Nonspeech sequence skill learning under single and dual task conditions in adults who stutter

Apprentissage de séquences non verbales dans des conditions de tâches simples et doubles chez des adultes qui bégaient

Kim R. Bauerly
Luc F. De Nil

KEY WORDS
STUTTERING
MOTOR LEARNING
FINGER TAPPING TASK
CONSOLIDATION
AUTOMATICITY
DUAL TASK

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. Learning was measured by comparing 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 plateau in performance while PWS' continued to show improvements in practice on day two. Tests of retention showed that PWS were able to retain the task following retention for accuracy and sequence duration but not reaction time. Although no significant interactions were found for tests of condition, additional assessment showed larger differences in finger tapping performance in PWS compared to PNS when transitioning from the single to dual task condition.

Abrégé

La présente étude a comparé les effets de la pratique et les aptitudes d'apprentissage chez 11 personnes qui bégaient et 12 personnes qui ne bégaient pas en utilisant une tâche de tapotement des doigts dans des conditions de tâches simples et doubles. L'apprentissage a été mesuré en comparant les courbes de performance d'exactitude, de temps de réaction et de durée de séquence. En plus, on a obtenu des mesures pour la capacité de rétention ainsi que pour les effets d'interférence dans les conditions de tâches doubles. Pour les données de temps de réaction et de durée de séquence, les résultats ont montré que la performance des non bègues atteignait un plateau tandis que les bègues continuaient à s'améliorer dans la pratique, le deuxième jour. De plus, les résultats ont montré que les bègues étaient capables de retenir la tâche à la suite de la période de rétention pour l'exactitude et la durée de séquence, mais pas le temps de réaction. Même si on n'a pas trouvé d'interactions significatives, une évaluation additionnelle a montré des différences plus importantes dans la performance du tapotement de doigts chez les bègues, comparativement aux non bègues quand ils passaient d'une condition de tâche simple à une de tâche double.

Kim R. Bauerly, Ph.D., CCC-SLP
Department of Communication Disorders and Sciences, Plattsburgh State University, 224 Sibley Hall, Plattsburgh, NY 12901
U.S.A

Luc F. De Nil
Department of Speech-Language Pathology, University of Toronto, 160-500 University Ave
Toronto, ON
CANADA

Toronto Western Research Institute, University Health Network, Toronto, ON
CANADA

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 client's 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 slower performance gains in PWS compared to PNS when practicing speech or nonspeech tasks (Ludlow, Siren & Zikria, 1997; Neilson & Neilson, 1991; Smits-Bandstra, De Nil, & Saint-Cyr, 2006a; Smits-Bandstra, De Nil, Rochon, 2006b). Using a speech task, Bauerly and De Nil (2011) and Namasivayam and 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.

1. 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).

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 is 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.

1.1. 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; Press, Casement, Pascual-Leone, & Robertson, 2005; Robertson, 2004). 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).

1.2. 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 & Posner, 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 (Fitss & 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 et al., 2002; Schumacher et al., 2001).

2. 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 et al., 1997; Smits-Bandstra et al., 2006b) and nonspeech (Namasivayam 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 et al. (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.

2.1. 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 & 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.

2.2. 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 (Bosshardt, Ballmer & De Nil, 2002; Caruso, Chodzko-Zajko, Bidinger & Sommers, 1994). 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.

2.3. Present Investigation

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 show reduced finger tapping speed and more errors following practice of a sequential finger-tapping task 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?

3. Methodology

3.1. Subjects

Eleven right-handed English speaking males who stutter, ranging in age from 23.1 to 40.1 years (*M* = 33.4, 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, 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, Cooke, & Greiner, 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 as playing a musical instrument or as being 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 no 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 4000 Hz 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 1. PWS' stuttering severity and overall scores using the SSI-4 (Riley, 1994).

PWS	Reading (%)	Speaking (%)	Total Overall Scores(Severity)
1	3	2	10 (very mild)
2	11	10	18 (mild)
3	1	9	11 (very mild)
4	1	5	10 (very mild)
5	0	8	11 (very mild)
6	5	14	18 (mild)
7	1	5	9 (very mild)
8	3	4	18 (mild)
9	1	23	19 (moderate)
10	1	14	12 (mild)
11	14	25	32 (severe)

3.2. 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).

3.2.1. 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 120 practice trials on day one and on day two. The same ten-number sequence was used for all participants. 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.

3.2.2. 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 (250, 500, 1000, 2000 Hz), 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. 250, 1000, 250, 2000 Hz). 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 number 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.

3.2.3. 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 trials, totaling 135 trials. A trial under single conditions consisted of one finger tapping sequence and a trial under dual conditions consisted of one finger-tapping sequence simultaneous with one tone sequence. 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.

3.2.4. 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.

4. 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). For the dual task condition, performance on the tone-monitoring task was assessed using the variables accuracy and reaction time.

4.1 Finger tapping sequence task

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 individual'saverage 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 task condition).

4.2 Tone-monitoring task

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).

4.3 Tests of retention

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.

5. 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).

interaction for Condition x Trial, F (3, 63) = 6.99, $p < .05$, $ή_p^2 = .250$ was found. This interaction indicated that practice of the task reduced the interference effect in the dual task condition, and that this was true equally for both groups. A significant Day x Trial interaction, F (3, 63) = 5.87, $p < .05$, $ή_p^2 = .219$ occurred because of a difference in the effect of practice on the performance curves. For both subject groups, the effect was greatest on day one, while on day two, their changes in performances began to level off (Figure 1). However, this Day x Trial interaction is qualified by the significant Group x Trial interaction F (3, 63) = 2.97, $p < .05$, $ή_p^2 = .240$, pointing to the fact that the two subject groups differed in the overall amount of practice effect across both conditions, with the PWS showing a more pronounced improvement. No other significant interactions were found, nor was there a main effect for Group.

Table 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.

Group	Day	Single			Dual		
	1	Block 1	Block 6	Block 12	Block 1	Block 6	Block 12
PWS		.36 (35)	.90 (.32)	.455 (.25)	1.1 (.25)	.81 (.25)	.81 (.28)
PNS		1.25 (.33)	.50 (.35)	.91 (.37)	1.0 (.4)	.58 (.34)	.41 (.13)
	2						
PWS		.09 (.15)	.63 (.36)	.62 (.39)	.63 (.41)	.81 (.36)	.18 (.14)
PNS		.41 (.15)	.91 (.35)	.91 (.37)	1.0 (.4)	.58 (.34)	.41 (.13)

5.1 Finger tapping sequence task

5.1.1 Accuracy

The results for accuracy are shown in Table 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.

5.1.2 Reaction time

The results for reaction time are shown in Table 3. Both groups showed significant improvements in performance across trials, Trial F (3,63) = 80.71, $p < .001$, $ή_p^2 = .794$ and days, Day F (1, 21) = 89.86, $p < .001$, $ή_p^2 = .811$. A 2-way

5.1.3 Sequence Duration

The duration data are shown in Table 4. PWS showed significantly slower sequence durations compared to PNS across trials, Group F(1,21) = 9.63, $p < .05$, $ή_p^2 = .314$. A significant Group x Trial interaction F (3,63) = 5.64, $p < .05$, $ή_p^2 = .212$ was found because, with practice, sequence durations of PNS reached a relative plateau while PWS continued to show improvement (Figure 2). These group differences were not as pronounced on day two and this may explain why a Group x Day interaction (1, 21) = 5.53, $p < .05$, $ή_p^2 = .209$ occurred. No significant main effect for Condition or significant 4-way interaction was found.

Table 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.

Group	Day	Single			Dual		
	1	Block 1	Block 6	Block 12	Block 1	Block 6	Block 12
PWS		966(46)	744(48)	638(53)	779(72)	598(45)	572(43)
PNS		827(44)	627(46)	525(50)	690(69)	577(43)	480(41)
	2						
PWS		790(45)	555(53)	505(45)	613(48)	477(31)	479(37)
PNS		604(43)	496(51)	472(43)	466(46)	431(30)	410(36)

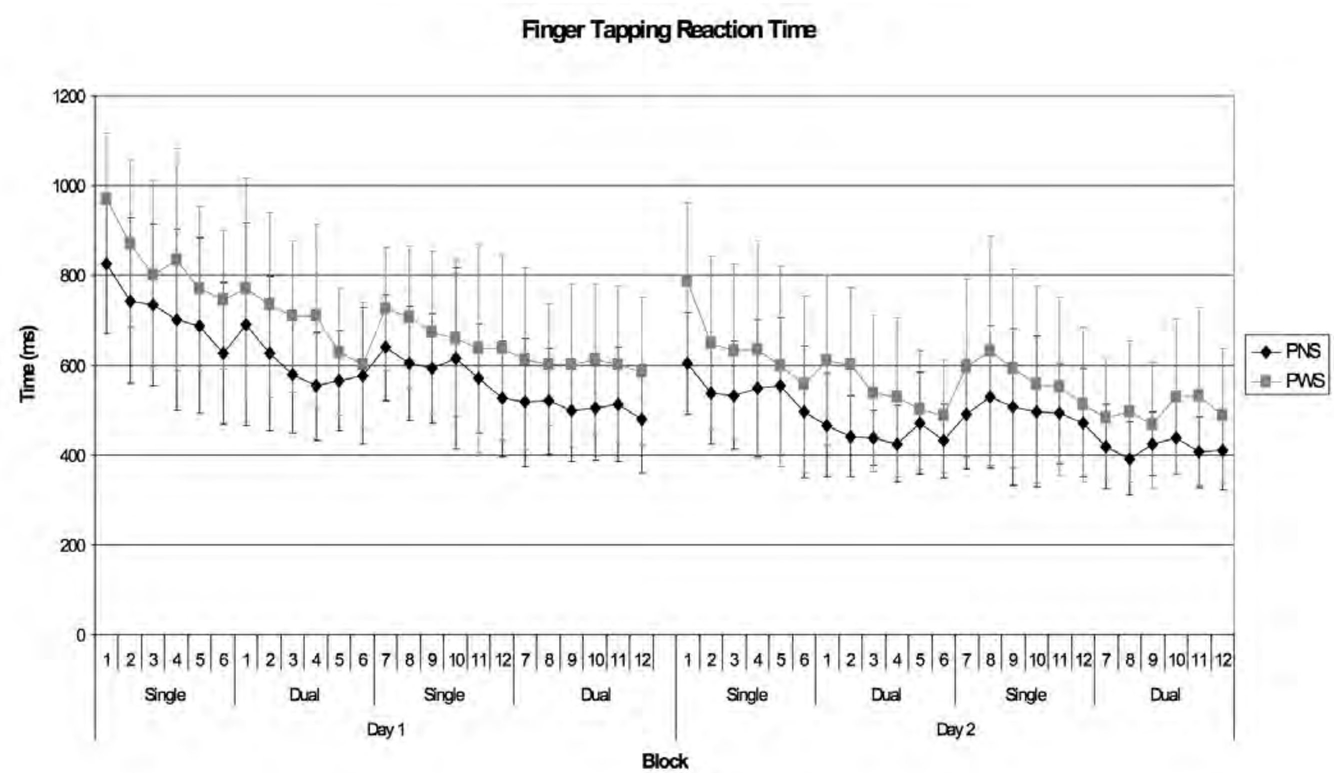

Figure 1. Mean finger tapping reaction times (ms) for single and dual task conditions on day 1 and day 2 for PWS and PNS.

Table 4. The 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.

Group	Day	Single			Dual		
	1	Block 1	Block 6	Block 12	Block 1	Block 6	Block 12
PWS		5166(381)	3528(256)	2800(189)	4623(331)	3606(239)	3213(184)
PNS		3968(365)	2620(245)	2370(181)	3140(317)	2585(229)	2418(176)
	2						
PWS		3018(201)	2526(161)	2403(170)	2941(173)	2710(162)	2602(176)
PNS		2275(193)	2040(154)	2104(163)	2080(165)	2060(155)	2115(169)

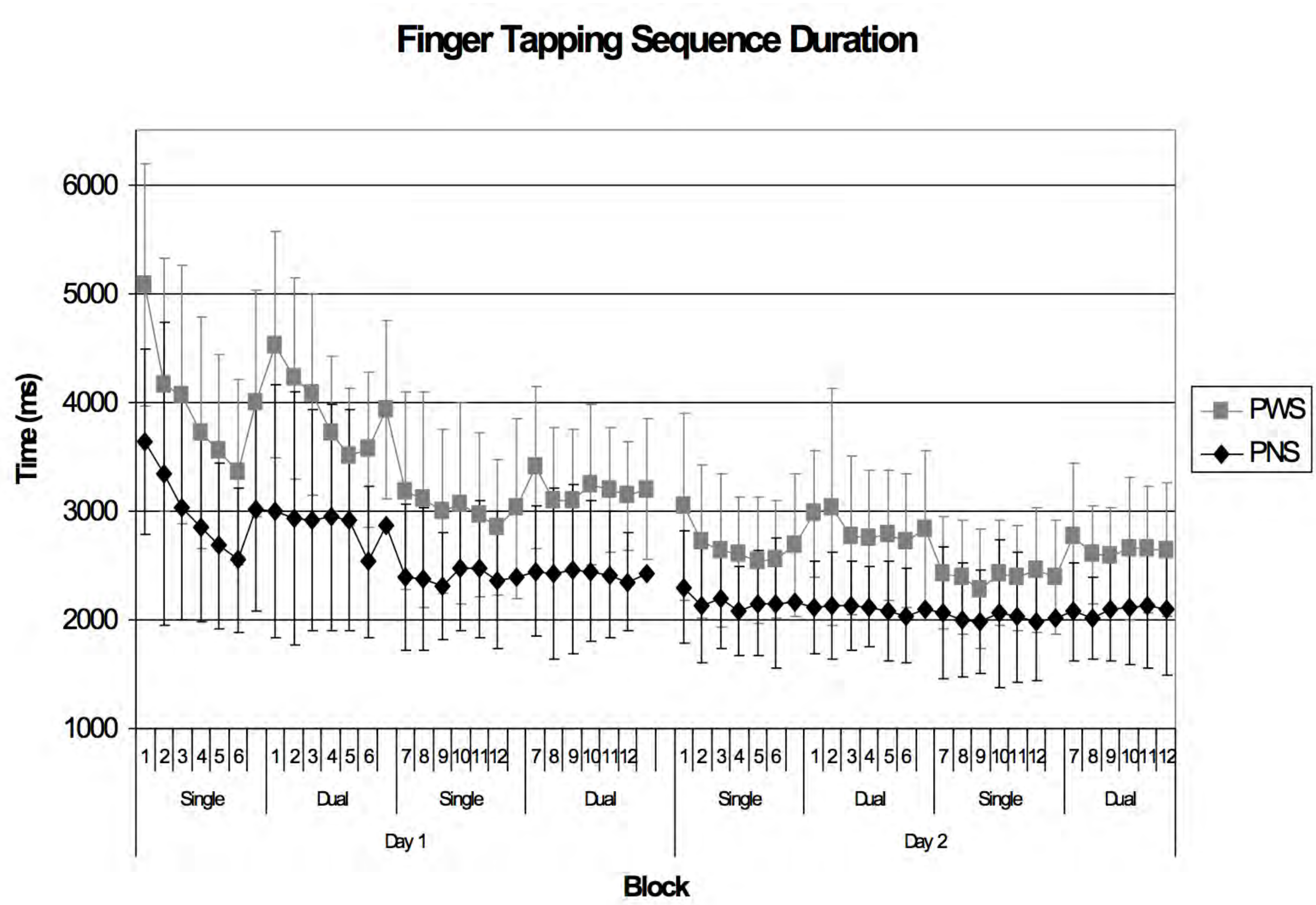

Figure 2. Mean finger tapping sequence duration (ms) for single and dual task conditions on day 1 and day 2 for PWS and PNS

5.2 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 or reaction time 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, $p < .05$, $\acute{\eta}_p^2 = .239$ (Figure 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, $p < .001$, $\acute{\eta}_p^2 = .277$. 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, $p < .05$, $\acute{\eta}_p^2 = .173$. No main effect for Group was found, nor was there a 3-way Group x Day x Trial interaction.

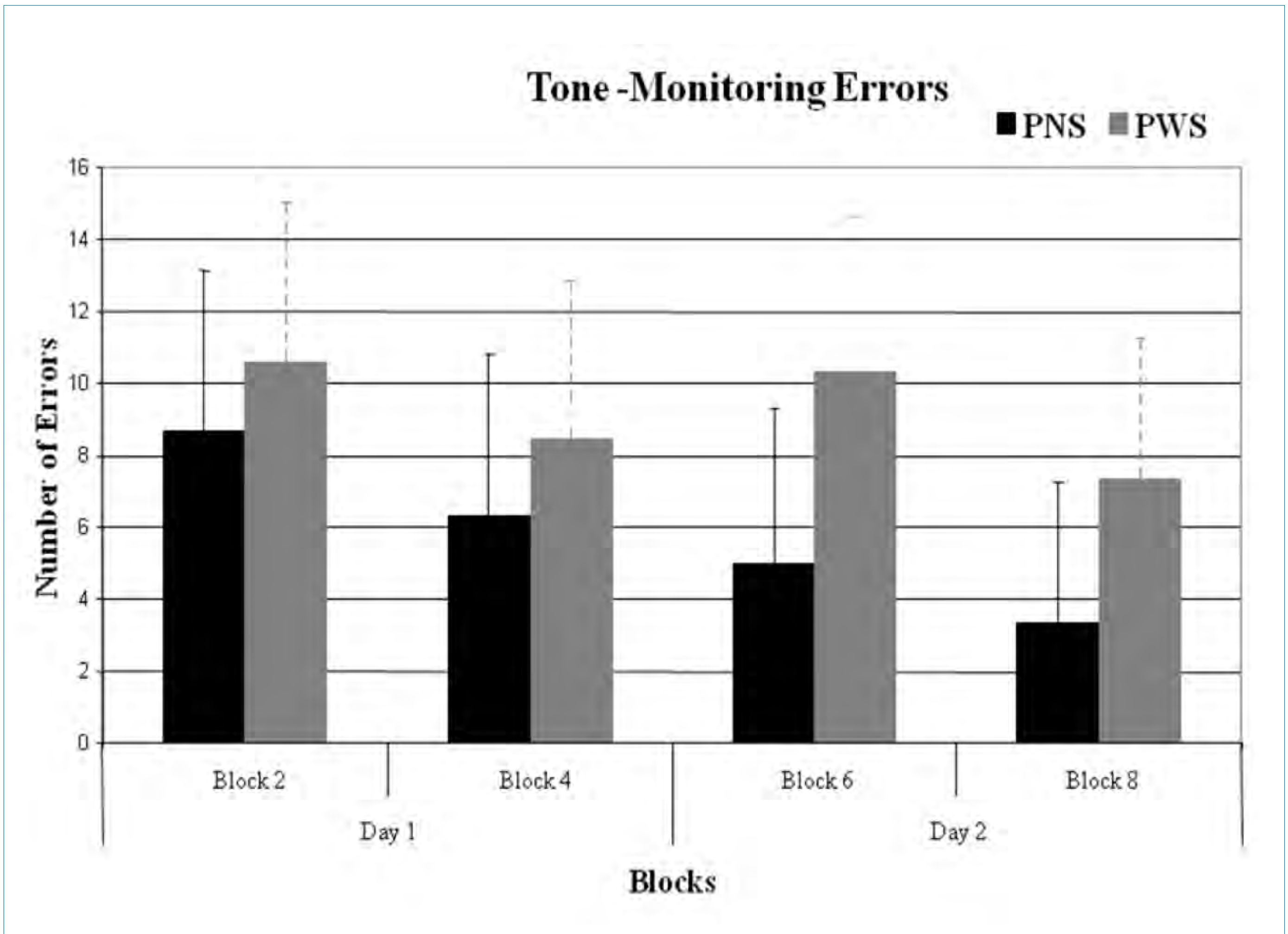

Figure 3. Mean number of tone monitoring errors for PWS and PNS across blocks of 30 trials each on day 1 and day 2.

5.3 Tests of retention

Retention is the ability to maintain improvements in performance from a practice session following a rest period. The results for retention are shown in Table 3 for reaction time and Table 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.

5.4 Analysis of single to dual task transition

Post hoc analysis was conducted to test the interference effects between the single and dual task conditions. Tests of interference were included in order to assess the ability of participants to practice and learn the finger-tapping task under competing conditions. It was assumed that a decrease in interference from the tone-monitoring task would be a reflection of the participants' ability to automatize the primary, finger-tapping task with practice. Interference effects were measured by taking the difference score 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 for each of the following measures: accuracy, reaction time, and sequence duration.

The between-group Levene's Test of Equality of Error Variance was not significant for accuracy, reaction time, or sequence duration data (alpha .05). Because the Mauchly's Tests of Sphericity were significant for reaction time and sequence duration, a Greenhouse-Geisser correction was used. The Mauchly's Test of Sphericity was not significant for the accuracy data (Portney & Watkins, 2000).

No significant difference was found between the single to dual task difference scores for finger-tapping accuracy between PWS and PNS. Likewise, no significant Group main effect or Group x Transition interaction was found. For finger tapping reaction time, no main effect for Group or Transition was found, nor was there an interaction (see Figure 4). With regard to finger tapping duration, both groups improved on their finger-tapping sequence duration as they transitioned from the single to the dual task conditions, Transition: $F(3,63)= 7.86$, $p< .001$, $\acute{\eta}_p^2 = .272$. In addition, PWS showed significantly larger dual task interference effects on both days compared to controls, Group: $F(1, 21) = 14.25$, $p < .001$, $\acute{\eta}_p^2 = .404$ (see Figure 5). No Group x Transition interaction was found.

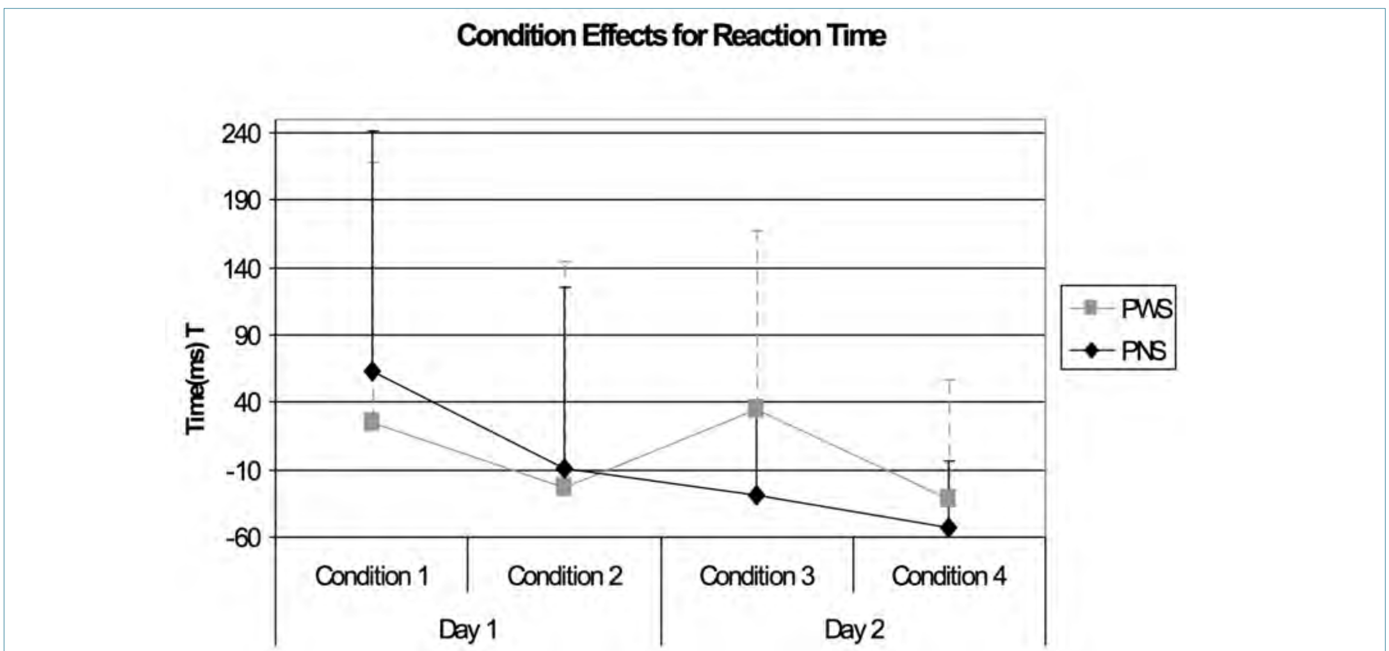

Figure 4. Mean difference in reaction time and variability (S.D.) between the last 5 trials in each single, finger tapping session and the first 5 trials in each subsequent dual session (condition effects) for day one and day two.

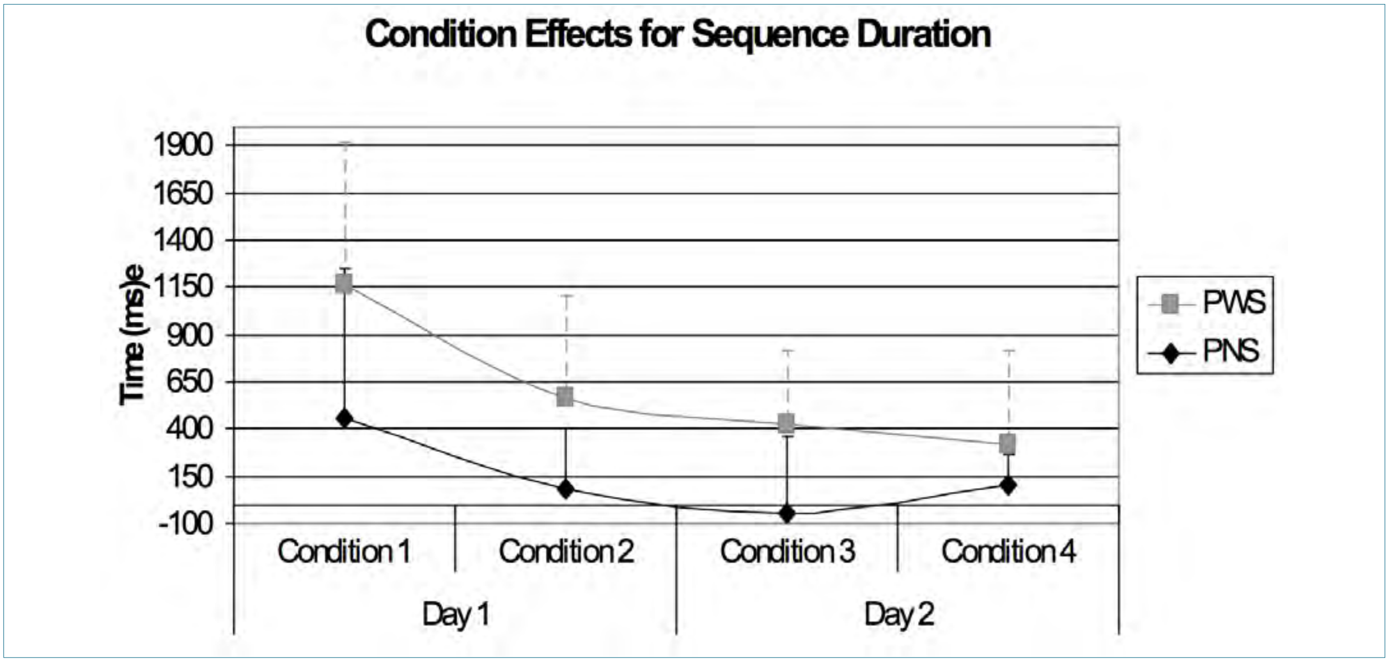

Figure 5. Mean difference in sequence duration and variability (S.D.) between the last 5 trials in each single, finger tapping session and the first 5 trials in each subsequent dual session (condition effects) for day one and day two.

In studies with a small sample size (power = .42) effect size may be more valid than the p-value as an indication of important differences (Portney & Watkins, 2000). The effect sizes in the current study are considered to be moderate to large ($ή_p^2$= .201 to .404) indicating differences between groups that support further investigation using larger sample sizes.

6. 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.

6.1 Finger tapping sequence task

Our first research question was *"Do PWS compared to PNS show reduced finger tapping speed and more errors following practice of a sequential finger-tapping task under single and dual task conditions?"* . 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, 2011; 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 (Forster & Webster, 2001; Max, Caruso & Gracco, 2003). In addition, studies specifically designed to assess practice related differences have found slower performance in PWS when practicing non-speech 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.

6.2. Tests of retention

The second research question addressed was *"Do PWS, compared to PNS, demonstrate a reduced ability to retain the sequential, non-speech task following a 24-hour rest period?"*. 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 non-speech tasks (Cross & Luper, 1979; 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.

6.3 Tests of Interference

The third research question addressed in this study was *"Do PWS show a reduced ability to automatize the sequential, non-speech task compared to PNS by demonstrating greater interference when performing under dual task conditions?"*. 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, post hoc 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 (Brutten & Trotter, 1986 Greiner et al., 1986; Sussman, 1982). Although interference effects for sequence duration in PWS remained following a relatively large number of practice trials, descriptive analysis showed that these group differences lessened with practice, suggesting that PWS may have the potential to automatize the task to the same degree observed in PNS, but at a slower rate (Figure 5).

6.4 Implications for motor skill limitations in PWS

As discussed above, compared to controls, PWS showed: (1) slower sequence durations across practice trials on day one and day two, (2) a reduced ability to retain the finger tapping sequence following a retention period (reaction time only), (3) an increase in tone monitoring errors, and (4) greater interference from the dual task (sequence duration only). One explanation for these differences in performance may be that they show limited motor abilities (De Nil, 1999 Van Lieshout, 2004; Van Lieshout, Hulstijn, & Peters, 1996). 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 (Magill, 1998; Schmidt, 1988).

In regards to individual differences in motor skill, PWS' reduced performance compared to controls demonstrated in the current study reflects limitations in motor skill and 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 non-word 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, particularly under the dual task condition (De Nil & Abbs, 1991; De Nil, 1999; Loucks & De Nil, 2001; Van Lieshout, 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 slower sequence durations under dual task conditions 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, Herbrich Hess, Hoyt, Rosenfield, 1987) 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.

7. Conclusion

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. Instead, results from the current study support the theoretical viewpoint that PWS possess limitations in motor skill. Future research in the area of motor abilities and motor learning is clearly needed, especially given the potential implications for clinical intervention.

References

Arends, N., Povel, D.J., & Kolk, H. (1988). Stuttering as an attentional phenomenon. *Journal of Fluency Disorders, 13,* 141-151.

Baddeley, A. (2003). Working memory: Looking back and looking forward. *Nature Reviews, 4*, 829-839.

Bauerly, K.R. & De Nil, L.F. (2011). Speech sequence skills learning in adults who stutter. *Journal of Fluency Disorders, 36*, 349-360.

Bosshardt, H. G. (1999). Effects of concurrent mental calculation on stuttering, inhalation, and speech timing. *Journal of Fluency Disorders, 24*, 43-72.

Bosshardt, H. G. (2002). Effects of concurrent cognitive processing on the fluency of word repetition: Comparison between persons who do and do not stutter. *Journal of Fluency Disorders, 27*, 93-113.

Bosshardt, H. G., Ballmer, W., & De Nil, L. (2002). Effects of category and rhyme decisions on sentence production. *Journal of Speech, Language, and Hearing Research, 45,* 844-857.

Brutten, G. J. & Trotter, A. C. (1986). A dual-task investigation of young stutterers and nonstutterers. *Journal of Fluency Disorders, 11*, 275-284.

Carusuo, A. J., Chodzko-Zajko, W. J., Bidinger, D. A., & Sommers, R. K. (1994). Adults who stutter: Responses to cognitive stress. *Journal of Speech, Language, and Hearing Research, 37*, 746-754.

Corbera, S. L., Corral, M., Escera, C., & Idiazabal, M. (2005). Abnormal speech sound representation in persistant developmental stuttering. *Neurology, 65*, 1246-1252.

Curran, T., & Keele, S. (1993). Attention and nonattentional forms of sequence learning. *Journal of Experimental Psychology: Learning, Memory and Cognition, 19,* 189-202.

Cross, D.E. & Luper, H.L. (1979). Voice reaction time of stuttering and nonstuttering children and adults. *Journal of Fluency Disorders, 4*, 59-77.

De Nil, L. F. (1999). Stuttering: A neurophysiological perspective. In N. Bernstein-Ratner & C. Healey (Eds.), *Stuttering research and practice: Bridging the gap* (pp. 85-102). Mahwah, NJ: Erlbaum.

De Nil, L.F. & Abbs, J.H. (1991). Kinesthetic acuity of stutterers and non-stutterers for oral and non-oral movements. *Brain, 114*, 2145-2158.

Doyon, J., & Ungerleider, L. G. (2002). Functional anatomy of motor skill learning. In L. R. Squire & D. L. Schacter (Eds.), *Neuropsychology of memory* (pp. 553-564). New York: Guilford Press.

Fischer, S., Hallschmid, M., Elsner, A. L., & Born, J. (2002). Sleep forms memory for finger skills. *Proceedings of the National Academy of Sciences of the United States of America, 99*, 11987-11991.

Fitts, P. M. & Posner, M. I. (1967). *Human performance*. Belmont, CA: Brooks/Cole.

Fitzgerald, H. E., Cooke, P. A., & Greiner, J. R. (1984). Speech and bimanual hand organization in adult stutterers and nonstutterers. *Journal of Fluency Disorders, 9*, 51-65.

Fleishman, E.A. & Bartlett, C.J. (1969). Human abilities. *Annual Review of Psychology, 20*, 349-380.

Fleishman, E.A. & Rich, S. (1963). Role of kinesthetic and spatial-visual abilities in perceptual motor learning. *Journal of Experimental Psychology, 66*, 6-11.

Forster, D.C., & Webster, W.G. (2001). Speech-motor control and interhemispheric relations in recovered and persistent stutterers. *Developmental Neuropsychology, 19*, 125-145.

Greiner, J., Fitzgerald, H., & Cooke, P. (1986). Speech fluency and hand performance on a sequential tapping task in left and right handed stutterers and nonstutterers. *Journal of Fluency Disorders, 11*, 55-69.

Hazeltine, E., Teague, D., & Ivry, R. (2002). Simultanous dual-task performance reveals parallel response selection after practice. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 527-545.

Hampton, A., & Weber-Fox, C. (2008). Non-linguistic auditory processing in stuttering: Evidence from behavioral and event-related brain potentials. *Journal of Fluency Disorders, 33*, 253-273.

Jog, M. S., Kubota, Y., Connolly, C. I., & Graybiel, A. M. (1999). Building neural representations of habits. *Science, 286*, 1745-1749.

Karni, A., Meyer, G., Rey-Hipolito, C., Jezzard, P., Adams, M. M., Turner, R. (1998). The acquisition of skilled motor performance: Fast and slow experience-driven changes in primary motor cortex. *Proceedings of the National Academy of Sciences of the United States of America, 95*, 861-868.

Logan, G., & Etherton, J. (1994). What is learned during automatization? The role of attention in constructuring an instance. *Journal of Experimental Psychology: Learning, Memory and Cognition, 20*, 1022-1050.

Loucks, T.M.J., & De Nil, L.F. (2001). Oral kinesthetic deficit in stuttering evaluated by movement accuracy and tendon vibration. In B. Maassen, W. Hultijn, R. Kent, H.F.M. Peters & P.H.H.M. van Lieshout (Eds.), *Speech motor control in normal and disordered speech.* New York, NY: Oxford University Press.

Ludlow, C. L., Siren, K. A., & Zikria, M. (1997). Speech production learning in adults with chrnoic developmental stuttering. In H. F. M. Peters, W. Hulstijn, & C. W. Starkweather (Eds.), *Speech motor control and stuttering.* New York, NY: Oxford University Press.

Magill, R. A. (1998). *Motor learning* (5th ed.). Boston, MA: McGraw-Hill Inc.

Max, L., Caruso, A., & Gracco, V. (2003). Kinematic analysis of speech, orofacial nonspeech, and finger movements in stuttering and nonstuttering adults. Journal of Speech, *Language, and Hearing Research, 46*, 215-232.

Namasivayam, A. K., & van Lieshout, P. (2008). Investigating speech motor practice and learning in people who stutter. *Journal of Fluency Disorders, 33*, 32-51.

Neilson, M. D., & Neilson, P. D. (1991). Adaptive model theory of speech motor control and stuttering. In H. F. M. Peters, W. Hulstijn, & C. W. Starkweather (Eds.), *Speech motor control and stuttering* (pp. 149-156). New York: Elsevier Press.

Newell, A., & Rosenbloom, P. (1981). Mechanisms of skill acquisition and the law of practice. In J. Anderson (Ed.) *Cognitive skills and their acquisition* (pp. 1-56). Hillsdale, N.J.: Erlbaum.

Nudelman, H. B., Herbrich, K. E., Hoyt, B. D., & Rosenfield, D. B. (1987). Dynamic characteristics of vocal frequency tracking in stutterers and nonstutterers. In H. F. M. Peters & W. Hulstijn (Eds.), *Speech motor dynamics in stuttering* (pp. 161-169). New York: Springer.

Oldfield, R. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia, 9*, 97-113.

Portney, L., & Watkins, M. (2000). *Foundations of clinical research: Applications to practice* (2nd Edition). Stamford, Connecticut: Appleton & Lange.

Press, D. Z., Casement, M. D.,Pascual-Leone, A., & Robertson, E. M. (2005). The time course of off-line motor sequence learning. *Cognitive Brain Research, 25,* 375-378.

Riley, G. D. (1994). *Stuttering severity instrument for children and adults*. Austin, TX: Pro-Ed.

Robertson, E. M. (2004). Skill learning: Putting procedural consolidation in context. *Current Biology, 14*, R1061- R1063.

Rose, D.J. (1997). *A multilevel approach to the study of motor control and learning*. Needham Heights, MA: Allyn & Bacon.

Sasisekaran, J., De Nil, L. F., Smyth, R., & Johnson, C. (2006). Phonolgoical encoding into silent speech of persons who stutter. *Journal of Fluency Disorders, 31*, 1-21.

Schmidt, R. A. (1988). *Motor control and learning: A behavioral emphasis*. Champaign, IL: Human Kinematic Publishers.

Schmidt, R. A. & Wrisberg, C.A. (2004). *Motor learning and performance* (3rd ed.). Champaign, IL: Human Kinetics.

Schmidt, R. A. & Lee, T. D. (2005). *Motor control and learning: A behavioral emphasis* (4th ed). Champaign, IL: Human Kinetics.

Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D. E., Lambes, E. J., Kieras, D.E., & Meyer, D.E. (2001). Virtually perfect time sharing in dual-task performance: Uncorking the central cognitive bottleneck. *Psychological Science, 12*, 101-108.

Smits-Bandstra, S., De Nil, L. F., & Rochon, E. (2006a). The transition to increased automaticity during finger sequence learning in adult males who stutter. *Journal of Fluency Disorders, 31*, 22-42.

Smits-Bandstra, S., De Nil, L. F., & Saint-Cyr, J. A. (2006b). Speech and nonspeech sequence skill learning in adults who stutter. *Journal of Fluency Disorders, 31*, 116-136.

Stickgold, R., & Walker, M.P. (2007). Sleep-dependent memory consolidation and reconsolidation. *Sleep Medicine, 8*, 331-343.

Sussman, H. M. (1982). Constrastive patterns of intrahemispheric interference to verbal and spatial concurrent tasks in right-handed, left-handed and stuttering populations. *Neuropsycholgia, 20*, 675-684.

Van Lieshout, P. H. H. M. (2004). Searching for the weak link in the speech production chain of people who stutter: A motor skill approach. In B. Maassen, R. Kent, H.F.M. Peters, P.H.H.M. Van Lieshout, & W. Hulstijn (Eds.), *Speech motor control in normal and disordered speech* (pp. 313- 355). Oxford, UK: Oxford University Press.

Van Lieshout, P. H. H. M., Hulstijn, W., & Peters, H. F. M. (1996). From planning to articulation in speech production: What differentiates a person who stutters from a person who does not stutter? *Journal of Speech, Language, and Hearing Research, 39*(3), 546-564.

Walker, M. P., & Stickgold, R. (2004). Sleep-dependent learning and memory consolidation. *Neuron, 44*, 121-133.

Weinstein, J., Caruso, A. J., Severing, K., & VerHoeve, J. (1989). Abnormalities of oculomotor control in stutterers [abstract]. *Investigative Ophthalmology and Visual Science*, (30), 480.

Weschler, D. (1997). WAIS-III: *Weschler Adult Intelligence Scale*, Revised. New York: Psychological Corporation.

Acknowledgements

We would like to acknowledge the Natural Science and Engineering Research Council of Canada (RGPIN 105626-04) for their financial support and Sophie Lafaille for her performance on the reliability measures. We would also like to acknowledge the scholarly contributions and advice of Dr. Elizabeth Rochon and Dr. Pascal Van Lieshout.

Authors' Note

Correspondence concerning this article should be addressed to Kim R. Bauerly, Ph.D., CCC-SLP; Department of Communication Disorders and Sciences, Plattsburgh State University, 224 Sibley Hall, Plattsburgh, NY 12901 U.S.A. Email: kimberly.bauerly@plattsburgh.edu.