Journal of Communication Disorders 81 (2019) 105911

Contents lists available at ScienceDirect

Journal of Communication Disorders

journal homepage: www.elsevier.com/locate/jcomdis

Bimanual task performance: Adults who do and do not stutter

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ARTICLE INFO

Keywords:
Stuttering
Disfluency
Manual
Purdue Pegboard Test
Motor

ABSTRACT

Research has demonstrated children who stutter score significantly lower than children who do not stutter on the Purdue Pegboard Test. Past data also suggest performance on this task may be associated with stuttering frequency (Choo et al., 2016; Mohammadi et al., 2016). The purpose of this study was to explore whether these performance differences and the relationship to stuttering frequency are present in adults who stutter (AWS). Forty-eight participants (AWS = 24, and AWNS = 24) matched for age, gender, education, and handedness completed all four tasks of the Purdue Pegboard Test. There were no significant between group differences and stuttering frequency did not predict performance. These findings suggest previous differences may only be applicable to subgroups and/or that, with development, the manual tasks unique to the Purdue Pegboard Test may not be sensitive enough to reveal differences.

1. Introduction

There are significant data to suggest that deficits in speech motor control contribute to stuttered speech (e.g., Alm, 2004; Max, Caruso, & Gracco, 2003; McClean, Tasko, & Runyan, 2004; Namasivayam & Van Lieshout, 2008, 2011; Smith & Kleinow, 2000), leading to investigations as to whether differences in speech motor control are subsystem-specific or part of a global underlying difference in motor control in people who stutter. Both neuro-imaging (e.g., Braun et al., 1997; Chang, Kenney, Loucks, & Ludlow, 2009) and behavioral research (e.g., Forster & Webster, 2001; Max & Yudman, 2003) have documented non-speech sensorimotor differences in people who stutter, compared to people who do not stutter. A subset of behavioral investigations into global motoric differences have focused on manual movements of adults who do and do not stutter, with studies focusing on rhythmic timing, finger displacement, as well as bimanual coordination and dual-task paradigms (e.g. Hulstijn, Summers, van Lieshout, & Peters, 1992; Max & Yudman, 2003; Webster, 1985, 1986).

To date, in terms of unimanual finger tapping, no differences between adults who stutter (AWS) and adults who do not stutter (AWNS) have been found with respect to pattern accuracy of rhythmic timing tasks (Hulstijn et al., 1992; Max & Yudman, 2003; Webster, 1985, 1986). However, when a speech task is administered concurrently with finger tapping, AWS demonstrate more variable manual coordination (Hulstijn et al., 1992). Additionally, in unimanual finger flexion-extension tasks, researchers (Max et al., 2003; Zelaznik, Smith, Franz, & Ho, 1997) have reported differences in displacement, peak velocities and duration of movements, with AWS producing slower, and smaller movements. Max et al. (2003) suggested these differences in flexion-extension movements mirror kinematic differences observed in AWS during lip and jaw closing and opening and lend further support to a generalized motor deficit. To describe the etiological implications of these findings, Zelaznik et al. (1997) posit that stuttering,

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https://doi.org/10.1016/j.jcomdis.2019.105911
Received 17 October 2018; Received in revised form 15 May 2019; Accepted 19 May 2019
Available online 24 May 2019
0021-9924/ Published by Elsevier Inc.

though primarily a disorder impacting speech motor processes, "may produce subtle differences in individual's performance of a wide range of skilled actions" (p. 241). To understand the degree to which these skilled actions may be compromised in persons who stutter, Max and Yudman (2003) called for investigations into more complex movement and timing tasks, such as sequential or coordinated unimanual or bimanual tasks.

1.1. Bimanual coordination and lateralization in people who stutter

In a series of studies investigating performance on concurrent bimanual tasks, AWS have demonstrated slower reaction times, longer completion times, and increased motoric errors (Webster, 1986, 1988, 1989, 1990; Webster & Ryan, 1991). Similarly, children who stutter (CWS) have demonstrated significantly different timing variability from children who do not stutter (CWNS) during bimanual coordination (Olander, Smith, & Zelaznik, 2010). There is no evidence that errors are a result of a speed-accuracy trade-off (Webster, 1990), nor are these differences contingent upon task complexity (Webster & Ryan, 1991). Based upon performance differences across different types of bimanual tasks, Webster suggests that synchronous bimanual movement might be more susceptible to interference than sequential (1989).

Bimanual investigations have also analyzed performance differences between dominant versus non-dominant hands in both people who stutter and people who do not stutter. Differences in laterality, or symmetry in performance across hands, have been linked to over-activation or compensatory activation of the right hemisphere and reduced interhemispheric reciprocal inhibition in AWS (Neef et al., 2011; Webster, 1990). Adults who stutter have demonstrated differential performances between hands when completing a concurrent task with the other hand, suggesting interhemispheric disruption (Webster, 1986), or when receiving contralateral transcranial magnetic stimulation to inhibit one hemisphere of the brain (Neef et al., 2011). Furthermore, bimanual performance of AWS has been characterized as having reduced bimanual asymmetry. Webster (1990) found right-handed AWNS demonstrate significantly poorer performance in finger tapping tasks when transitioning from their dominant to their non-dominant hand. Adults who stutter, however, were similar to left-handed AWNS, as they performed more evenly across each hand; and this decrease in bimanual asymmetry was correlated with increased stuttering severity (Webster, 1990).

1.2. A tool for standardized analysis of manual performance

Among the variety of tasks employed to analyze manual performance, only one provides norms for comparison. The Purdue Pegboard Test is a test of manual performance originally developed to assess the dexterity of candidates for assembly line positions (Tiffin & Asher, 1948). Today, the assessment is widely used to test hand function for rehabilitation (Gonzalez, Rowson, & Yoxall, 2017). Most pertinent to the present investigation, the Purdue Pegboard Test has been utilized to assess bimanual dexterity as well as lateralization of brain damage in research (e.g., Costa, Vaughan, Levita, & Farber, 1963; Gallus & Mathiowetz, 2003; Verdino & Dingman, 1998).

With respect to individuals without brain damage, Verdino and Dingman (1998) found the Purdue Pegboard Test to be more sensitive than the commonly used Edinburgh Handedness Inventory (Oldfield, 1971) in investigating laterality of handedness preference for individuals who are left-handed. Left-handed participants in their study who presented as extremely left-handed per the Edinburgh Handedness Inventory, demonstrated a significantly smaller difference in performance between their dominant and nondominant hands compared to the right-handed participants. The authors proposed that the Purdue Pegboard Test could be utilized to detect subgroups of more ambidextrous dexterity not captured by the Edinburgh Handedness Inventory (Verdino & Dingman, 1998). Similarly, Costa et al. (1963) found the Purdue Pegboard Test to be a promising screening tool to detect lateralization of cerebral lesions based upon the comparison of unimanual performance.

Components of the test assess both unimanual and synchronous as well as sequential bimanual movement. All components of the test are timed to evaluate the speed and accuracy of fine motor coordination of the hands. In addition to being used to investigate motor performance of individuals with language impairment (e.g., Brookman, McDonald, McDonald, & Bishop, 2013) or speech delay (e.g., Barbeau, Meilleur, Zeffiro, & Mottron, 2015), the Purdue Pegboard Test has also been utilized in investigations of tic severity in children with Tourette's syndrome (Bloch, Sukhodolsky, Leckman, & Schultz, 2006). Bloch et al. (2006) found performance on the Purdue Pegboard Test for children with Tourette's syndrome to be predictive of tic severity and overall psychosocial well-being into later adolescence, with poorer performance indicating increased severity later in life. Given the influence of basal ganglia dysfunction in individuals with Tourette's syndrome (e.g., Caligiore, Mannella, Arbib, & Baldassarre, 2017; Müller, 2007; Schultz, Carter, Scahill, & Leckman, 1999), the authors suggest that the Purdue Pegboard Test may be a useful measure in identifying the degree of basal ganglia deficit present. Previous literature has suggested that motoric differences seen in people who stutter compared to people who do not stutter may be related to differences or deficits in basal ganglia function (e.g., Alm, 2004; Civier, Bullock, Max, & Guenther, 2013; Giraud et al., 2008; Ludlow & Loucks, 2003; Smits-Bandstra & De Nil, 2007). Taken together these data, along with prior literature demonstrating differences in manual speed and accuracy in people who stutter, especially in synchronous bimanual movement, it is reasonable to suggest the Purdue Pegboard Test may be an appropriate measure to assess manual performance for this population.

1.3. Performance on the Purdue Pegboard Test in persons who stutter

To date, performance on the Purdue Pegboard Test has only been explored in CWS. Choo, Burnham, Hicks, and Chang (2016) administered the Dominant Hand, NonDominant Hand, and simultaneous Both Hands conditions of the Purdue Pegboard Test along with a battery of speech, language, and cognitive measures to 66 CWS, and 53 CWNS with ages ranging from three to 10 years old. Children who stutter performed significantly more poorly in the Dominant Hand and Both Hands conditions compared to CWNS (Choo et al., 2016). Furthermore, boys who stutter demonstrated a strong negative correlation between percent of stuttering-like disfluencies (SLD) and performance on the NonDominant Hand and Both Hands conditions, suggesting that increased frequency of SLD may be related to poorer manual performance in boys who stutter. These results echo Webster (1989, 1990) findings of AWS performing more poorly during synchronous bimanual tasks and demonstrating decreased bimanual asymmetry with increased stuttering severity.

Mohammadi, Khazaie, Rezaei, and Joghataei (2016) also investigated manual performance of CWS in their longitudinal study with an older cohort of children aged 7–14. Critically different from Choo et al. (2016), this investigation did not include a normative sample for group comparison. The authors collected case history and speech samples of 20 right-handed CWS, and during the six-year follow-up added the Persian version of the Victoria Stroop Color Word Test and the Dominant Hand, NonDominant Hand, and Assembly conditions of the Purdue Pegboard Test to investigate predictors of persistent stuttering. In addition to traditional scoring of the Purdue Pegboard Test, the authors also created a Handedness Index to assess laterality, in which the Dominant Hand scores were divided by the NonDominant Hand. Participants who recovered from stuttering showed significantly more hand asymmetry than those who persisted as evidenced by significantly higher Dominant Hand vs. NonDominant Hand scores. Furthermore, children who persisted in stuttering were documented with significantly higher NonDominant Hand scores than children who recovered. As a result, there was a significant between-group difference in Handedness Index. Of all measures investigated, Handedness Index distinguished those who recovered from those who persisted with 94% sensitivity and 84% specificity. Results of their study are also in line with the results of Webster (1990) study in which AWS demonstrated less hand asymmetry than AWNS. These results also suggest reduced hand asymmetry may be uniquely related to stuttering severity. Findings from these two studies suggest that the Purdue Pegboard Test may be a relatively efficient tool to measure non-speech motor differences, and potentially predict stuttering persistence in children.

1.4. Purpose of the current study

An analysis of adult performance may reveal whether manual performance differences on the Purdue Pegboard Test exist into adulthood. Furthermore, of the two studies that assessed performance of CWS on the Purdue Pegboard Test, neither administered the test in its entirety. The purpose of the current study is to assess the unimanual and bimanual performance of adults who do and do not stutter via the Purdue Pegboard Test and to extend current literature by assessing simultaneous and sequential bimanual performance via administration of all four tasks.

The aims of the current study were threefold. The first was to assess the unimanual as well as simultaneous and sequential bimanual performance on the Purdue Pegboard Test of AWS and AWNS. Investigation into the performance of AWS is particularly important given the methodological differences in investigations with CWS at different age groups. Poorer performance in dominant unimanual and simultaneous bimanual tasks were documented in younger CWS, and older CWS who persisted in stuttering were primarily documented with more symmetrical unimanual performance than those who recovered (Choo et al., 2016; Mohammadi et al., 2016). Furthermore, the older group of CWS was not compared to performance by a normative sample (Mohammadi et al., 2016). Thus, investigation into AWS will characterize whether patterns of manual performance documented on the performance of CWS on the Purdue Pegboard Task exist into adulthood. We predicted that if significant between-group performances existed, they would be characterized by poorer performance by AWS particularly during the simultaneous bimanual condition.

The second aim of the study was to explore the contribution of stuttering frequency to performance on manual tasks within AWS. Previous research has documented differential manual performance with increased stuttering frequency and severity (Choo et al., 2016; Webster, 1990). We predicted that if differential manual performance existed for AWS, it would be more pronounced with increased stuttering frequency.

The third and final aim of the study was to explore the manual symmetry of AWS and AWNS. Previous research has documented reduced hand asymmetry in both AWS and CWS (Mohammadi et al., 2016; Webster, 1990). We predicted that if differences in unimanual performance existed between AWS and AWNS, they would be characterized by more comparable performance across dominant and non-dominant hands in AWS.

2. Method

2.1. Participants

A total of 48 participants were recruited for this study (24 AWS, 24 AWNS). The mean age of AWS was 27.5 (age range: 18–44 years) and the mean age of AWNS was 27.1 (age range: 18–46 years). Both groups consisted of 21 males and 3 females each. Every participant in the study completed an extensive case history form and no prior or current neurological, social, emotional, or psychiatric diagnoses or treatments were recorded. The form also included information about the participants' educational level and handedness. All participants reported right hand dominance. Finally, in order to participate in the study, participants needed to be over 18 years old. The Institutional Review Board at the university of the first, second and third author approved the present study and informed consent was obtained for each participant.

Classification as an AWS included self-identification as a person who stutters, and a disfluency analysis of a speech sample completed by or under the supervision of a licensed speech-language pathologist. All AWS were either seeking speech therapy for

Table 1
Demographic information for participants who stutter. Education indicates highest degree obtained. %SLD indicates percentage of syllables stuttering in a speaking sample.

AWS	Age	Gender	Education	%SLD	Previous treatment
1	18	M	High School	6.55	Yes
2	21	M	Undergraduate	5.91	No
3	32	F	Graduate	5.29	Yes
4	34	M	Undergraduate	16.30	Yes
5	25	M	Graduate	5.35	Yes
6	25	M	Graduate	1.91	Yes
7	32	M	High School	2.52	Yes
8	32	M	Undergraduate	0.34	Yes
9	18	M	High School	16.55	Yes
10	44	M	Graduate	1.63	Yes
11	21	M	High School	19.00	Yes
12	28	M	Undergraduate	2.00	Yes
13	26	M	Undergraduate	3.25	Yes
14	35	F	Graduate	3.50	Yes
15	37	F	Graduate	5.39	Yes
16	29	M	Graduate	6.35	Yes
17	21	M	High School	10.81	Yes
18	44	M	Undergraduate	2.00	Yes
19	19	M	High School	1.70	No
20	29	M	Undergraduate	9.40	Yes
21	21	M	High School	1.50	Yes
22	21	M	Undergraduate	8.27	No
23	24	M	Undergraduate	3.73	Yes
24	25	M	Graduate	0.35	No

stuttering or reported having received it in the past. However, our knowledge of their history is limited to either an affirmation that they have participated in therapy previously or that they have not (Table 1). Additionally, adults who stutter are likely to have had multiple previous therapy experiences, all of which are also likely to be diverse in nature, limiting our ability to match or draw meaningful connections to performance relative to therapy experience. Participants were matched by age (± 2 years), gender, and education. Stuttering frequency for AWS was based on the percentage of stuttering-like disfluencies of all syllables (%SLD), obtained from narrative and conversational speaking samples (mean: 5.89, range: 0.34–19). Narrative samples were collected via story telling of wordless picture books, and conversational samples were conducted with the participant speaking with a pre-service student clinician supervised by a licensed speech-language pathologist. Stuttering-like disfluencies included part or whole word repetitions (e.g. sh-sh-sh-she wants; she-she-she-she wants), audible and inaudible prolongations produced with tension and arrhythmicity (————she wants; sssshhhe wants). Frequency calculations were completed by trained pre-service student clinicians following extensive training in the identification of stuttering-like disfluencies, and reviewed by the first author, a licensed speech-language pathologist.

2.2. Materials and procedures

The Purdue Pegboard Test (Tiffin & Asher, 1948) was utilized to assess unimanual and bimanual motor performance. This test consists of a board with 50 holes in two equal columns of 25, 50 straight pegs, 40 washers, and 40 collars. The test consists of four conditions; conditions were administered in accordance with the Purdue Pegboard Test user instructions manual (Tiffin & Asher, 1948). First, participants completed their dominant hand task, next the non-dominant hand task, next both hands task and finally the assembly task. The participants completed all conditions sitting with the board placed in front of them on a table. For each condition, the administrator verbally explained the task, and demonstrated if necessary, and all participants practiced each task untimed until they felt comfortable. Each condition was administered once. Conditions were timed via a digital stopwatch and performance on each task was manually recorded.

2.2.1. Unimanual tasks

For unimanual tasks, participants were instructed to use a designated hand (dominant or nondominant) to place as many pegs into the holes in the designated column on the pegboard as possible in 30 s. For example, in the Dominant Hand condition, participants used their right hand to grab pegs from the cup on the outer right and place them into the right column on the board. Participants were instructed to grab and place pegs only one at a time. They were also instructed that in the event they drop a peg to move on to grabbing a new one instead of reaching for the fallen peg. Participants had 30 s to complete each task, and the number of accurately placed pegs was recorded at the conclusion of each condition.

2.2.2. Bimanual tasks

In the Both Hands condition, participants were instructed to utilize both of their hands to *simultaneously* grab one peg from the left cup and one peg from the right cup and place them into their respective columns on the board at the same time. Similar to the unimanual tasks, participants had 30 s to place as many peg pairs as possible. The number of accurately placed peg pairs, not individual pegs, was recorded.

In the Assembly condition, participants were instructed to build a tower utilizing four pieces: one peg, two washers, and one collar. Assembly began with the participant's dominant hand reaching for the first component. Towers were constructed so that while the dominant hand was placing the first component, the non-dominant hand was to be reaching for and grabbing the next component. In this way, hands were always to be continuously alternating to construct as many four-piece towers as possible in 60 s. In this task, scores reflected each component of a tower that was accurately placed. For example, if a participant completed nine full towers and the first two pieces of an additional tower, their score would be 38.

2.3. Data analysis

Analyses were carried out using the afex package (Singmann et al., 2015) in Rstudio, version 3.3.3 (Rstudio Team, 2015). To assess unimanual and simultaneous bimanual performance in AWS and AWNS, a repeated measures two-way ANOVA was utilized to assess performance differences between the groups by condition. The Dominant Hand, NonDominant Hand, and Both Hands conditions were included in this model for direct comparison. The Assembly condition was not included due to its differences in overall movement type, length, and scoring from the other three conditions. Talker group (i.e., AWS vs. AWNS) was utilized as the between-group factor and condition (i.e., Dominant Hand, NonDominant Hand, Both Hands) the within-group factor. The dependent measure of the study was the number of pegs accurately placed within a time constraint (i.e., 30 s). To assess sequentially coordinated bimanual performance, a Welch two-sample *t*-test was utilized to compare performance between AWS and AWNS on the Assembly condition.

To assess the relationship between stuttering frequency, as measured by percentage of stuttering-like disfluencies (%SLD), with manual performance, a within group analysis of AWS was completed. Four separate linear regression models were employed in which %SLD was utilized as the predictor variable for the number of pegs placed in each of the four conditions.

3. Results

The present study investigated how AWS and AWNS coordinate manual movement for performance on the Purdue Pegboard Test. Analyses assessed the relationship between the performance of the two talker groups during Dominant Hand, NonDominant Hand, Both Hands, and Assembly conditions. Additionally, we were interested in the relationship between performance by AWS and stuttering severity, as measured by %SLD, repeating the analysis which found a negative correlation in CWS between performance in the task and stuttering frequency (Choo et al., 2016).

3.1. Unimanual and bimanual performance in adults who do and do not stutter

In analyzing performance of both groups, a main effect was found for condition, $F(2, 92) = 28.576$, $p < 0.001$, which was characterized by all participants placing the least number of pegs in the Both Hands condition, as depicted in Fig. 1. No main effect for group, $F(1, 46) = 1.060$, $p = 0.309$, or interaction of condition x group, $F(2, 92) = 0.121$, $p = 0.886$, were found to be significant. Similarly, no significant performance difference for the Assembly condition was observed between the groups, $t(45.963) = -0.681$, $p = 0.499$.

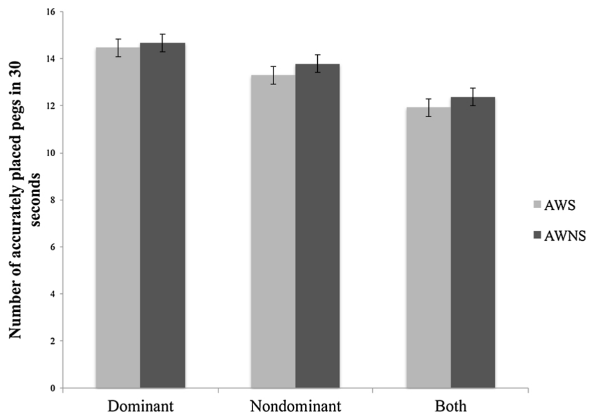

Fig. 1. Estimated marginal means and standard error of number of pegs placed by AWS and AWNS for dominant hand, non-dominant hand, and both hands conditions.

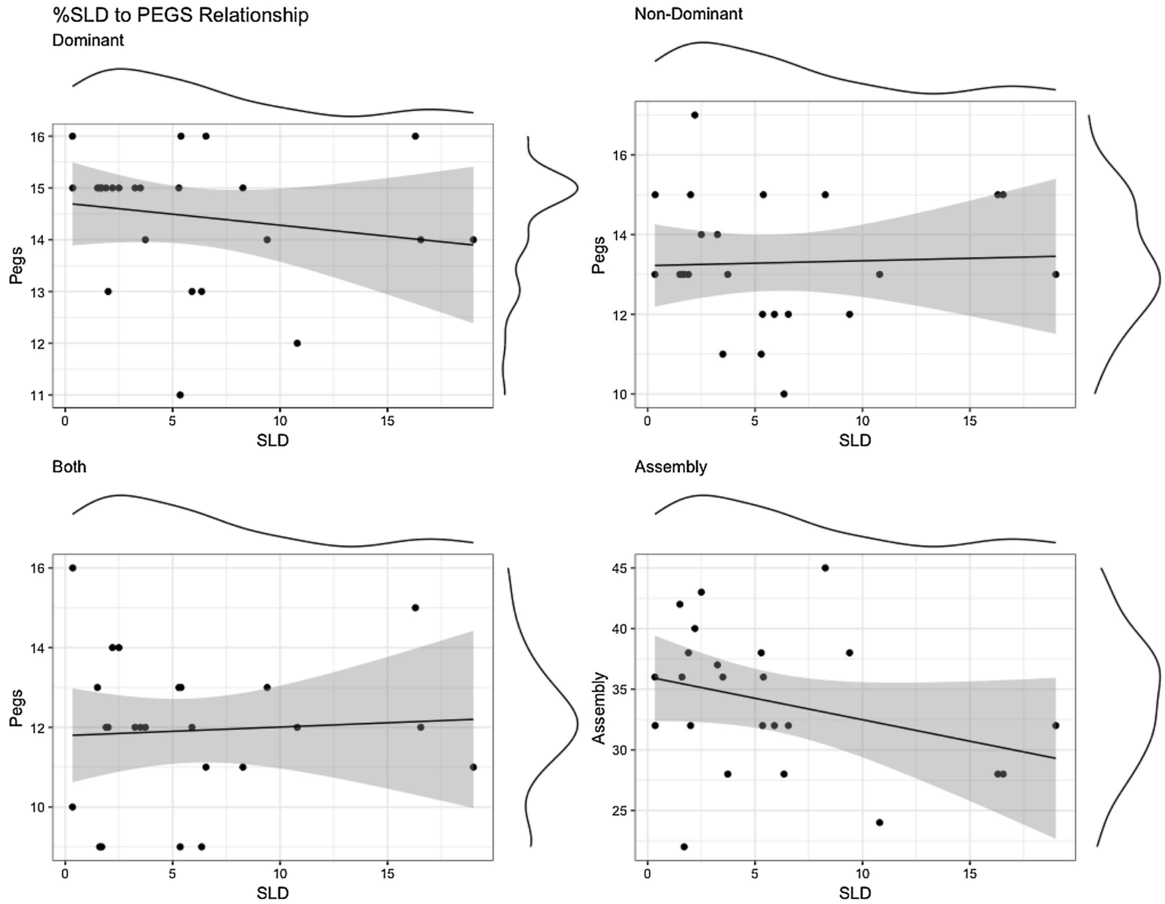

Fig. 2. Results of the simple linear regression assessing stuttering frequency and motor performance for each condition with density plots to illustrate the distribution of peg placement and %SLD for each condition.

3.2. Stuttering frequency and motor performance in adults who stutter

For all conditions, %SLD was not found to be a significant predictor of peg placement (Dominant Hand: $\beta = -0.043$, $t(22) = -0.824$ $p = 0.419$, $R^2 = 0.029$; NonDominant Hand: $\beta = 0.012$, $t(22) = 0.185$, $p = 0.855$, $R^2 = 0.002$; Both Hands: $\beta = 0.021$, $t(22) = 0.282$, $p = 0.781$, $R^2 = 0.004$; Assembly: $\beta = -0.354$, $t(22) = -1.562$, $p = 0.133$, $R^2 = 0.099$). Visual inspection of the data revealed %SLD to be positively skewed, with three outliers presenting with greater than 16% SLD. However, statistical analysis of these outliers revealed they were not influential in nature. Cook's distance was calculated for outliers in each condition. The greatest Cook's distance for any of the outliers in any of the conditions was found in the Dominant Hand condition, and below accepted levels for being influential ($D = 0.417$, $F = 0.336$) (Fig. 2).

4. Discussion

4.1. Do AWS exhibit differences in unimanual or (simultaneous or sequential) bimanual performance compared to AWNS?

In order to investigate whether AWS demonstrated differences in manual performance from AWS, we compared performance on all four tasks of the Purdue Pegboard Test. Results indicated that both groups demonstrated the same overall pattern of performance across unimanual and simultaneous bimanual tasks. Specifically, both groups accurately placed the most pegs in the Dominant Hand condition, followed by the NonDominant Hand condition, and the least number of pegs in the Both Hands condition, resulting in a significant main effect for condition. There was no main effect for group and there was no group x condition interaction for performance across these three tasks. Additionally, results revealed no significant differences between Talker Groups on the Assembly task, a condition assessing sequential bimanual performance. Together, these findings suggest the differences observed in the performance of CWS on this task may no longer be detectable in AWS. It is possible that this finding is related to typical processes of motor development. Sensitive motor tasks have previously found that normally developing children would perform more poorly compared to adults within the age range included in this study (Sigmundsson, Lorås, & Haga, 2016). Had we included participants aged 60 years or older, we would predict manual differences may again be observable, due to normal deterioration in motor skills.

However, whether these differences are related to the presence or persistence of stuttering would need to be investigated. It is also possible that with development, shared neural pathways between speech motor and non-speech motor control diverge. In reviewing evidence from both individuals with neurogenic speech disorders such as dysarthria and apraxia of speech as well as normal controls, Ziegler (2003) posits neural motor control systems for vegetative functions, emotional expression, speech, and non-speech oral motor control develop into highly specialized subsystems that may be distinguished only via task-specific paradigms. In this view, children may perform equally poorly on non-speech and speech motor tasks, but with maturation show distinctions in performance as these networks become more specified. That is, that previous literature reported CWS exhibited differences on the Purdue Pegboard Test and our results showed AWS do not, we might surmise that in earlier motor development CWS exhibit deficits in multiple motor subsystems, and that through development these deficits become distinct only to the oral speech motor subsystem.

To the present authors' knowledge, no study has explicitly analyzed performance on the Purdue Pegboard Test between AWS and AWNS. Given that ours is the first to make this comparison, we must look to other studies for a comparative analysis of manual performance in adults. Through these comparisons, we find that the lack of group differences in our participants' overall performance seems to differ from previous investigations, which have documented AWS with slower, more variable manual performance (Webster, 1986, 1988, 1989, 1990; Webster & Ryan, 1991). However, our results are congruent with studies which have assessed performance on more simple tasks (Hulstijn et al., 1992; Max & Yudman, 2003; Webster, 1985, 1986), suggesting that more complex and demanding motor tasks may be required in order for between group differences to emerge.

Two previous investigations have focused on Purdue Pegboard Test performance in CWS. Our current finding of comparable performance between AWS and AWNS seems to indicate that the earlier finding of poorer Purdue Pegboard Test performance (Dominant Hand and Both Hands conditions) in 3- to 10-year old CWS (Choo et al., 2016) may no longer be present in adults. Similar patterns have been documented in CWS in other developmental areas, including phonological development. CWS have been documented with deficits in phonological processing and production (e.g., Blood, Ridenour, Qualls, & Hammer, 2003; Byrd, Conture, & Ohde, 2007; Hakim & Bernstein Ratner, 2004; Louko, Edwards, & Conture, 1990; Nippold, 2002; Pelczarski & Yaruss, 2016; Sasisekaran & Byrd, 2013). Over the course of development, these differences attenuate such that AWS are only documented with phonological processing deficits in paradigms which are complex, and disproportionally tax cognitive load or phonological working memory (e.g., Byrd, Vallely, Anderson, & Sussman, 2012; Coalson & Byrd, 2017; Jones, Fox, & Jacewicz, 2012; Sasisekaran & Weisberg, 2014). Therefore, it is possible that at a younger age, CWS may present with global motoric differences (i.e., including both speech motor and nonspeech motor); but as this population develops these differences may attenuate such that the identifiable differences that remain in AWS require complex motor demands and/or more sensitive mechanisms of measurement.

A related, though distinct, interpretation is that the present study did not employ specific or sensitive enough measures to document an underlying global motoric difference; especially given that manual motoric differences have been documented in AWS. This explanation is plausible in light of the subclinical nature of other differences reported in individuals who stutter. As mentioned, differences in phonological working memory in AWS have been documented at the subclinical level, during tasks that require complex phonemic stimuli, or increased cognitive load (e.g., Byrd et al., 2012; Coalson & Byrd, 2017; Jones et al., 2012; Sasisekaran & Weisberg, 2014). In the motor realm, kinematic differences have been documented with more sensitive measures, such as peak velocities and finger displacement (Max et al., 2003; Zelaznik et al., 1997); or in more motoric and cognitively demanding task paradigms (Hulstijn et al., 1992; Webster, 1986, 1988, 1989, 1990; Webster & Ryan, 1991). Furthermore, in these latter behavioral tasks, AWS have been documented with comparable *overall* performance to AWNS, but increased variability and/or errors, supporting the subtle nature of non-speech motor differences in AWS. Perhaps, the use of the Purdue Pegboard Test does not allow for elucidation of these subclinical differences in AWS.

4.2. What is the relationship between stuttering frequency and manual performance in AWS?

Previous research has documented differences in hand symmetry to be related to perceived stuttering severity (Webster, 1990), and poorer performance on the Purdue Pegboard Test to be related to increased stuttering frequency as measured by %SLD in CWS (Choo et al., 2016). Results of the present study indicate that the findings observed in CWS cannot be extended into the adult population. Stuttering frequency did not predict performance in any tasks on the Purdue Pegboard Test in the present study. However, our findings may be directly related to both the population sample tested, and the metric utilized.

Specifically, the present cohort of AWS was observed with relatively low levels of %SLD, with an overall mean of 5.82, and without outliers a mean of 4.18. A lack of correlation between performance and %SLD may be related to the positively skewed distribution of %SLD. A more robust sample in terms of both size and range of %SLD may reveal behavioral differences within the group. Previous literature has also noted significant correlations between %SLD and basal ganglia functioning in AWS (Giraud et al., 2008). Critically, as %SLD decreased post-treatment, compensatory basal ganglia functioning also reduced to normalized levels of functioning. Although speculative, a possible explanation to consider may be the relationship between %SLD, basal ganglia function, and speech-language therapy. Comparison between the present sample of AWS and the sample of CWS from Choo et al.'s (2016) investigation reveal similar levels of %SLD (CWS mean = 6.51, standard deviation = 5.21). Though previous treatment history was not documented in either study, it is feasible to consider the AWS in the present study were more likely to have experienced speech-therapy, and for more prolonged periods than the CWS of the Choo et al. study. If more normalized basal ganglia functioning is to be expected post-therapy, this could explain why behavioral differences correlated to stuttering frequency were observed in CWS and not in AWS. In other words, though frequency rates were similar, CWS may be recruiting overall compensatory basal ganglia involvement that AWS are not due to extended engagement in treatment.

4.3. Do AWS differ in hand symmetry from AWNS?

Previous investigations have documented reduced hand asymmetry, that is, more even performance across dominant and non-dominant hands in children and adults who stutter (Mohammadi et al., 2016; Webster, 1990). Webster documented that reduced hand asymmetry was more pronounced with increased perceived stuttering severity (1990). Mohammadi et al. (2016) reported that reduced hand asymmetry, as measured by a Handedness Index (i.e., dividing Dominant Hand by NonDominant Hand scores), predicted stuttering persistence with 94% sensitivity and 84% specificity in CWS. Results of the present study do not confirm the results reported in these previous investigations. However, previous findings need to be interpreted with caution, given the methodological concerns in each of these two studies. Stuttering severity in the Webster (1990) investigation was based upon subjective judgments made by family or friends, not a standardized assessment, or an objective measure such as stuttering frequency. Additionally, the CWS followed by Mohammadi et al. (2016) were not compared to a normative group and potential predictors of persistence were limited to case history information and two standardized assessments. Regarding the present study, the majority of our participants presented with reasonably low %SLD, indicative of mild stuttering. Perhaps, previously reported differences in hand asymmetry are only present when stuttering severity is high.

An alternative explanation is that reduced hand asymmetry is present for a subgroup of people who stutter, though not all. In this case, it would be wise to caution against the use of Handedness Index as a sole predictor for stuttering persistence in children, as it may not capture children who persist in stuttering into adulthood. It is important to note that differences in laterality have not been reported across all manual investigations. In fact, in AWS, differences in laterality have been reported during tasks which either require increased cognitive recruitment due to complex task design (Webster, 1990) or inhibition due to transcranial magnetic stimulation (Neef et al., 2011). It is reasonable to consider that for CWS, but not AWS, performance on the Purdue Pegboard Test would require more cognitive recruitment, resulting in differences in laterality.

4.4. Limitations

Although the present preliminary data provide further valuable considerations relative to the motoric contributions to stuttered speech, there are some limitations to consider for future research. Ideally, multiple motoric measures (e.g., reaction time, practice effects etc.) would allow for a more comprehensive picture of the participants' performance in simple motor tasks. Therefore, we suggest future studies investigating performance of AWS on the Purdue Pegboard Test to include measures of initial reaction time across conditions as well as document practice effects across conditions. As reviewed, people who stutter have been documented with slower reaction times across manual tasks, in the presence of comparable accuracy and/or duration of tasks (Webster & Ryan, 1991). Investigation into reaction time during performance on the Purdue Pegboard Test may reveal if manual differences exist for these tasks, especially during sequence initiation. Furthermore, investigation into practice effects, including transfer and retention of the sequential and synchronous patterns required for the Purdue Pegboard Test, may provide additional insight into the breadth of sequential motor learning differences documented in individuals who stutter. Examination of how individuals who stutter learn and transition between the motor patterns required of the Purdue Pegboard Test by administering multiple timed trials of conditions, and conditions in various orders of complexity (compared to the standardized administration) may provide meaningful insight in to the sequential motor learning patterns of AWS compared to AWNS. Finally, a sample containing more robust representations of stuttering frequency should be investigated. Particularly, a sample containing higher levels of %SLD may reveal more insight as to the relationship between stuttering frequency and bimanual motor control.

4.5. Conclusion

The results of the present study found no significant differences in AWS and AWNS in manual performance across all four tasks of the Purdue Pegboard Test. Previous research has documented CWS performing more poorly on the Purdue Pegboard Test, suggesting performance on this task may be an indicator of persistence of stuttering. However, present findings suggest either these differences attenuate throughout development and/or the Purdue Pegboard Test ceases to be a measure sensitive and/or specific enough to assess manual motoric differences in AWS. Future research should more explicitly explore sequential motor learning as it relates to performance across Purdue Pegboard Test tasks. Comparison of the current paper with an investigation into practiced, transfer, and retention tasks may reveal whether sequential skill learning is the foundation of motoric differences seen in individuals who stutter during patterned, complex tasks.

CRediT authorship contribution statement

Danielle Werle: Investigation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Courtney Byrd:** Conceptualization, Methodology, Resources, Writing - review & editing. **Zoi Gkalitsiou:** Investigation, Writing - original draft, Writing - review & editing. **Kurt Eggers:** Writing - review & editing, Supervision.

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