s
ability level on the primary task. Therefore, a secondary task may have allowed a clearer depiction of these differences.

Second, post treatment measures were limited to a six month follow-up. Although greater differences among individuals may have emerged if given a longer time period, there is a greater risk for other non-related factors to effect results if follow-up measures were taken at one or two-year follow-up periods such as a life changing family event or career change.

Conclusions

Our findings did not support our main hypothesis that the ability to learn a simple speech and nonspeech motor task is predictive of treatment outcome. Nor did results show that working memory ability is linearly related to treatment outcome. Although treatment proved successful as evidenced by % syllables stuttered and scores on the OASES, scores on the SEFE indicated that participants still required a high degree of effort when using their newly learned skills in everyday conversations. Considering many stuttering treatment programs for adults include practice and automatization of new speech skills, continued research into the relationship between motor learning and treatment outcome is needed, perhaps using a more complex study design that includes a dual task component.
CHAPTER VIII

DISCUSSION

The purpose of this dissertation was to address the following research questions.

I. Do PWS differ from PNS in their ability to learn a novel speech sequence skill task given extended practice and a retention period?

II. Do PWS differ from PNS in their ability to learn a novel nonspeech sequence skill task when given extended practice and a retention period?

III. Is the suspected deficiency in motor learning a contributing factor to long-term treatment outcome?

In the opening sections of this chapter the results of the speech and nonspeech sequence skill learning studies (Chapter 3 and 4) are interpreted from the perspective of the Schema Theory. Overall, findings showed that PWS were similar to PNS in performance curves and retention abilities but showed some differences on tests of interference. Following this is a review of the study assessing motor learning as a predictive factor to long term treatment outcome (Chapter 5). Overall findings from this study showed no correlations between individual differences in motor learning abilities and treatment outcome measures. The central section of this chapter describes why the similarities in practice and learning between PWS and PNS do not support the hypothesis of a motor learning deficit in PWS. Rather, the discussion focuses on the evidence that suggests PWS possess a limitation in motor abilities. Proposed limitations in motor abilities support the notion of a deficient feedforward control system that results in an overreliance on sensory feedback. The relevance of this assumption to our understanding of developmental stuttering is then discussed. This is followed by a discussion on possible implications of limited motor skills to treatment outcome. Finally, limitations of the experiments are considered and directions for future investigations proposed.

A review of the speech and nonspeech sequence skill learning studies: Evidence of limitations in motor abilities

When performing the syllable reading and finger tapping tasks, initial practice for both groups showed improvements in sequence duration. Significant improvements in response time were also found
for both groups when practicing the finger tapping task but not the syllable reading task. Neither group showed significant improvements in reaction time under syllable reading task conditions. Similarly, both groups showed a consistently small number of errors across practice blocks for both the syllable reading and finger tapping tasks.

According to the Schema Theory (Schmidt, 1988), first attempts at performing a task involve retrieving the GMP from memory and scaling it to meet the current task demands. For example, finger presses involve a basic flexion and extension motion, but with each repetition the overall duration and amplitude of that movement, as well as specific muscles to use (parameters) are tested. The improvements in movement speed observed in Chapters 4 and 5 reflected the ability of both PWS and PNS to take into account the desired outcome and initial conditions as well as select the most appropriate parameters, based on previous trials, for accomplishing the task goals.

Cognitive processes are thought to be heavily engaged during the initial stages of learning any new motor skill as the learner is attempting to understand task requirements and how best to attempt the first few trials. Results from Chapters 4 and 5 suggested similar cognitive abilities between PWS and PNS as both groups showed relatively rapid performance gains during this early phase of learning. In support, scores on a test of working memory (Letter-Number Sequencing Subtest, Weschler, 1997) reported in Chapter 5 were not significantly different between groups.

According to Schmidt (1988), once the individual has determined the most effective way of doing the task, performance improvements are more gradual as the task is executed with more consistent speeds and greater accuracy. For sequential skill learning, an increase in movement speed is thought to represent the development of a new motor program where the entire sequence is controlled as a single unit (Miller, 1956; Schmidt, 2004). At this time, a shift is proposed to occur in the method of motor control to a progressively “lower” level in the neural system (Keele, 1976). PWS appeared to make this progression in
learning at the same rate as PNS when performing the speech motor task as descriptive analysis showed that performance curves began to level off in both groups for reaction time and sequence duration.

A similar pattern of practice effects was observed between the PWS and PNS when performing the finger tapping task under the single task condition on day one. Both groups showed an initial, rapid decrease in reaction time and sequence duration with practice; however group differences emerged as practice continued into day two. In this case, PNS’ performance reached a relative plateau; whereas PWS’ remained relatively variable with improvements in performance still occurring well into practice on day two. This explained why a significant interaction for reaction time and sequence duration on day two emerged when performing under the single, finger tapping condition. One possibility for why group differences emerged under the nonspeech task and not the speech task may be due to differences in task presentation. For the syllable reading task, participants repeated the sequence with no interruptions. However, the finger tapping task included a dual, interference task that was interleaved into the practice session. This secondary task may have interfered with the learning process, hindering the PWS’ ability to internalize the motor program and thus execute the motor operation using a lower level of control. These group differences only emerged on day two when PNS’ performance began to plateau while PWS’ continued to show improvements.

In summary, our findings did not support the hypothesis that PWS show differences in practice effects when repeating a syllable reading task as there was no significant interactions between group x practice for the variables accuracy, response time or sequence duration. However, when practicing a sequential finger tapping task, partial support for differences in practice effects were found between groups. With this task, significant group x practice interactions emerged on day two for the variables reaction time and sequence duration due to PNS reaching a relative plateau in performance while PWS continued to show improvements.

*Motor learning abilities in PWS*
One condition that needs to be met in order to assume learning has occurred is that improvements in performance from practice must be maintained following a retention period. This is based on the theoretical assumption that learning does not stop when practice ends. Instead, a combination of practice and rest leads to a process of consolidation in which an initial unstable motor memory is transformed into a stable state with the passage of time. Although the time it takes for a motor task to stabilize is dependent on many factors (e.g. number of practice trials), studies using simple, sequential tasks have observed the stabilization of a motor memory following a relatively short 24-h rest period (Walker & Stickgold, 2004; Press et al., 2005).

Similar to PNS, PWS showed relatively permanent gains in performance for the syllable reading task as evidenced by the ability to retain what they had learned during practice on all measured variables (accuracy, reaction time, sequence) following a 24-hour retention period. Similarly, the amount of finger tapping skill “lost” over the 24-hour retention period was insignificant for accuracy and sequence duration, but not reaction time for the PWS. With the variable reaction time, only the PWS showed some loss in finger tapping performance following the retention interval. Results are very similar to what was reported by Smits-Bandstra et al. (2006) where performance on a syllable reading and finger tapping task yielded a significant loss in retention for the PWS compared to the PNS for reaction time data only. Also, Namasivayam and Van Lieshout (2008) found significant decreases in the strength of inter-gestural frequency coupling for PWS compared to PNS at normal, habitual speaking rates following a one week retention period. Stronger coupling is thought to be associated with greater inter-gestural stability (Goldstein et al., 2007; Nam, 2007) and reduced flexibility (Kelso, 1995), characteristics associated with learning.

Due to the fact that PWS showed the ability to retain the finger tapping and syllable reading task for all other variables, it is reasonable to assume that the loss in retention for the finger tapping reaction time data was not due to limited motor learning abilities. Some loss in performance is typical for tasks
requiring discrete responses (e.g. tapping a number sequence) versus tasks requiring continuous responses that have no identifiable beginning or end (e.g. riding a bike; Fleishman & Parker, 1962). Some loss in skill in non-disordered individuals when performing motor tasks have been observed in a number of studies using retention intervals ranging from 20 minutes (Neumann & Ammons, 1957) to one year (Lersten, 1969). According to Nacson and Schmidt (1971) a decrement in performance following a retention period may be due to the loss of some temporary internal state or set that underlies and supports the skill, such as the level of arousal required for performing the task or attention being directed to the appropriate sources of input or feedback. This hypothesis suggests that some loss in these internal states occur as these internal sets are adjusted to become most compatible to the behavioral requirements at rest. Once the task is resumed, these sets are re-adjusted and the decrement in performance is eliminated in only a few practice trials. In many cases, the relearning of the task is more rapid than the original learning, indicating that some memory for the skill was retained (Schmidt, 1988).

This seemed to be the case for the PWS when performing the finger tapping task as their reaction time performance quickly “caught up” with the level at which it was performed during the last trials on the previous day. In this case, the loss in retention may have been due to the need to “warm up” for the task after rest, a phenomenon called “warm up decrement” (Adams, 1961; Schmidt, 1988). PNS also showed some loss in reaction time performance for the finger tapping task on day two, although insignificant compared to the PWS. It is unclear why PWS showed weaker retention abilities compared to the PNS; however, it is reasonable to speculate that the finger tapping task was more taxing on the PWS and as a result they required more time and/or energy to reach the previous day’s performance level.

Tests of Interference

Another condition that needs to be met in order to assume learning has occurred is that performance is resistant to interference by a secondary, dual task. On day two of practice, PWS showed significantly larger interference effects compared to PNS for the variable sequence duration when
practicing the finger tapping sequence alone and with a competing, tone monitoring task. This was accompanied by significantly more tone monitoring errors on day two of practice in the PWS compared to the PNS. Visual inspection of graphed data showed that PNS’ finger tapping sequence durations remained relatively constant across the single and dual task trials by the time they reached the last dual block on day one; whereas PWS’ finger tapping sequence duration under dual task conditions remained slower compared to their performance under the single task condition.

According to the Schema Theory for fast movements (Schmidt & Lee, 2004), the initial conditions and desired outcomes are fed into the motor response system in order to produce the most appropriate parameters and expected sensory consequences (proprioceptive feedback). Following the movement, the sensory information is fed back into the system and compared with the expected sensory consequences; any difference in the desired and expected outcomes are fed back and used as subjective reinforcement (Schmidt, 1988). With practice, the parameters come to be chosen more effectively and the difference between the desired and expected outcomes become less and less, leading eventually to the development of a new rule or schema. At this time, it is thought that movement execution transitions from a higher to lower level of motor control (Magill, 1998; Schmidt, 1988; Schmidt & Lee, 2004). Adhering to the Schema Theory, it can be assumed that the PWS, relative to PNS, had not transitioned the finger tapping sequence to a lower level motor control and as a result, showed greater sensitively to an imposing task.

In summary, performance curves for all measured variables were similar between groups for the speech task on day one. On day two, performance curves for all measured variables were also similar between groups for the speech task; however differences in reaction time and syllable reading emerged between groups when performing the nonspeech task. Syllable reading and finger tapping errors were not significantly different between groups. Furthermore, PWS performed similar to PNS under the motor learning conditions of retention and interference with the exception of larger interference effects for
sequence duration when performing the finger tapping task under concurrent conditions. Although larger interference effects suggest a deficiency in motor skill learning (Smits-Bandstra et al., 2006; Namasivayam et al., 2008), as described later in this chapter, another explanation is possible. That is, PWS may possess limitations in their motor abilities which may have hindered their ability to transition the finger tapping sequence to a more automated state.

A Review of Chapter 6: Motor learning abilities in adults who stutter: Predictive Factors to Treatment Outcome

The main objective of the study described in Chapter 6 was to examine whether individual differences in speech and nonspeech sequence skill acquisition are predictors of the successful learning of a new fluency skill. Results showed no correlation between performance on a speech or nonspeech sequence skill task and measures of treatment outcome. That is, those who showed relatively poorer performance gains as observed by slower reaction times or sequence durations or more errors on either the syllable reading or finger tapping task were not the ones who showed difficulty learning a new fluency skill. Similarly, there was no relationship between individual differences in working memory and treatment outcome.

The question of whether working memory abilities in PWS are predictors of treatment outcome was also examined. Results showed that individual differences in working memory ability were not a predictive factor to treatment outcome. Results are in concordance with the syllable reading and finger tapping studies described in Chapters 4 and 5, respectively, where PWS and PNS showed similar cognitive abilities as evidenced by showing comparable performance gains early in practice, and lend further support for the notion that the slower speech and nonspeech performances observed in PWS are motoric in nature.

Subgroups of people who stutter
Similar to the motor learning studies described in Chapter 4 and 5, large individual differences in sequence duration were observed for both the syllable reading and finger tapping task. Descriptive analysis showed a subgroup of PWS who were slower and more variable in performance and made relatively little improvement gains across practice trials. This is consistent with Smits-Bandstra et al. (2006) and Ludlow et al. (1997) where similar subgroups based on motor learning performance were identified. While there has been some research efforts to identify subtypes of PWS based on family history (Poulos & Webster, 1991; Yairi & Ambrose, 2005), frequency and type of stuttering (Schwartz & Conture, 1988), language development (Preus, 1981), and neurological differences (Giraud et al., 2007; Neumann et al., 2003), no study has systematically investigated individual differences in motor abilities, with the exception of Foundas et al. (2004) who reported poor auditory – motor abilities in a subgroup of adults who stutter. This area of investigation may prove useful in the clinic when considering how to structure treatment in order to maximize the learning of a new fluency skill. This topic is discussed in more detail later in this chapter.

In summary, findings did not support the hypothesis that the ability to learn a simple, sequential speech and nonspeech motor task is predictive of treatment outcome. Nor did the results show that working memory ability is linearly related to treatment outcome. Results from Chapter 3 and Chapter 4 led to the assumption that PWS possess limitations in motor abilities rather than a deficiency in motor learning. If this is the case, then perhaps an investigation into the extent to which individual differences in motor ability is related to differences in treatment outcome would have been more successful. The following section discusses how the differences in practice effects and learning reported in this dissertation may be a reflection of limitations in motor ability.

Motor skill limitations in people who stutter

Findings from the current studies do not support limitations in motor learning abilities in PWS for the following reasons. First, PWS showed practice-related improvements in performance in reaction time
and sequence duration that were similar to the PNS’ on the syllable reading task. That is, both groups showed log-linear performance slopes (Newell & Rosenbloom, 1981). Similar performance gains were observed in the PWS and PNS when performing the finger tapping task despite showing an interference effect in the PWS on day two. Second, as discussed previously, PWS showed the ability to retain improvements in syllable reading and finger tapping skill following a 24-h retention period. Third, visual inspection of the graphed data for finger tapping sequence duration under single and dual task conditions showed that, with practice, the difference in performance between the single and dual task condition for PWS lessoned (improved) and came closer to the differences observed in the PNS. This observation suggests the potential for PWS to transition the finger tapping skill to a more automatic state if given more opportunity to practice. Last, individual differences in motor practice on a speech and nonspeech task were not correlated with fluency treatment outcome.

Instead of a deficiency in motor learning, it is more likely that PWS’ inability to reach the speed of performance observed in the PNS following the practice and retention of the syllable reading and finger tapping task is a result of limitations in their motor skill. Motor skills are thought to fall along a continuum in which individuals across a normal population vary in their level of ability used to carry out a task. This notion is most evident when considering performance in music, sports or art. As Van Lieshout et al. (2004) describes if practice was all that was required to master a skill such as singing or playing the piano we could all be considered experts if we put in our time and energy to practice. However, we know this not to be the case. This is because a motor skill is composed of a number of different underlying abilities used to master a particular task (Schmidt, 1988). These abilities include higher level cognitive processes such as working memory, emotion, motivation as well as sensory integration and motor processes. For instance, finger tapping a sequence of numbers printed on a computer screen requires cognitive ability for focused attention and strategy development as well as motor abilities to react quickly and carry out the sequence of alternating finger movements with good
speed. The collection of abilities used to carry out a particular task are thought to be relatively stable traits that are either genetically determined or developed during growth and maturation (Schmidt, 1988).

While a motor skill is thought to recruit a very specific set of underlying abilities, one hypothesis states that this set of abilities recruited to perform a particular task will change with practice (Fleishman & Hempel, 1955; Fleishman & Rich, 1963; Fitts & Posner, 1967). For instance, performance during the early stages of practicing the finger tapping task described in Chapter 4 is thought to be largely dependent on an individual’s cognitive abilities such as thinking and reasoning; while later in practice there is less reliance on cognitive functioning as reaction time, movement speed and stability become more important (Fleishman & Rich, 1963; Schmidt, 1988). Adhering to this assumption, findings from the current study point to differences in PWS that are specific to motor control due to the fact that group differences remained later in practice when motor abilities are thought to dominate.

The influence an individual’s ability level has on their overall motor control and learning is unclear. For instance, PWS’ reduced motor abilities may influence their ability to activate and/or parameterize GMPs, a difficulty observed to occur in individuals with apraxia of speech (Aichert & Ziegler, 2004; Clark & Robin, 1998). Or difficulties in error detection may have led to a disruption in the development of a sufficient recognition schema (Kent & Rosenbek, 1983). Nonetheless, the studies included in this dissertation show that PWS’ reduced performance on simple, sequential motor tasks may be due to limited motor abilities which may have an effect on their forward control system.

The idea that PWS possess limited motor skills has been proposed by Van Lieshout et al. (2004) and others (De Nil, 1999; Hulstijn & Van Lieshout, 1998) due to findings of differences in PWS compared to matched controls in movement initiation and control (Peters, Hulstijn & Van Lieshout, 2000; Van Lieshout et al., 1993; Zimmerman, 1980). Slower initiation of speech (e.g. phonatory and articulatory movements; Peters et al., 1989) and nonspeech movements (e.g. finger tapping; Webster, 1986) have been demonstrated in a number of reaction time studies (see Peters et al., 2000 for a review). Similarly,
producing single words (Chang et al., 2002; Van Lieshout et al., 1996) and sentences (Bosshardt et al., 1997; Cooper & Allen, 1977) as well as sequences of finger movements (Smits-Bandstra et al., 2006; Zelaznik et al., 1997) have elicited slower movement durations in PWS compared to controls (see also Van Lieshout, 1995). Other areas of investigation provide further support for the notion of limited motor skills in PWS and are described in the following sections.

Cognitive-linguistic demands on the speech-motor system in PWS

Limitations in PWS’ motor skill become most evident when speaking demands exceed the capacity of the individual’s speech motor system. This has been most evident in studies assessing the relationship between speech motor performance and cognitive-linguistic properties of the utterance to be spoken (Howell, Au-Yeung & Sackin, 2000; Kleinow & Smith, 2000). For instance, Kleinow and Smith (2000) assessed the articulatory stability of the lower lip in PWS and PNS when producing a baseline utterance manipulated in length and complexity using a measure called the spatiotemporal index (STI). Although PWS demonstrated higher overall STI values (lower stability) compared to the PNS across all experimental conditions; unlike PNS, the speech motor stability of PWS decreased when the target utterance increased in complexity. Results emphasize the influence of linguistic factors on the speech motor system (see also Van Lieshout et al., 1995) and highlight the vulnerability of the motor system in PWS compared to PNS.

Several other studies have shown that increasing the length (Logan & Conture, 1995; Yaruss, 1999) or complexity (Kleinow & Smith, 2006; Logan & LaSalle, 1999; Zackheim & Conture, 2003) of a spoken utterance elicits an increase in the frequency of stuttering. Also, studies have shown the frequency of stuttering increases with an increase in cognitive demands under dual task conditions (Bosshardt, 1999; Greiner et al., 1986). For instance, Bosshardt (1999) found an increase in stuttering frequency in PWS when asked to repeat random three-word sequences concurrently with a mental calculation task. The Demands and Capacity Model (Starkweather, 1987) proposed that an innate weakness in the speech-
motor system may render a PWS’ system more vulnerable to fluency breakdown when environmental and/or task demands increase. Although this model proposed that PWS may possess limitations in their cognitive, linguistic, motor or emotional capacities, the current findings point to limitations in motor control only, thus are adhering more to Namasivayam and Van Lieshout’s (2011) theory of motor skill limitations in PWS.

It is important to keep in mind that an increase in cognitive-linguistic demands also place additional strain on PNS (Colburn & Mysak, 1982; Kleinow & Smith). This becomes most evident when observing normal disfluencies in children when producing emerging grammar forms (Rispoli & Hadley, 2001). However, through maturation, a PNS learns to handle these demands under most circumstances.

In sum, it appears that an increase in cognitive – linguistic demands are thought to affect the stability of the speech-motor system in PWS (Kleinow & Smith, 2000) as evidenced by an increase in speech-motor variability (Kleinow & Smith, 2000) and stuttering frequency (Bosshardt, 1999; Zackheim & Conture, 2003). This increase in vulnerability of the speech-motor system in PWS compared to PNS may be due to limitations in motor skill.

**PWS’ over-reliance on intrinsic feedback**

The notion that PWS possess limitations in motor skill may help explain the experimental research that has found PWS to rely more on sensory feedback compared to controls when performing motor tasks (De Nil et al., 2001; Jancke, 1991; Kalveram, 1991; Van Lieshout, Peters, Starkweather, & Hulstijn, 1993; Van Riper, 1982). This is because PWS’ motor limitations make their performance more characteristic of the early stages of skill learning when motor processing and execution is largely dependent on sensory feedback (Namasivayam & Van Lieshout, 2011).

Namasivayam, Van Lieshout, and De Nil (2008) proposed that PWS benefit from an overreliance on sensory feedback and that selectively increasing kinesthetic feedback may be a strategy used to maintain stability. In this study, PWS showed larger amplitudes and peak velocities in upper lip
movements when producing bi-syllabic nonwords under bite block conditions at a fast speaking rate. Larger upper lip amplitudes allowed for an increase in sensory feedback which subsequently resulted in greater stability (decrease in variability) compared to controls. The authors posit that PWS may employ larger movement amplitudes as a motor control strategy used to compensate for a limitation in their speech motor skill.

Others posit that an overreliance on sensory feedback is due to a deficient feedforward control system (Civier, Tasko, & Guenther, 2010; Max et al., 2004). In this case, an overreliance on feedback control is hypothesized to be the source for the sound/syllable repetitions of PWS. As Neilson and Neilson (1987) state, speech is too rapid to rely on auditory feedback alone and that instead it is more dependent on a feedforward control system. As Civier et al. (2010) proposed, speech repetitions in PWS are a result of a mismatch between feedforward and feedback (auditory) control, resulting in production errors, which in turn cause the motor system to “reset” and repeat the current sound or syllable. This hypothesis is based on the computationally simulated consequences of a feedback and feedforward pattern in a neural network model called DIVA (Directions into Velocities of Articulators; Guenther, Ghosh, & Tourville, 2006).

According to the DIVA model, speech motor control is comprised of both a feedforward and feedback control system. Under feedforward control, speech production is based on learned speech motor programs that are acquired through previous attempts at producing the speech sound targets. The feedback control subsystem monitors any mismatches between the sensory expectations of a speech motor program and the actual incoming sensory feedback. According to the DIVA model, the feedforward and feedback commands work together when developing speech motor commands. This enables the speaker to produce the rapid speech which is required during conversation while still remaining sensitive to errors. The DIVA model assumes that through practice and experience, an individual learns the speech targets required in connected speech and as a result becomes less reliant on
the feedback control mechanism, and subsequently runs primarily on feedforward control. Under this premise, an overreliance on auditory feedback control results in time lags between the desired speech output and the actual sensory feedback during speech, resulting in a sensorimotor error. When this error becomes too large during speaking, the system’s immediate response is to self repair by disrupting phonation and attempting to reproduce the erroneous syllable. This repeated attempt to produce the syllable without error is what the listener observes as a sound/syllable repetition (Civier et al., 2010).

Although the studies included in this thesis did not investigate the kinematic or coordination abilities from external feedback, it is reasonable to assume that the significantly slower movements in PWS compared to PNS on both the speech and nonspeech task may have been an affect from a weakness in the feedforward system of movement (Civier et al., 2010). It is possible that an overreliance on sensory feedback due to the need to continually monitor their movement caused the need for sustained attention on the primary task, which was shown by greater interference from the tone monitoring task.

In summary, PWS’ limited speech motor skill results in movement characteristics that resemble the early stages of learning a novel motor skill. That is, relative to PNS, their performance is slow, more variable, and reliant on sensory feedback. While an overreliance on sensory feedback is suggested to be a compensatory strategy (Namasivayam & Van Lieshout, 2011), others posit it to be due to impairment in the feedforward motor system and is the source for fluency disruptions.

*Neurological evidence for limitations in a feedforward motor system*

It seems likely that the limitations in motor abilities in PWS observed on a behavioral level may explain some of the reported structural and functional neurological differences in imaging studies that set them apart from matched controls. Significant to the current findings is the neurological differences that have been reported in the feedforward processing mechanism proposed for fluent speech processing (Chang, et al., 2011; Salmelin et al., 2000; Sommer et al., 2002). Golfinopoulus (2010) proposed that as opposed to feedback processing, which is heavily reliant on sensory feedback, the more efficient
feedforward processing of speech involves inferior frontal to motor connectivity. Using MEG during a task of single word reading, Salmelin et al. (2000) found that PNS had activity changes first in the inferior frontal regions, which were then followed by changes in the primary motor area. However, the reverse order in brain activity was observed in the PWS, even during fluent speech. This suggested abnormal connectivity between the inferior frontal and the motor areas for speech production. Several other studies also report abnormalities involving the connectivity between the left inferior frontal and premotor/motor cortex (Chang et al., 2008; Sommer et al., 2002; Watkins et al., 2008). In addition, Chang et al. (2011) found that connectivity differences in motor regions in PWS are not limited to the orolaryngeal representations of the motor cortex but may include motor regions important for nonspeech movements as well. Findings coincide with the proposed disrupted feedforward processing in the stuttered speech of PWS (Civier et al., 2010; Max et al., 2004) thus leading to an overreliance on feedback processing (De Nil et al., 2001; Van Lieshout et al., 1993). Differences in the feedforward control system in PWS may manifest itself as slower movements that require more time and effort for sensory processing.

The notion that PWS possess limitations in motor skill seems plausible considering the evidence, however it is still a rather oversimplification, especially when considering the research that has found that performance on a particular task is dependent on not one but a collection of abilities (Fleishman, 1967, 1978). What specific motor abilities are limited in PWS remains to be seen but considering that PWS’ slower syllable reading and finger tapping performances continued following a significant number of practice trials and retention, well after cognitive abilities were thought to be needed, it can be assumed that the inherent differences between PWS and PNS are motoric in nature. Furthermore, the current findings suggest that the same motor abilities that appear to be limited in PWS are recruited when performing a speech and finger tapping task. One explanation for this is that the finger tapping task may have involved silent articulation which is thought to recruit the same motor areas as overt articulatory
motor control (Cowell, Egan, Code, Harasty, & Watson, 2000; McGuire, Sibersweig, & Frith, 1996; Ryding, Bradvik, & Ingvar, 1996; Desmond, Grabrieli, Wagner, Ginier, & Glover, 1997).

In summary, findings from the studies included in this dissertation support the notion of limitations in the motor abilities of PWS. It is proposed that these limitations may have a negative effect on their feedforward control system, leading them to rely too heavily on sensory feedback control. Limited motor abilities in PWS provides the rationale for the findings presented in this dissertation, primarily the consistent slow speech and nonspeech movement and the increase in sensitivity compared to PNS to an interfering task. This hypothesis conforms to previous behavioral (Chang et al., 2002; Peters et al., 2000; Zimmerman, 1980) and neuroimaging studies (Chang et al., 2011; Salmelin et al., 2000; Sommer et al., 2002). The following section discusses possible implications of limited motor abilities to our understanding of treatment outcome.

**Implication to Treatment**

As more and more research is pointed to limitations in PWS’ motor abilities, it seems worthy to gain a deeper insight into the effects limited motor abilities can have on the learning and maintenance of a new fluency skill by drawing from principles of motor learning (Maas et al., 2008). For instance, Guadagnoli and Lee (2004)’s Challenge Point Framework provide insights into how treatment can be structured to optimizing learning by taking into account task difficulty as it relates to an individual’s skill level. According to this framework, to optimize learning, the learner must be challenged, and that learning may be hampered if the challenge is too great or not great enough. According to this framework, the learner is able to benefit the most if the availability and interpretability of task information is optimal. However, if task difficulty exceeds an individual’s capacity (challenge point), the potential benefit to learning diminishes. In other words, even though the amount of information available increases, it is too much information to be used effectively (Marteniuk, 1976; Guadagnoli & Lee, 2004). In terms of PWS, it seems straightforward that their limitations in motor abilities, as presented in the current studies, would classify
them as what Guadagnoli and Lee (2004) term ‘lower skilled performers’. Fluency techniques should, therefore, be first introduced under conditions of very low task difficulty. Some examples of conditions that have the potential to optimize learning for individuals with a reduced motor ability are described below.

*Variable versus constant practice*

An important factor shown to affect learning and the generalization of a skill is the amount of variability in a practice session (Schmidt, 1988). Constant practice refers to practice on only one variation (parameter) of a movement (GMP); as opposed to variable practice which targets more than one variable of a given movement (Maas et al., 2008). Speech and nonspeech motor learning studies suggest that variable practice increases the ability to generalize a skill (Adams & Page, 2000; Lee, Magill, & Weeks, 1985; Wulf & Schmidt, 1997). For instance, Adams and Page (2000) found that participants who practiced the utterance “Buy Bobby a poppy” at two different speaking rates (2400ms and 3600ms) showed significantly less errors on tests of retention compared to participants who practiced the same utterance at one speaking rate (2400ms). Results such as this suggest that variable practice shows more benefits for speech motor learning compared to constant practice.

The importance of incorporating variability within a practice session seems obvious when considering the fact that many tasks have variability inherent to them, especially in regards to speaking. Variable practice allows experience with a wide range of movement outcomes, initial states, and sensory consequences which ultimately leads to the development of a rule (schema) for selecting parameters of the GMP. Schmidt & Bjork (1992) propose that variable practice results in a more reliable schema that facilitates the transfer and generalization of a rule to other novel movements requiring the same motor program.

In Kroll and Scott-Sulsky’s (2010) Fluency Plus Program, the target ‘2-second stretch’, is practiced for the first six days of the program, followed with ‘1-second stretch’ until day nine of the program. After this clients learn to produce just enough stretch so that the client can feel each target being
completed accurately, yet is natural enough to be transferred to everyday conversations. Based on what we know about motor learning and the benefits of variable practice, it seems reasonable to assume that PWS would show better transfer and generalization of this fluency skill if given variable practice earlier in the treatment program. For instance, when first learning the speech target on day one or two of the program, practice conditions could vary and include alternating blocks of 1-second and 2-second stretch.

Variable practice could also be applied to O'Brian et al.’s (2008) Camperdown Program. In this program, clients listen to an exemplar of prolonged speech and then reproduce this pattern of speaking until mastered. At that time, clients apply this new pattern of prolonged speech to monologue and conversation. Perhaps the prolonged speech exemplars could vary in speaking rates in order to provide the client with opportunity to practice more than one variation of the movement.

*Blocked versus random practice*

Practice schedule has been shown to strongly influence learning outcome, for example when referring to random versus blocked practice schedules (Maas et al., 2008; Guadagnoli & Lee, 2004; Schmidt, 1988). Blocked practice refers to a practice schedule where an individual practices the same target movements in a repetitive way (e.g. AAAA); whereas random practice refers to a practice schedule where different movements (i.e. GMPs) are practiced in random order (e.g. ACB, BAC, etc) or simultaneously (Maas et al., 2008; Schmidt, 1988). Knock et al., (2000) is the only study to date that has compared the effects from blocked versus random practice in treatment for individuals with a speech-motor impairment. In this study, two individuals with severe apraxia of speech appeared to benefit more on retention tests when practicing the targets in random versus blocked practice. However, using a nonspeech task, Guadagnoli and Lee (2004) showed that participants with lower skill level benefited more from blocked practice; while highly skilled individuals benefited more from random practice.

It is more common for fluency programs such as the Fluency Plus Program (Kroll & Scott-Sulsky, 2008) and Comprehensive Stuttering Program (Boberg & Kully, 1985) to have clients practice a
new fluency target in combination with other targets that have already been established. In this case, very little time, if any, is given to practicing the targets in isolation. Results from the nonspeech study reported in Chapter 5 found that PWS showed larger interference compared to PNS when practicing a finger tapping task under competing conditions. This interference effect was shown to continue following a 24-hour retention period. Based on these findings, it seems reasonable to speculate that applying multiple fluency targets at such an early stage of learning may interfere with the learning process. Perhaps if PWS were given more opportunity to practice a fluency target under less-competing conditions (e.g. in isolation at word and sentence level) they would show stronger retention and generalization of skills. This is further supported when reviewing motor learning studies investigating the benefits of practicing a repetitive task in isolation among skilled versus unskilled performers (Wulf & Shea, 2002; Wright, Black, Immink, Brueckner, & Magnuson, 2004) and leads to the assumption that PWS would benefit the most if given the opportunity to practice a single fluency technique in isolation as opposed to performing a new fluency target together with other targets that have already been established.

In summary, a great deal of research has been devoted to understanding variables that are involved in maximizing learning (Schmidt, 1988), some prove pertinent to our understanding of ways to optimize the learning of new fluency skill in PWS with limited motor abilities. Variability and scheduling of practice are two examples.

Limitations and future directions

The syllable reading and finger tapping tasks used in this dissertation were relatively simple in nature. The purpose of using simple, repetitive strings of nonsense words and numbers was to minimize the risk of confounding variables from higher order cognitive processing and thus remain motoric in nature. However, it is possible that these tasks were too simple to elicit differences in motor learning between PWS and PNS. This was suggested in the performance curves for the speech task where both groups quickly reached a plateau in only a few trials. Future analysis may find that a task requiring more complex
sensorimotor integration is more effective at teasing apart differences in learning among groups. For example, a serial reaction time task requires participants to press one of four buttons, as quickly and as accurately as possible, corresponding to the location of stimuli presented at different locations on a computer screen (e.g. Doyon et al., 2002). Future analysis may also consider the use of a transfer task as a means to measure motor learning. The ability to transfer gains in performance on one task as a result of practice on another task is considered a strong indicator of motor learning. While retention tests revealed only slight differences between PWS and PNS; transfer tests may have proved more challenging and as a result, yielded stronger group differences.

The behavioral changes that occur in accuracy, reaction time, and sequence duration during practice are considered strong indicators of motor learning and are frequently used when measuring practice-related changes on sequence skill tasks (Schmidt & Lee, 2004). An important caveat is that these behavioral measures may not have been sufficient in capturing the small and rapid changes in performance that occur with practice, particularly with a sequence skill learning task where individual segments are combined to form one continues unit. Therefore, it may be beneficial to explore motor learning abilities in PWS under a different level of analysis, such as using kinematic and neurological measures. Kinematic measures of variability/stability may be more effective at differentiating motor learning between PWS and PNS. A decrease in variability is an important indicator of motor learning (Schmidt & Wrisberg, 2004) and some studies have found more variability in performance in PWS when performing speech and nonspeech tasks. For instance, Kleinow and Smith (2000) found that the difference in variability in upper lip movement in PWS compared to PNS increased as sentence complexity increased. Results such as this suggest that PWS’ motor control system is particularly sensitive to an increase in demands, perhaps due to limited motor abilities.

Neurological analysis may also yield important insights into the neural processes underlying motor control under conditions of practice and learning in PWS. While recent brain imaging studies have
demonstrated significant activation and structural differences in PWS in sites proven to play a role in motor learning (De Nil et al., 2003; Fox, 2003; Giraud et al., 2008; Wu et al., 1995), the functional relevance of these differences and their effects on skill learning still remain to be studied.

One observation that was apparent across all three studies presented in this dissertation was the large within group differences in sequence duration for the PWS compared to PNS. Descriptive analysis showed a subgroup of PWS who, not only performed consistently slow across practice and retention, but also failed to improve with practice. This descriptive finding raises some interesting questions, particularly with respect to treatment outcome variability. Future investigations aimed specifically at identifying subgroups of PWS based on motor abilities are warranted.

For those who do not recover spontaneously, the disorder can be hard to treat, especially in older children and adults, and partial or complete relapse following treatment is likely to happen (Bloodstein & Bernstein Ratner, 2008; De Nil & Kroll, 1995). Although research has investigated many factors that may predict the long term fluency success from treatment, the motor abilities of PWS have not yet been explored. Based on the present findings, future research might consider investigating ways treatment programs can be modified in order to facilitate long term maintenance of a fluency skill in PWS with limited motor abilities by drawing from principles of motor learning. For instance, studies of motor learning show that retention and transfer is dependent on the ability to perform a task within a random practice schedule. In this case, PWS may benefit from practicing randomly assigned fluency skills on target words or utterances, an approach that has not been used. This would equip the PWS with the ability to apply a fluency skill in a speaking situation on short notice and in situations with unexpected changes. Another example would be to incorporate dual tasking into a treatment program, an area of research that is already underway (Metten et al., 2011). Metten et al. (2011) found that clients benefit from practicing newly learned fluency skills under dual task conditions as it helps in maintaining their newly learned skills in more realistic speaking situations where attentional resources are often diverted away from the use of controlled
fluency. In short, more research is needed in testing whether one or more principles of motor learning, if applied to a treatment protocol, would facilitate the long term maintenance of a fluency skill.

In the study presented in chapter 5, performance on a syllable reading and finger tapping task was hypothesized to be a predictive factor to long term treatment outcome. An important caveat is that these tasks may have not captured the same skills that are required when learning a new fluency technique. Therefore, it may be beneficial to explore the learning abilities in PWS compared to controls using some of the same fluency enhancing techniques used in the clinic within a controlled laboratory setting.

Although it is reasonable to assume that motor learning abilities play a predictive factor in the establishment of fluency enhancing skills, other factors such as the nature and severity of negative attitudes and emotions related to stuttering are considered to be equally important to treatment outcome (Huinck et al., 2006; Yaruss, 2010). After all, stuttering is a multidimensional disorder that not only includes both overt behaviors of stuttering but the introspective characteristics associated with many years of living with the disorder such as negative attitudes and emotions. In fact, stuttering severity and introspective clinical characteristics are considered related but individual phenomenon (Huinck et al., 2006; Watson & Alfonso, 1987). Due to these issues, many comprehensive stuttering treatment programs for adolescents and adults place a strong emphasize cognitive restructuring (e.g. Kroll & Scott-Sulsky, 2010).

Huinck et al. (2006) found that stuttering severity and negative emotions and cognition did not correlate with each other. This was based on the finding that the adult participants in an intensive fluency enhancing program (i.e. ISTAR) who showed severe emotional and attitudinal problems associated with the disorder showed a relatively low frequency of stuttering, even before treatment. As a result, Huinck et al. (2006) suggested that different treatment approaches (fluency shaping versus cognitive restructuring) should be used depending on the individual clinical profile. Results such as these highlight an important issue regarding treatment outcome. That is, treatment success may not always reflect the learning and retention of fluency enhancing skills but instead may be due to a decrease in negative attitudes and
emotions that have mounted within an individual over the years of living with the disorder. In this type of scenario, the relationship between the ability to learn an unrelated motor task and treatment success is not being captured. Due to these concerns, future research could investigate the two distinct dimensions of stuttering (overt and covert aspects) and how they each relate to a proposed interaction between motor learning ability and treatment outcome. In addition, research efforts should be aimed at directly examining practice and learning of fluency targets using kinematic and behavioral measures on both a short and long term basis.

**Conclusions**

The results presented in this dissertation did not support the hypothesis of a deficiency in motor learning abilities in PWS. Instead, results suggest PWS’ inability to reach the speed of performance observed in PNS following the practice and retention of the sequential syllable reading (Chapter 4) and finger tapping (Chapter 5) tasks are due to limitations in their motor abilities. When repeating a syllable reading task (Chapter 4), PWS showed practice-related improvements in performance in reaction time and sequence duration that were similar to the PNS’. Similar performance gains were observed between groups when performing the finger tapping task (Chapter 5) despite showing an interference effect in the PWS on day two. Also, results from Chapter 4 and Chapter 5 suggested similar working memory abilities between PWS and PNS as both groups showed relatively rapid performance gains during this early phase of learning when cognitive abilities are thought to dominate. In regards to measures of motor learning, PWS showed the ability to retain improvements in syllable reading and finger tapping skill following a 24-h retention period. Although interference effects for sequence duration in PWS remained following the practice and retention of a finger tapping task (Chapter 5), descriptive analysis showed that these group differences lessoned with practice, suggesting that PWS did have the potential to automatize the task to the same degree observed in PNS, but at a slower rate. In the pre- and post-treatment study (Chapter 6), individual
differences in motor practice on a speech and nonspeech task were not correlated with fluency treatment outcome.

When combined, all three studies provide evidence for limited motor abilities in individuals with developmental stuttering. These results are consistent with theories of a limited (Namasivayam & Van Lieshout, 2011; Van Lieshout et al., 2004) or impaired (Civier et al., 2010; Max et al., 2004) feedforward control system which results in an overreliance on sensory feedback. Research is needed in order to determine whether stuttering treatment outcomes can be improved by drawing from principles of motor learning in order to optimize learning in PWS with limited motor abilities.
Appendix A

Self-Evaluation of Fluency Effort

Name ___________________
Date _____________________

Instructions: Please complete the following list of 25 situations by rating your effort at using your new speech targets. Please make these judgments honestly with respect to your present ability, not according to what you want to do or think you should do. Even if you don’t experience a situation described, please rate how much effort you think it would take at using your fluency skills in that situation. Rate your effort by circling a number from 1 to 5 after each situation when 1 indicates no effort and 5 indicates extreme effort.

<table>
<thead>
<tr>
<th>No Effort</th>
<th>Extreme Effort</th>
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<tbody>
<tr>
<td>1. Phoning a friend to confirm a time to meet.</td>
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<tr>
<td>2. Placing a person – to – person long distance phone call with the assistance of an operator</td>
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<tr>
<td>3. Introducing oneself to a stranger</td>
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<tr>
<td>4. Introducing one friend to another friend.</td>
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<tr>
<td>5. Talking informally at a dinner with 4 or 5 acquaintances.</td>
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<tr>
<td>6. Ordering a meal for yourself and a friend in a restaurant.</td>
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<td>7. Ordering food over an intercom at a drive-in restaurant.</td>
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<tr>
<td>8. Asking a neighbor for a ride.</td>
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</table>
9. Explaining to a bank teller what you want to deposit.  

10. Calling room service in a hotel to order breakfast for tomorrow  

11. Talking to a doctor about a health problem  

12. Telling a taxicab driver where to take you  

13. Speaking with an elderly person with a hearing problem  

14. Speaking with a supervisor or teacher  

15. Being at an office or school party with 40 or 50 others  

16. Phoning a stranger to ask for information  

17. Having lunch with someone you have recently met  

18. Asking a question in a meeting or classroom  

19. Leading a group discussion  

20. Giving a short talk at a group meeting or in class  

21. Asking a bus driver for information  

22. Taking one’s car in for service at a garage  

23. Answering questions in class (or at a work meeting)  

24. Talking to your teacher (or your child’s teacher)  

25. Phoning to make an appointment to see a doctor or dentist
Appendix B

Performance Rating Scale Week 1 – Week 3

Name_________________
Date _________________

Performance Rating Scale-Week 1

Instructions: Please circle the correct answer below.

Please rate how you are doing at the following speech targets. Circle the number that best describes how you are doing when 1 indicates you’re completely on target and 7 indicates you’re completely off target.

1. Using 2-second stretch syllables

1  2  3  4  5  6  7
Completely  Completely
on target  off target

2. Stretching the first stretchable sound of the syllable

1  2  3  4  5  6  7
Completely  Completely
on target  off target

3. Doing gentle onsets

1  2  3  4  5  6  7
Completely  Completely
Performance Rating Scale-Week 2

Instructions: Please circle the correct answer below. Please rate how you are doing at the following speech targets. Circle the number that best describes how you are doing when 1 indicates you’re completely on target and 7 indicates you’re completely off target.

1. Using 1-second and ½ second stretch syllables
   
   1  2  3  4  5  6  7
   Completely on target

2. Stretching the first stretchable sound of the syllable
   
   1  2  3  4  5  6  7
   Completely on target

3. Doing gentle onsets
   
   1  2  3  4  5  6  7
   Completely on target

4. Doing RAP 1 and RAP 2
   
   1  2  3  4  5  6  7
   Completely on target

5. Doing FAM
Performance Rating Scale - Week 3

*Instructions: Please circle the correct answer below.* Please rate how you are doing at the following speech targets. Circle the number that best describes how you are doing when 1 indicates you’re completely on target and 7 indicates you’re completely off target.

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1. **Use of New Normal**

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2. **Stretching the first stretchable sound of the syllable**

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3. **Doing gentle onsets**

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4. **Doing RAP 1 and RAP 2**

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5. **Doing FAM**

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