Published in final edited form as:

J Speech Lang Hear Res. 2014 December 1; 57(6): 2131–2141. doi:10.1044/2014_JSLHR-S-13-0333.

Control and prediction components of movement planning in stuttering vs. nonstuttering adults

Ayoub Daliri,

Department of Speech and Hearing Sciences, University of Washington, Seattle, WA

Roman A. Prokopenko,

Russian Academy of Sciences, Moscow, Russia

J. Randall Flanagan, and

Department of Psychology, Queen's University, Kingston, Canada

Ludo Max

Department of Speech and Hearing Sciences, University of Washington, Seattle, WA., and
Haskins Laboratories, New Haven, CT

Abstract

Purpose—Stuttering individuals show speech and nonspeech sensorimotor deficiencies. To perform accurate movements, the sensorimotor system needs to generate appropriate control signals and correctly predict their sensory consequences. Using a reaching task, we examined the integrity of these control and prediction components, separately, for movements unrelated to the speech motor system.

Method—Nine stuttering and nine nonstuttering adults made fast reaching movements to visual targets while sliding an object under the index finger. To quantify control, we determined initial direction error and end-point error. To quantify prediction, we calculated the correlation between vertical and horizontal forces applied to the object—an index of how well vertical force (preventing slip) anticipated direction-dependent variations in horizontal force (moving the object).

Results—Directional and end-point error were significantly larger for the stuttering group. Both groups performed similarly in scaling vertical force with horizontal force.

Conclusions—The stuttering group's reduced reaching accuracy suggests limitations in generating control signals for voluntary movements, even for non-oro-facial effectors. Typical scaling of vertical force with horizontal force suggests an intact ability to predict the consequences of planned control signals. Stuttering may be associated with generalized deficiencies in planning control signals rather than predicting the consequences of those signals.

Correspondence should be addressed to Ludo Max, Ph.D., Department of Speech and Hearing Sciences, University of Washington, 1417 N.E. 42nd St., Seattle, WA 98105-6246. LudoMax@uw.edu. Phone: 206 543 2674. Fax: 206 543 1093.

The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institute on Deafness and Other Communication Disorders, the National Institutes of Health, or the Donaghue Foundation.

Keywords

stuttering; movement planning; sensorimotor control; prediction; internal model; reaching

A large body of evidence suggests that stuttering is a movement disorder involving deficiencies in fundamental sensorimotor processes (see Bloodstein & Bernstein-Ratner, 2008). Based on kinematic studies of speech production in stuttering and nonstuttering individuals, researchers have reported between-group differences in the variability, speed, duration, and coordination of articulatory movements (Caruso, Abbs, & Gracco, 1988; Kleinow & Smith, 2000; Max, Caruso, & Gracco, 2003; Max & Gracco, 2005; McClean & Runyan, 2000; McClean, Tasko, & Runyan, 2004; Smith, Sadagopan, Walsh, & Weber-Fox, 2010; Zimmermann, 1980). Such differences are not limited to speech production, however, as stuttering individuals have also been shown to move with greater variability, lower speed, and longer movement durations when the same orofacial effectors are used for nonspeech tasks (Archibald & De Nil, 1999; De Nil & Abbs, 1991; Hand & Haynes, 1983; Howell, Sackin, & Rustin, 1995; Loucks & De Nil, 2006; Max et al., 2003; Reich, Till, & Goldsmith, 1981; Riley & Riley, 1986; Starkweather, Franklin, & Smigo, 1984). It should be noted that some studies have failed to find such between-group differences or have found differences that were restricted to certain experimental conditions (Cooper & Allen, 1977; De Nil, 1995; Jancke, 1994; Janssen, Wieneke, Vanne, 1983; Jancke, Kaiser, Bauer, & Kalveram, 1995; Wieneke, Eijken, Janssen, & Brutton, 2001); however, the preponderance of evidence suggests that stuttering and nonstuttering speakers differ in various measures of both speech and nonspeech motor control.

For the purpose of developing a theoretical model of the neurobiological mechanisms underlying this disorder of speech fluency, it is important that the results from a vast number of studies indicate that at least some aspects of stuttering individuals' sensorimotor deficiencies are not limited to the orofacial system, and that they are also observed in other effector systems. First, although there are again some exceptions (e.g., Venkatagiri, 1981; Watson & Alfonso, 1982), longer movement initiation and execution durations for stuttering vs. nonstuttering individuals have been found in a large variety of finger movement tasks (Borden, 1983; Howell et al., 1995; Max et al., 2003; Prosek, Montgomery, Walden, & Schwartz, 1979; Reich et al., 1981; Starkweather et al. 1984; Webster & Ryan, 1991). Second, stuttering participants perform less accurately than nonstuttering participants when reproducing sequences of finger movements (Webster, 1985, 1986, 1989, 1997), and their performance is more susceptible to interference by a secondary task (Forster & Webster, 2001; Smits-Bandstra, De Nil, & Rochon, 2006; Webster & Ryan, 1991; Webster, 1990, 1997). Third, during finger movement sequencing tasks, stuttering individuals' improvements in speed and accuracy as a result of practice (i.e., motor learning) are more limited than those of nonstuttering individuals (Bauerly & De Nil, 2011; Namasivayam & Van Lieshout, 2008; Smits-Bandstra & De Nil, 2013; Smits-Bandstra et al., 2006; Smits-Bandstra, De Nil, & Saint-Cyr, 2006).

Further confirmation that the basic deficiencies underlying stuttering are sensorimotor in nature is provided by the results from numerous structural and functional neuroimaging

studies. Structural imaging has revealed that stuttering individuals show both white and gray matter abnormalities in several brain regions, including those involved in the sensorimotor control of speech (Beal, Gracco, Lafaille, & De Nil, 2007; Chang, Horwitz, Ostuni, Reynolds, & Ludlow, 2011; Cykowski et al., 2008; Foundas et al., 2003; Jancke, Hanggi, & Steinmetz, 2004; Kell et al., 2009; Sommer, Koch, Paulus, Weiller, & Buchel, 2002; Watkins, Smith, Davis, & Howell, 2008). Similarly, functional imaging has revealed, in stuttering individuals, abnormal activation patterns in a widely distributed network involved in the sensorimotor control of speech (Braun et al., 1997; Brown, Ingham, Ingham, Laird, & Fox, 2005; Chang, Kenney, Loucks, & Ludlow, 2009; De Nil, Kroll, Kapur, & Houle, 2000; De Nil, Kroll, Lafaille, & Houle, 2003; De Nil et al., 2008; Fox et al., 1996; Fox et al., 2000; Neumann et al., 2003; Sakai, Masuda, Shimotomai, & Mori, 2009; Watkins et al., 2008). Generally, these studies indicate that stuttering individuals, as compared with nonstuttering controls, have higher levels of brain activation in areas such as primary motor cortex, premotor cortex, supplementary motor area, and cerebellum, but lower levels of activation in areas such as superior and middle temporal gyrus. Interestingly, these neuroimaging studies, too, have confirmed that between-group differences in brain activation are not limited to speech tasks and also exist during nonspeech orofacial movements (Braun et al., 1997; Chang et al., 2009; Chang et al., 2011).

Given the combined results of these behavioral and neuroimaging studies, it can be concluded that at least some individuals who stutter show generalized deficits that affect aspects of both speech and nonspeech sensorimotor control (Caruso, 1991; Fitzgerald, Cooke, & Greiner, 1984; Grosjean, Van Galen, De Jong, Van Lieshout, & Hulstijn, 1997; Max, 2004; Olander, Smith, & Zelaznik, 2010; Zelaznik, Smith, Franz, & Ho, 1997). In terms of the exact mechanisms and affected processes, other researchers and our own laboratory have proposed that the above findings are compatible with a theoretical framework in which the central nervous system (CNS) of stuttering individuals fails to learn accurate and precise *internal models* of the body's effector systems (Cai et al., 2012; Daliri, Prokopenko, & Max, 2013; Max, 2004; Max et al., 2004; Neilson & Neilson, 1987, 1991). This perspective is based on empirical, theoretical, and computational work suggesting that, in order to produce accurate voluntary movements, the CNS (a) generates *control* signals based on inverse internal models (inverse neural mappings of motor-to-sensory transformations; i.e., which motor commands will achieve the desired output), and (b) makes *predictions* of the control signals' consequences based on forward internal models (forward neural maps of motor-to-sensory transformations; i.e., which consequences will result from issuing these motor commands) (Kawato, 1999; Shadmehr, Smith, & Krakauer, 2010; Wolpert, Miall, & Kawato, 1998).

Here, we examined both the control component and the prediction component of the sensorimotor system of stuttering and nonstuttering individuals using a previously reported nonspeech movement task that allows separate measures of control signal accuracy and prediction accuracy (Flanagan & Lolley, 2001). Stuttering and nonstuttering adults made ballistic reaching movements (i.e., without online corrections based on sensory input) to visual targets while sliding a test object under the right index finger. To quantify control accuracy, we examined both the accuracy of the initial aiming direction and the accuracy of

the final hand position at movement end-point: specifically, we calculated for each reach the initial direction error (i.e., the deviation between the initial direction of hand movement and a straight line from the start position to the target) and the end-point error (i.e., the distance between the final hand position and the target). To quantify prediction accuracy, we examined how well unintended consequences of the planned control signals are taken into account and compensated. For this purpose, we determined the correlation between the horizontal force (typically referred to as the tangential force) that the subject applies to slide the object across the table surface and the vertical force (typically referred to as the normal force) that the subject applies to avoid slip between the finger and the object. This approach is directly based on the known fact that during a reach in the horizontal plane, the arm's acceleration—and thus the tangential force on an object under the index finger—varies across different movement directions (Flanagan & Lolley, 2001; Gordon, Ghilardi, Cooper, & Ghez, 1994; Gordon, Ghilardi, & Ghez, 1994; Pfann, Corcos, Moore, & Hasan, 2002). This property of the arm (known as inertial anisotropy) causes the likelihood of slip between the index finger and object to also vary with movement direction (as there is an increased likelihood of slip with larger tangential force). To prevent slip of the finger relative to the object, the CNS of neurologically healthy individuals takes this inertial anisotropy into account during movement planning, and scales the normal force in parallel with the direction-dependent variations in tangential force (Flanagan & Lolley, 2001; Flanagan, Vetter, Johansson, & Wolpert, 2003; Wolpert, Diedrichsen, & Flanagan, 2011). Thus, the strength of the coupling between tangential force and normal force reflects how well the consequences of the planned motor commands (namely, the inertial anisotropy and associated level of tangential force) were predicted during movement planning.

We hypothesized that (a) if stuttering is associated with deficiencies in the control component, stuttering participants would perform less accurately in reaching to the targets—as reflected in greater directional error and end-point error relative to the control participants, whereas (b) if stuttering is associated with deficiencies in the prediction component, stuttering participants would show a reduced capacity to scale normal force in parallel with the direction-dependent variations in tangential force—as reflected in a reduced correlation between tangential and normal force as compared with the control participants.

Method

Participants

Participants were 9 right-handed male stuttering adults ranging from 20–46 years of age ($M = 32.67$ years) and 9 right-handed male nonstuttering adults ranging from 19–44 years of age ($M = 32.60$ years). The stuttering participants were recruited through radio advertisements, referrals from local speech-language pathologists, stuttering support groups, and the University of Washington Communication Studies Participant Pool (UWCSSP). The nonstuttering participants were recruited through the UWCSSP. Interested individuals were first screened for eligibility by phone or e-mail, and then—if eligible—invited to participate. The first 9 eligible stuttering individuals and the first 9 eligible nonstuttering individuals participated in the study, and there was no attrition of subjects during data collection or analysis.

None of the participants reported a history of psychological, neurological, or communication disorders (other than stuttering in the stuttering group). Additional inclusion criteria for the stuttering participants required (a) confirmation of the diagnosis of stuttering by the research team, and (b) self-reported stuttering onset during childhood. Using the Stuttering Severity Instrument, Fourth Edition (SSI-4; Riley, 2008), each stuttering participant's severity was determined by an American Speech-Language-Hearing Association-certified speech-language pathologist or a graduate student in speech-language pathology with training and experience in the evaluation of stuttering. Table 1 lists each individual stuttering participant's age, sex, handedness, native language (L1), overall SSI-4 score (Riley, 2008), SSI-4 stuttering severity classification, average frequency of stuttering across the SSI-4 speaking and reading tasks, and the time elapsed since the individual's most recent participation in stuttering treatment. Nonstuttering participants were individually matched with the stuttering participants based on age (± 3 years), sex, and self-reported handedness. All participants were naive to the purpose of the study and gave informed consent prior to participation.

Apparatus

The experimental set-up was based on one previously described by Flanagan & Lolley (2001). Participants used their right arm to perform horizontal-plane reaching movements toward visual targets presented in a virtual display system. Direct vision of the hand was prevented at all times, and no visual feedback of the hand was provided during the reaching movements (see Procedure). In this display system (Figure 1A), images were projected onto a horizontal back-projection screen and shown to the participant by means of a mirror placed below the screen. The participant's right forearm was supported by a light weight air sled (303 g) that allowed near-frictionless motion over a glasswork surface below the mirror (Figure 1A). The arm was braced to the air sled by means of straps with fastening tape (Figure 1D). Participants were instructed to hold a custom-made test object (212 g) under the tip of right index finger throughout the experiment (Figure 1C). The object was mounted on an air sled and instrumented with a force/torque sensor (Nano17, ATI Industrial Automation, Apex, NC). The top surface of the object was covered with medium sandpaper (220 grit). An electromagnetic motion tracking system (Liberty, Polhemus, Colchester, VT) was used to record the hand position during each reaching movement. The motion sensor was attached to the middle phalanx of the right index finger (Figure 1D).

Procedure

Prior to the experiment, seat height was adjusted such that the angle between the participant's upper arm and trunk was approximately 90 degrees (Figure 1A). The participant's right index finger was positioned in the mid-sagittal plane such that the angle between the forearm and upper arm was approximately 90 degrees (Figure 1B). This position was used as a start position and represented as a white circle (1 cm radius) in the virtual display system. Twelve possible visual targets were used, located radially 14 cm from the start position and evenly spaced at 30 degrees intervals (Figure 1B). The visual targets were represented as green circles (1 cm radius). A red circle (0.8 cm radius) was used to represent the position of the hand (cursor). A scale factor of (1:1) was used to relate displacement in real space to distance on the screen.

At the beginning of the recording session, participants were instructed to make fast and accurate reaching movements to the appearing targets, without corrective adjustments. They were also told that they could start moving at any time after the appearance of a new target (i.e., no time pressure). An entire session consisted of (a) 24 practice trials to familiarize the participant with the procedure, (b) 10 consecutive blocks of 12 trials that constituted the actual experiment (a block consisted of one trial for each of the 12 directions), and (c) 24 friction trials to examine the friction between the fingertip and the object. The order of presentation of the visual targets was randomized within each block. Participants were instructed to move the cursor to the visual targets while sliding the object with their fingertip. Before each trial, participants positioned the cursor at the start position for 1 second. Then, the trial started: a visual target appeared, and the cursor disappeared. Therefore, participants were not able to see the position of their hand during the movement. After each trial, participants were provided with visual feedback of the movement trajectory for 1 second. Throughout the session, participants were continually encouraged to make fast and accurate movements.

To reduce the likelihood of some participants applying an excessive amount of normal force even before the start of a trial—such excessive force could eliminate the need for any modulation of the normal force during this type of sliding movement (Flanagan & Lolley, 2001)—the 24 practice trials included a maximum pre-movement force limit. During these practice trials, the target did not appear if the participant initially pressed the object with a normal force that exceeded 0.3 N. After the experiment, we found that pre-movement normal force in the 10 blocks of actual test trials was very close to the target for both the stuttering group ($M = .395$ N, $SD = .084$) and the nonstuttering group ($M = .401$ N, $SD = .041$), with no statistically significant difference between the two groups, $t(16) = 0.086$, $p = .774$, $\eta_p^2 = .005$. Thus, any effects of individual variability in pre-movement force were negligible.

We also tested for a between-group difference in friction between the fingertip and object because differences in friction affect the amount of vertical force needed to avoid slip (Hager-Ross, Cole, & Johansson, 1996). Participants completed 24 friction trials (2 trials in each of the 12 directions). They were instructed to keep the object stable and still with their left hand, press down on the object with the tip of their right index finger, and then push with the index finger in the direction of each visual target until the finger slipped off the object. For each participant, a coefficient of friction was calculated as the ratio of tangential force to normal force at the moment that slip occurred (with slip operationally defined as the movement velocity exceeding 0.5 cm/s). An independent samples t -test showed that this coefficient of friction was not statistically significantly different between the stuttering and nonstuttering groups, $t(16) = -0.665$, $p = .516$, $\eta_p^2 = .027$. Therefore, these coefficient of friction data are not further considered here.

Signal conditioning

Force and position signals were recorded at a sampling rate of 240 Hz. The signals were digitally filtered using a low-pass, fourth-order Butterworth filter with a cutoff frequency of 10 Hz. The position signals from the motion tracking system were used to calculate

movement velocity along the workspace's x and y axes (V_x and V_y) using a central difference equation. The tangential velocity (hereafter velocity) was then calculated as $V = \sqrt{V_x^2 + V_y^2}$. From the 6-axis data provided by the force sensor's strain gauges, we extracted the normal force (F_n) that was applied vertically onto the object and two orthogonal forces (F_x and F_y) that were applied to the surface of the object in the horizontal plane (Figure 1C). F_x and F_y were recorded in the intrinsic coordinate system of the force sensor and, thus, not influenced by its orientation relative to the subject. These two orthogonal forces were used to calculate the tangential force that first accelerates and then decelerates the object along its movement path in the horizontal plane ($F_t = \sqrt{F_x^2 + F_y^2}$). Figure 2 (A and B) shows sample data for F_t and F_n . As shown, F_t signals include two peaks: one corresponding to the acceleration phase of the movement and one corresponding to the deceleration phase of the movement. Lastly, the rate of change in F_t and F_n was computed using a central difference equation.

The onset time for all signals was defined as the first time during the acceleration phase when the rate of F_t exceeded 2 N/s and stayed above this threshold for at least 100 ms. Individual trials were excluded from analysis in the following cases: (a) the movement was not completed 4 seconds after the target appeared, (b) the velocity profile was not bell-shaped, (c) peak F_n was more than 3 standard deviation above the mean peak F_n across trials for that participant, (d) F_t at the beginning of the trial was higher than the peak F_t in that trial, and (e) F_t or F_n showed an atypical, abrupt change within 1000 ms from movement onset. These criteria were included to eliminate outlier trials during which participants may have made corrective adjustments or failed to slide the test object within the trial time window. Using these criteria, approximately 11% of all trials were excluded. Importantly, the number of excluded trials was not statistically significantly different between the stuttering and nonstuttering groups ($t(16)=1.304$, $p=.211$, $\eta_p^2=.092$).

Dependent variables

As dependent variables quantifying the movement planning *control* component, two kinematic measures of accuracy were included. Directional error for an individual trial was defined as the absolute value of the difference between the angle of a straight line from start position to target and the angle of a straight line from start position to hand position at the time of peak velocity (Figure 2F). End-point error for an individual trial was defined as the distance (in cm) between the final hand position at movement end-point and the target location (Figure 2G). Consistent with previous studies (e.g., Gordon et al., 1994), participants tended to overshoot the target distance.

Quantifying the *prediction* component of movement planning was based on the force data—more specifically on the predictive scaling of F_n in relation to direction-dependent variations in F_t —and followed the same steps as described by Flanagan and Lolley (2001). For each trial, the peak F_t value as well as the F_n value at the time of peak F_t were extracted. Correlational analyses (see below) were then used to determine the strength of the coupling between these two forces.

To determine whether the stuttering and nonstuttering participants differed in any *general movement parameters*, a number of additional kinematic and kinetic measures were extracted. Besides peak F_t and F_n at peak F_t , additional measures made from the force signals included peak F_t latency, peak F_n , and peak F_n latency. Additional measures made from the position signals included peak velocity, peak velocity latency, and movement duration. Movement duration was defined as the time period between the first and last time points where velocity was higher than 0.5 cm/s.

Statistical analyses

All statistical analyses were conducted in the IBM SPSS Statistics 19 software package (IBM, Armonk, NY) using repeated measures analysis of variance (ANOVA) with Group as a between-subjects factor, and with Direction (12 levels) and Time (2 levels) as repeated measures. Time was included as a repeated measure to examine potential practice effects. The rationale for including Time as a factor was based on suggestions that stuttering is associated with deficits in motor learning (Namasivayam & Van Lieshout, 2011) and that stuttering individuals may benefit less from repeated performance than nonstuttering individuals (Smits-Bandstra, 2010). For this purpose, the total set of 10 trials for each direction was split into a set of early trials (i.e., trials 1–5) and a set of late trials (i.e., trials 6–10). Data from the five trials in each set were averaged. Given that the direction factor involved more than two levels, the degrees of freedom were adjusted using the Huynh-Feldt correction to account for potential violations of the sphericity assumption (Max & Onghena, 1999).

To quantify the strength of direction-dependent coupling between F_n and F_t for each participant, we determined the correlation between peak F_t and F_n at the time of peak F_t across the 12 movement directions (Figure 2E). The Pearson correlation coefficient was calculated separately for the set of early trials and the set of late trials (F_t and F_n were averaged across the five early or late trials in the same direction). Repeated measures ANOVA with Group as a between-subjects factor and Time (two levels) as the repeated measure was used to statistically compare the calculated correlation coefficients. Lastly, Pearson correlation coefficients were also used to investigate the relationship between each of the dependent variables and the stuttering participants' mean stuttering frequency (in percent syllables stuttered) across the conversational and reading speech samples of the SSI–

4. All significance levels were set at $\alpha = .05$, and partial Eta squared (η_p^2) was calculated to estimate effect sizes.

Results

Movement accuracy

The Group main effect was statistically significant for both directional error, $F(1,16) = 7.540$, $p = .014$, $\eta_p^2 = .320$, and end-point error, $F(1,16) = 13.911$, $p = .002$, $\eta_p^2 = .465$. Both measurements revealed that the stuttering group's reaching movements were less accurate than those of the nonstuttering group. As can be seen in Figure 3 (A and B), the directional and end-point errors for most stuttering individuals were larger than the median directional and end-point errors for the nonstuttering group, and approximately 50% of the stuttering

individuals showed directional and end-point errors outside the total range of the errors observed for the nonstuttering individuals. There was also a statistically significant main effect of Direction, but not Time, on both directional error, $F(7.884, 126.147) = 10.907, p < .001, \eta_p^2 = .405$, and end-point error, $F(4.254, 68.062) = 4.348, p = .003, \eta_p^2 = .214$. Descriptively, the between-group differences in directional and end-point error were larger for certain movement directions (e.g., 150° and 330° for directional error and 60° and 240° for end-point error), but the Direction $\times$ Group interaction did not reach statistical significance for either directional error ($p = .064$) or end-point error ($p = .061$). The remaining interactions that involved the Group factor (Time $\times$ Group, Time $\times$ Direction $\times$ Group) were also not statistically significant for either directional or end-point error ($p > .200$).

Coupling between tangential force (horizontal force) and normal force (vertical force)

Results replicated the direction dependency of F_t and the corresponding scaling of F_n in parallel with F_t (Flanagan & Lolley, 2001). Figure 2 shows two individual trials from one nonstuttering participant for movements to targets at 60° and 150° . F_t for the 60° trial was greater than F_t for the 150° trial (panel A), and F_n was scaled accordingly (panel B). Averaged across the five early trials and five late trials, both peak F_t (panel C) and F_n at peak F_t (panel D) show a dependence on movement direction. Using the same participant's data averaged across the early trials and late trials for each of the 12 movement directions, the relationship between peak F_t and F_n at the time of peak F_t is illustrated in Figure 2E for early and late trials separately. Group data together with the data from all individual participants are shown in Figure 3C. Analyses revealed no statistically significant effects for Group, Time, or the Time $\times$ Group interaction ($p > .380$; note that the correlation coefficients were calculated across movement directions and, thus, this ANOVA did not include a Direction factor). As can be seen in Figure 3C, the correlation coefficients for the stuttering group were completely within the range of those for the nonstuttering group.

General movement parameters

There was a statistically significant main effect of Direction on peak F_t , $F(3.594, 57.497) = 4.117, p = .007, \eta_p^2 = .205$, peak F_t latency, $F(5.295, 84.715) = 4.704, p = .001, \eta_p^2 = .227$, F_n at the time of peak F_t , $F(4.249, 67.985) = 2.561, p = .043, \eta_p^2 = .138$, peak F_n , $F(4.958, 79.329) = 2.596, p = .032, \eta_p^2 = .140$, peak F_n latency, $F(5.814, 93.026) = 3.127, p = .008, \eta_p^2 = .163$, peak velocity, $F(6.296, 100.729) = 6.507, p < .001, \eta_p^2 = .289$, and peak velocity latency, $F(6.380, 102.081) = 6.463, p < .001, \eta_p^2 = .288$. Movement duration was the only measure that did not show a statistically significant Direction effect ($p = .115$). None of the other main effects (Time, Group) or interactions (Time $\times$ Group, Direction $\times$ Group, Time $\times$ Direction, and Time $\times$ Direction $\times$ Group) were statistically significant for any of the kinetic and kinematic variables ($p > .081$).

Correlation between dependent variables and stuttering frequency

There were no statistically significant correlations between any of the dependent variables and stuttering frequency ($p > .254$).

Discussion

Several researchers have interpreted the available literature on stuttering as indicating that the disorder is best characterized as a sensorimotor deficit (e.g., Hickok, Houde, & Rong, 2011; Max, 2004; Max et al., 2004; Namasivayam & Van Lieshout, 2011; Neilson & Neilson, 1987, 1991). The purpose of the present study, therefore, was to start gaining a more in-depth understanding of which specific aspects of sensorimotor control may be impaired in individuals who stutter. Toward this goal, we used a nonspeech movement task that allowed separate analyses of kinematic measures related to the planned *control* signals and kinetic measures related to the *prediction* of those control signals' consequences. Specifically, the task involved ballistic reaching toward visual targets (without visual feedback as the hand was not visible) while sliding an object under the tip of the index finger. Besides allowing measures of movement accuracy as indices of the control component, this task can be used to examine how accurately the CNS predicts the amount of normal force (vertical force needed to avoid slip) when the tangential force (horizontal force applied to move the object) varies with movement direction (Flanagan & Lolley, 2001; Gordon, Ghilardi, Cooper, & Ghez, 1994; Gordon, Ghilardi, & Ghez, 1994). Thus, it is possible with this ballistic task to analyze separately (a) the accuracy of the planning of reaching direction and distance and (b) the extent to which the consequences of the planned movement are correctly predicted (e.g., faster acceleration along the end-effector's low-impedance axis) and accounted for (e.g., increasing vertical force in directions with faster acceleration to avoid slip).

We reasoned that (a) if stuttering is associated with deficiencies in the control component, stuttering participants would perform less accurately in reaching to the targets (as reflected in increased directional error and/or end-point error), whereas (b) if stuttering is associated with deficiencies in the prediction component, stuttering participants would show a reduced capacity to scale normal force in parallel with the direction-dependent variations in tangential force (as reflected in a reduced correlation between normal and tangential force). Results show that for the samples of participants included here ($n = 9$ in each group), the stuttering group was indeed less accurate than the nonstuttering group in reaching to the visual targets. Both directional errors and end-point errors were statistically significantly larger for the adults who stutter as compared with the adults who do not stutter. Examining individual participant data, we found that the directional error and end-point error for approximately half of the stuttering individuals were outside the range of the errors seen for the nonstuttering individuals. Although further replication studies will be necessary, the overall finding of reduced accuracy in upper limb reaching movements performed without visual feedback is consistent with Loucks and De Nil's (2006, 2012) findings of reduced accuracy in the orofacial system when jaw movements to visual targets were also performed without visual feedback (but note that we have found no between-group difference in accuracy when moving the jaw to remembered somatosensory targets; Daliri et al., 2013). On the other hand, the strength of the correlation between peak tangential force and the normal force at the time of peak tangential force was similar for both groups. In other words, the stuttering group did not differ from the nonstuttering group in terms of appropriately predicting the normal force necessary to avoid slip as the tangential force varied across

movement directions. In addition, the two groups did not differ in any of the basic kinematic or kinetic measures (peak velocity, peak velocity latency, movement duration, peak F_t , F_n at peak F_t , peak F_t latency, peak F_n , peak F_n latency).

Thus, consistent with the results from several previous studies (see Introduction), this work again confirms that at least some adults who stutter show specific deficits in sensorimotor control even for tasks that do not involve speech production and that are performed with an entirely unrelated effector system (here the upper limb rather than the orofacial effectors involved in speech production). As an important new finding, the larger directional and end-point errors for the included sample of stuttering individuals in the absence of between-group differences in the coupling of tangential and normal forces suggest that it is the control component—rather than the predictive component—of voluntary movement planning that may be impaired. Given that determining accurate control signals for a desired movement outcome requires that context-specific kinematic and dynamic transformations in the neuro-mechanical effector system are taken into account during movement planning, our overall findings are consistent with the hypothesis that individuals who stutter may have generalized difficulties with the acquisition or updating of the inverse neural representations (i.e., inverse internal models) of those transformations (Daliri et al., 2013; Max, 2004; Max et al., 2004). From this same perspective, the finding that our sample of stuttering participants scaled normal force in parallel with tangential force in a similar manner as observed in nonstuttering participants (both here and in previous work by Flanagan & Lolley, 2001) might indicate that the related process of using forward internal models to predict movement consequences that should be taken into account during movement planning might be unaffected, or less affected, by the underlying sensorimotor limitations. Overall, these combined findings start to directly address, for the first time, specific hypotheses following from theoretical work in which a neurobiologically plausible framework was proposed to explain how the impaired acquiring or updating of either inverse or forward internal models may lead to speech dysfluencies (Max, 2004; Max et al., 2004).

Of course, the experimental approach used for this study, and the resulting interpretations of the data, have a number of important limitations that will need to be addressed in future studies. First, although the experimental task was performed in a ballistic manner and without the availability of visual feedback (at least until after completion of the trial), it cannot be completely ruled out that stuttering individuals' reaching accuracy may be negatively affected by somatosensory deficits during movement execution (as has been argued for orofacial nonspeech movement accuracy by Loucks & De Nil, 2006, 2012) rather than by deficits in movement planning. That explanation appears unlikely, however, because participants in the present study were asked to perform the movements as fast as possible, and the stuttering group showed not only increased end-point error but also increased initial direction error measured at the time of peak velocity (which, on average, occurred 246 ms after movement onset). Second, the present paradigm examined only the prediction of movement consequences that need to be accounted for during movement planning, but that are then compensated in an anticipatory manner such that no undesired consequences are experienced during movement execution. Thus, the necessary compensation is implemented in a feedforward mode of control. In light of previous empirical data and theoretical models regarding the sensorimotor bases of stuttering, it will be important to also investigate how

stuttering versus nonstuttering individuals modulate task-relevant sensory systems based on the predicted consequences of planned motor commands (Max, 2004; McClean, 1996; Zimmermann, 1980). Third, we used a nonspeech task specifically because this particular task had already been shown to allow a reliable analysis of the predictive component of movement planning (Flanagan & Lolley, 2001). However, it will be critical to also pursue the identification, or novel development, of speech tasks that allow a similar dissociation of the control and prediction components of movement planning. Fourth, it could be argued that the observed general sensorimotor deficit is unlikely to play an important role in the mechanisms underlying stuttering itself as our movement accuracy data did not show a correlation with stuttering frequency. However, the potential relationship between any movement-related dependent variable measured in an experimental study and stuttering frequency measured during a short conversation and during oral reading of a short passage is undoubtedly complex. It is well recognized that measures of stuttering frequency vary over time and do not necessarily reflect directly on the severity of the underlying stuttering problem: the overt stuttering behaviors also reflect the influence of the stuttering individual's reactions to the core dysfunction, including the avoidance/substitution of feared words, physical struggle, etc. Hence, it is not necessarily the case that an individual with less observable stuttering behavior also has less of the problem that causes the stuttering in the first place. Moreover, a participant's stuttering frequency can be expected to vary with the level of anxiety and communicative pressure subjectively experienced in the laboratory setting, and this may be affected, in turn, by the participant being familiar vs. unfamiliar with the research staff and the research environment. Lastly, the link between a fundamental sensorimotor deficit contributing to stuttering behavior and the occurrence of individual stuttering moments may be indirect and dependent on additional "trigger" variables in a wide variety of domains (e.g., physiological, neuro-chemical, linguistic, cognitive-emotional). Taking these considerations into account, the absence of a direct correlation between a measure of sensorimotor functioning and the stuttering frequency observed at a single moment in time is difficult to interpret at this time.

In sum, to more precisely identify the specific sensorimotor deficits underlying stuttering, we used an upper limb movement task in which participants slid an object under the index finger to visual targets. This task allowed us to quantify, separately, the accuracy of the neural control signals that move the hand to the target and the prediction of movement consequences related to the biomechanics of the effector system. Findings obtained from the present participant samples suggest that at least a subgroup of adults who stutter differ from adults who do not stutter in movement accuracy (as reflected in increased directional error and end-point error for the stuttering group) but not in the prediction of movement consequences that had to be accounted for (as reflected in the groups' similar coupling strength for the tangential and normal forces applied to the test object). Hence, although the generalizability of these findings to larger groups of stuttering individuals needs to be confirmed in future studies, stuttering appears to be associated with effector-independent deficiencies in the planning of movement control signals rather than with predicting the consequences of those control signals.

Acknowledgments

This research was supported in part by grants R01DC007603 and P30DC004661 from the National Institute on Deafness and Other Communication Disorders and grant DF05009 from The Patrick and Catherine Weldon Donaghue Medical Research Foundation.

References

- Archibald L, De Nil LF. The relationship between stuttering severity and kinesthetic acuity for jaw movements in adults who stutter. *Journal of Fluency Disorders*. 1999; 24(1):25–42.10.1016/S0094-730X(98)00023-0
- Bauerly KR, De Nil LF. Speech sequence skill learning in adults who stutter. *Journal of Fluency Disorders*. 2011; 36(4):349–360.10.1016/j.jfludis.2011.05.002 [PubMed: 22133413]
- Beal DS, Gracco VL, Lafaille SJ, De Nil LF. Voxel-based morphometry of auditory and speech-related cortex in stutterers. *Neuroreport*. 2007; 18(12):1257–1260.10.1097/WNR.0b013e3282202c4d [PubMed: 17632278]
- Bloodstein, O.; Bernstein-Ratner, N. A handbook on stuttering. 6th. Clifton Park, NY: Delmar; 2008.
- Borden GJ. Initiation versus execution time during manual and oral counting by stutterers. *Journal of Speech and Hearing Research*. 1983; 26(3):389–396. [PubMed: 6645464]
- Braun A, Varga M, Stager S, Schulz G, Selbie S, Maisog J, Ludlow C. Altered patterns of cerebral activity during speech and language production in developmental stuttering - an H-2 O-15 positron emission tomography study. *Brain*. 1997; 120:761–784.10.1093/brain/120.5.761 [PubMed: 9183248]
- Brown S, Ingham R, Ingham J, Laird A, Fox P. Stuttered and fluent speech production: An ALE meta-analysis of functional neuroimaging studies. *Human Brain Mapping*. 2005; 25(1):105–117.10.1002/hbm.20140 [PubMed: 15846815]
- Cai S, Beal DS, Ghosh SS, Tiede MK, Guenther FH, Perkell JS. Weak responses to auditory feedback perturbation during articulation in persons who stutter: Evidence for abnormal auditory-motor transformation. *PLoS ONE*. 2012; 7(7):e41830.10.1371/journal.pone.0041830 [PubMed: 22911857]
- Caruso, AJ. Neuromotor processes underlying stuttering. In: Peters, HF.; Hulstijn, W.; Starkweather, CW., editors. *Speech motor control and stuttering*. Amsterdam, The Netherlands: Elsevier; 1991. p. 101-116.
- Caruso AJ, Abbs JH, Gracco VL. Kinematic analysis of multiple movement coordination during speech in stutterers. *Brain*. 1988; 111:439–455.10.1093/brain/111.2.439 [PubMed: 3378144]
- Chang S, Horwitz B, Ostuni J, Reynolds R, Ludlow CL. Evidence of left inferior frontal-premotor structural and functional connectivity deficits in adults who stutter. *Cerebral Cortex*. 2011; 21(11):2507–2518.10.1093/cercor/bhr028 [PubMed: 21471556]
- Chang S, Kenney MK, Loucks TMJ, Ludlow CL. Brain activation abnormalities during speech and non-speech in stuttering speakers. *Neuroimage*. 2009; 46(1):201–212.10.1016/j.neuroimage.2009.01.066 [PubMed: 19401143]
- Cooper MH, Allen GD. Timing control accuracy in normal speakers and stutterers. *Journal of Speech and Hearing Research*. 1977; 20(1):55–71. [PubMed: 846204]
- Cykowski MD, Kochunov PV, Ingham RJ, Ingham JC, Mangin J, Riviere D, Fox PT. Perisylvian sulcal morphology and cerebral asymmetry patterns in adults who stutter. *Cerebral Cortex*. 2008; 18(3):571–583.10.1093/cercor/bhm093 [PubMed: 17584852]
- Daliri A, Prokopenko R, Max L. Afferent and efferent aspects of mandibular sensorimotor control in adults who stutter. *Journal of Speech, Language, and Hearing Research*. 2013; 56(6):1774–1788.10.1044/1092-4388(2013/12-0134)
- De Nil LF. The influence of phonetic context on temporal sequencing of upper lip, lower lip, and jaw peak velocity and movement onset during bilabial consonants in stuttering and nonstuttering adults. *Journal of Fluency Disorders*. 1995; 20:127–144.
- De Nil LF, Abbs JH. Kinaesthetic acuity of stutterers and non-stutterers for oral and non-oral movements. *Brain*. 1991; 114(5):2145–2158. [PubMed: 1933239]

- De Nil LF, Beal DS, Lafaille SJ, Kroll RM, Crawley AP, Gracco VL. The effects of simulated stuttering and prolonged speech on the neural activation patterns of stuttering and nonstuttering adults. *Brain and Language*. 2008; 107(2):114–123.10.1016/j.bandl.2008.07.003 [PubMed: 18822455]
- De Nil L, Kroll R, Kapur S, Houle S. A positron emission tomography study of silent and oral single word reading in stuttering and nonstuttering adults. *Journal of Speech, Language, and Hearing Research*. 2000; 43(4):1038–1053.
- De Nil L, Kroll R, Lafaille S, Houle S. A positron emission tomography study of short- and long-term treatment effects on functional brain activation in adults who stutter. *Journal of Fluency Disorders*. 2003; 28(4):357–380.10.1016/j.jfludis.2003.07.002 [PubMed: 14643070]
- Fitzgerald HE, Cooke PA, Greiner JR. Speech and bimanual hand organization in adult stutterers and nonstutterers. *Journal of Fluency Disorders*. 1984; 9(1):51–65.10.1016/0094-730X(84)90007-X
- Flanagan JR, Lolley S. The inertial anisotropy of the arm is accurately predicted during movement planning. *The Journal of Neuroscience*. 2001; 21(4):1361–1369. [PubMed: 11160407]
- Flanagan JR, Vetter P, Johansson RS, Wolpert DM. Prediction precedes control in motor learning. *Current Biology*. 2003; 13(2):146–150. [PubMed: 12546789]
- Forster DC, Webster WG. Speech-motor control and interhemispheric relations in recovered and persistent stuttering. *Developmental Neuropsychology*. 2001; 19(2):125–145.10.1207/S15326942DN1902_1 [PubMed: 11530972]
- Foundas AL, Corey DM, Angeles V, Bollich AM, Crabtree-Hartman E, Heilman KM. Atypical cerebral laterality in adults with persistent developmental stuttering. *Neurology*. 2003; 61(10):1378–1385. [PubMed: 14638959]
- Fox P, Ingham R, Ingham J, Hirsch T, Downs J, Martin C, Lancaster J. A PET study of the neural systems of stuttering. *Nature*. 1996; 382(6587):158–162.10.1038/382158a0 [PubMed: 8700204]
- Fox P, Ingham R, Ingham J, Zamarripa F, Xiong J, Lancaster J. Brain correlates of stuttering and syllable production - A PET performance-correlation analysis. *Brain*. 2000; 123:1985–2004.10.1093/brain/123.10.1985 [PubMed: 11004117]
- Gordon J, Ghilardi MF, Ghez C. Accuracy of planar reaching movements. 1. independence of direction and extent variability. *Experimental Brain Research*. 1994; 99(1):97–111.10.1007/BF00241415 [PubMed: 7925800]
- Gordon J, Ghilardi MF, Cooper SE, Ghez C. Accuracy of planar reaching movements. *Experimental Brain Research*. 1994; 99(1):112–130. [PubMed: 7925785]
- Grosjean, M.; van Galen, GP.; de Jong, WP.; van Lieshout, PHHM.; Hulstijn, W. Is stuttering caused by failing neuromuscular force control?. In: Hulstijn, W.; Peters, HFM.; van Lieshout, PHHM., editors. *Speech production: Motor control, brain research and fluency disorders*. Amsterdam, The Netherlands: Elsevier; 1997. p. 197-204.
- Hager-Ross C, Cole KJ, Johansson RS. Grip-force responses to unanticipated object loading: Load direction reveals body-and gravity-referenced intrinsic task variables. *Experimental Brain Research*. 1996; 110(1):142–150. [PubMed: 8817265]
- Hand CR, Haynes WO. Linguistic processing and reaction-time differences in stutterers and nonstutterers. *Journal of Speech and Hearing Research*. 1983; 26(2):181–185. [PubMed: 6887803]
- Hickok G, Houde J, Rong F. Sensorimotor integration in speech processing: Computational basis and neural organization. *Neuron*. 2011; 69(3):407–422.10.1016/j.neuron.2011.01.019 [PubMed: 21315253]
- Howell P, Sackin S, Rustin L. Comparison of speech motor development in stutterers and fluent speakers between 7 and 12 years old. *Journal of Fluency Disorders*. 1995; 20(3):243–255.10.1016/0094-730X(94)00011-H
- Jancke L. Variability and duration of voice onset time and phonation in stuttering and nonstuttering adults. *Journal of Fluency Disorders*. 1994; 19(1):21–37.
- Jancke L, Hanggi J, Steinmetz H. Morphological brain differences between adult stutterers and non-stutterers. *BMC Neurology*. 2004; 4(1):23.10.1186/1471-2377-4-23 [PubMed: 15588309]
- Jancke L, Kaiser P, Bauer A, Kalveram T. Upper lip, lower lip, and jaw peak velocity sequence during bilabial closures: No differences between stutterers and nonstutterers. *Journal of the Acoustical Society of America*. 1995; 97:3900–3903. [PubMed: 7790664]

- Janssen P, Wieneke G, Vaane E. Variability in the initiation of articulatory movements in the speech of stutterers and normal speakers. *Journal of Fluency Disorders*. 1983; 8(4):341–358.10.1016/0094-730X(83)90014-1
- Kawato M. Internal models for motor control and trajectory planning. *Current Opinion in Neurobiology*. 1999; 9(6):718–727.10.1016/S0959-4388(99)00028-8 [PubMed: 10607637]
- Kell CA, Neumann K, von Kriegstein K, Posenenske C, von Gudenberg AW, Euler H, Giraud AL. How the brain repairs stuttering. *Brain*. 2009; 132(10):2747–2760.10.1093/brain/awp185 [PubMed: 19710179]
- Kleinow J, Smith A. Influences of length and syntactic complexity on the speech motor stability of the fluent speech of adults who stutter. *Journal of Speech, Language, and Hearing Research*. 2000; 43(2):548–559.
- Loucks TMJ, De Nil LF. Oral kinesthetic deficit in adults who stutter: A target-accuracy study. *Journal of Motor Behavior*. 2006; 38(3):238–247.10.3200/JMBR.38.3.238-247 [PubMed: 16709563]
- Loucks TMJ, De Nil LF. Oral sensorimotor integration in adults who stutter. *Folia Phoniatrica et Logopaedica*. 2012; 64(3):116–121.10.1159/000338248 [PubMed: 22584121]
- Max, L. Stuttering and internal models for sensorimotor control: A theoretical perspective to generate testable hypotheses. In: Maassen, B.; Kent, R.; Peters, HFM.; van Lieshout, P.; Hulstijn, W., editors. *Speech motor control in normal and disordered speech*. Oxford, UK: Oxford University Press; 2004. p. 357-387.
- Max L, Gracco VL. Coordination of oral and laryngeal movements in the perceptually fluent speech of adults who stutter. *Journal of Speech, Language, and Hearing Research*. 2005; 48(3):524–542.10.1044/1092-4388(2005/036)
- Max L, Onghena P. Some issues in the statistical analysis of completely randomized and repeated measures designs for speech, language, and hearing research. *Journal of Speech, Language, and Hearing Research*. 1999; 42(2):261–270.
- Max L, Caruso AJ, Gracco VL. Kinematic analyses of speech, orofacial nonspeech, and finger movements in stuttering and nonstuttering adults. *Journal of Speech, Language, and Hearing Research*. 2003; 46(1):215–232.10.1044/1092-4388(2003/017)
- Max L, Guenther FH, Gracco VL, Ghosh SS, Wallace ME. Unstable or insufficiently activated internal models and feedback-biased motor control as sources of dysfluency: A theoretical model of stuttering. *Contemporary Issues in Communication Science and Disorders*. 2004; 31:105–122.
- McClellan MD. Lip-muscle reflexes during speech movement preparation in stutterers. *Journal of Fluency Disorders*. 1996; 21(1):49–60.
- McClellan MD, Runyan CM. Variations in the relative speeds of orofacial structures with stuttering severity. *Journal of Speech, Language, and Hearing Research*. 2000; 43(6):1524–1531.
- McClellan MD, Tasko SM, Runyan CM. Orofacial movements associated with fluent speech in persons who stutter. *Journal of Speech, Language, and Hearing Research*. 2004; 47(2):294–303.10.1044/1091-4388(2004/024)
- Namasivayam AK, Van Lieshout P. Investigating speech motor practice and learning in people who stutter. *Journal of Fluency Disorders*. 2008; 33(1):32–51.10.1016/j.jfludis.2007.11.005 [PubMed: 18280868]
- Namasivayam AK, Van Lieshout P. Speech motor skill and stuttering. *Journal of Motor Behavior*. 2011; 43(6):477–489.10.1080/00222895.2011.628347 [PubMed: 22106825]
- Neilson MD, Neilson PD. Speech motor control and stuttering: A computational model of adaptive sensory-motor processing. *Speech Communication*. 1987; 6(4):325–333.
- Neilson, MD.; Neilson, PD. Adaptive model theory of speech motor control and stuttering. In: Peters, HFM.; Hulstijn, W.; Starkweather, CW., editors. *Speech motor control and stuttering*. Amsterdam, The Netherlands: Excerpta Medica; 1991. p. 149-156.
- Neumann K, Euler H, von Gudenberg A, Giraud A, Lanfermann H, Gall V, Preibisch C. The nature and treatment of stuttering as revealed by fMRI - A within- and between-group comparison. *Journal of Fluency Disorders*. 2003; 28(4):381–410.10.1016/j.jfludis.2003.07.003 [PubMed: 14643071]
- Olander L, Smith A, Zelaznik HN. Evidence that a motor timing deficit is a factor in the development of stuttering. *Journal of Speech, Language, and Hearing Research*. 2010; 53(4):876–886.

- Pfann KD, Corcos DM, Moore CG, Hasan Z. Circle-drawing movements at different speeds: role of inertial anisotropy. *Journal of neurophysiology*. 2002; 88(5):2399–2407. [PubMed: 12424281]
- Prosek RA, Montgomery AA, Walden BE, Schwartz DM. Reaction-time measures of stutterers and nonstutterers. *Journal of Fluency Disorders*. 1979; 4(4):269–278.10.1016/0094-730X(79)90003-2
- Reich A, Till J, Goldsmith H. Laryngeal and manual reaction-times of stuttering and non-stuttering adults. *Journal of Speech and Hearing Research*. 1981; 24(2):192–196. [PubMed: 7265933]
- Riley, GD. SSI-4, Stuttering severity instrument for children and adults. 4th. Austin, TX: Pro Ed; 2008.
- Riley G, Riley J. Oral motor discoordination among children who stutter. *Journal of Fluency Disorders*. 1986; 11(4):335–344.10.1016/0094-730X(86)90021-5
- Sakai N, Masuda S, Shimotomai T, Mori K. Brain activation in adults who stutter under delayed auditory feedback: An fMRI study. *International Journal of Speech-Language Pathology*. 2009; 11(1):2–11.10.1080/17549500802588161
- Shadmehr R, Smith MA, Krakauer JW. Error correction, sensory prediction, and adaptation in motor control. *Annual Review of Neuroscience*. 2010; 3:89–108.10.1146/annurev-neuro-060909-153135
- Smith A, Sadagopan N, Walsh B, Weber-Fox C. Increasing phonological complexity reveals heightened instability in inter-articulatory coordination in adults who stutter. *Journal of Fluency Disorders*. 2010; 35(1):1–18.10.1016/j.jfludis.2009.12.001 [PubMed: 20412979]
- Smits-Bandstra S. Methodological considerations in the measurement of reaction time in persons who stutter. *Journal of Fluency Disorders*. 2010; 35(1):19–32.10.1016/j.jfludis.2009.12.002 [PubMed: 20412980]
- Smits-Bandstra S, De Nil LF. Early-stage chunking of finger tapping sequences by persons who stutter and fluent speakers. *Clinical Linguistics & Phonetics*. 2013; 27(1):72–84.10.3109/02699206.2012.746397 [PubMed: 23237418]
- Smits-Bandstra S, De Nil LF, Saint-Cyr JA. Speech and nonspeech sequence skill learning in adults who stutter. *Journal of Fluency Disorders*. 2006; 31(2):116–136.10.1016/j.jfludis.2006.04.003 [PubMed: 16735062]
- Smits-Bandstra S, De Nil L, Rochon E. The transition to increased automaticity during finger sequence learning in adult males who stutter. *Journal of Fluency Disorders*. 2006; 31(1):22–42.10.1016/j.jfludis.2005.11.004 [PubMed: 16445973]
- Sommer M, Koch M, Paulus W, Weiller C, Buchel C. Disconnection of speech-relevant brain areas in persistent developmental stuttering. *Lancet*. 2002; 360(9330):380–383.10.1016/S0140-6736(02)09610-1 [PubMed: 12241779]
- Starkweather CW, Franklin S, Smigo TM. Vocal and finger reaction-times in stutterers and nonstutterers - differences and correlations. *Journal of Speech and Hearing Research*. 1984; 27(2):193–196. [PubMed: 6738029]
- Venkatagiri HS. Reaction time for voiced and whispered/a/ in stutterers and nonstutterers. *Journal of Fluency Disorders*. 1981; 6(3):265–271.
- Watkins KE, Smith SM, Davis S, Howell P. Structural and functional abnormalities of the motor system in developmental stuttering. *Brain*. 2008; 131:50–59.10.1093/brain/awm241 [PubMed: 17928317]
- Watson BC, Alfonso PJ. A comparison of LRT and VOT values between stutterers and nonstutterers. *Journal of Fluency Disorders*. 1982; 7(2):219–241.
- Webster WG. Neuropsychological models of stuttering: 1. Representation of sequential response mechanisms. *Neuropsychologia*. 1985; 23(2):263–267.10.1016/0028-3932(85)90110-1 [PubMed: 4000461]
- Webster WG. Neuropsychological models of stuttering: 2. Interhemispheric interference. *Neuropsychologia*. 1986; 24(5):737–741.10.1016/0028-3932(86)90014-X [PubMed: 3785662]
- Webster WG. Sequence reproduction deficits in stutterers tested under nonspeeded response conditions. *Journal of Fluency Disorders*. 1989; 14(2):79–86.10.1016/0094-730X(89)90001-6
- Webster WG. Evidence in bimanual finger-tapping of an attentional component to stuttering. *Behavioural Brain Research*. 1990; 37(2):93–100.10.1016/0166-4328(90)90084-R [PubMed: 2322417]

- Webster, WG. Principles of human brain organization related to lateralization of language and speech motor functions in normal speakers and stutterers. In: Hulstijn, W.; Peters, HFM.; van Lieshout, PHHM., editors. *Speech production: Motor control, brain research and fluency disorders*. Amsterdam, The Netherlands: Elsevier; 1997. p. 119-139.
- Webster WG, Ryan CRL. Task complexity and manual reaction-times in people who stutter. *Journal of Speech and Hearing Research*. 1991; 34(4):708–714. [PubMed: 1956178]
- Wieneke GH, Eijken E, Janssen P, Brutten GJ. Durational variability in the fluent speech of stutterers and nonstutterers. *Journal of fluency disorders*. 2001; 26(1):43–53.
- Wolpert DM, Diedrichsen J, Flanagan JR. Principles of sensorimotor learning. *Nature Reviews Neuroscience*. 2011; 12(12):739–751.
- Wolpert DM, Miall RC, Kawato M. Internal models in the cerebellum. *Trends in Cognitive Sciences*. 1998; 2(9):338–347. 10.1016/S1364-6613(98)01221-2 [PubMed: 21227230]
- Zelaznik HN, Smith A, Franz EA, Ho M. Differences in bimanual coordination associated with stuttering. *Acta Psychologica*. 1997; 96(3):229–243. [PubMed: 9434590]
- Zimmermann G. Stuttering - a disorder of movement. *Journal of Speech and Hearing Research*. 1980; 23(1):122–136. [PubMed: 6777605]

Figure 1.

Participants performed arm movements in a horizontal plane toward visual targets presented in a virtual display system (A). Twelve visual targets were used, radially oriented at 30 degree intervals and 14 cm from the start position (B). The test object was instrumented with a force sensor (C). The participant's forearm was supported by a lightweight air sled (D). F_n (normal force) is the vertical force, preventing slip between the finger and object. F_x and F_y are the two components defining F_t (tangential force), the horizontal force that slides the object across the work surface.

Figure 2.

Tangential force (A) and normal force (B) of one nonstuttering participant for movements to the 60° (solid line) and 150° (dashed line) targets. Polar plots represent the average peak amplitude of tangential force for early trials (first 5 trials in each direction) and late trials (last 5 trials in each direction) (C) and the average amplitude of normal force at the time of peak tangential force for early and late trials (D) as a function of movement direction. The scatter plot shows the relationship between peak tangential force and normal force at the time of peak tangential force across all 12 directions for early and late trials separately (E). The calculated correlation coefficient served as the individual's measure of the predictive component of movement planning. Directional error (F) and end-point error (G) were used as the measures quantifying the control component of movement planning.

Figure 3. Stuttering (red) and nonstuttering (blue) group means (bars) and individual participant data (circles) for directional error (A), end-point error (B), and the correlation between peak tangential force and normal force at the time of peak tangential force (C). All data averaged across Direction and Time. Stuttering participants were significantly less accurate (A, B) than nonstuttering participants in reaching to visual targets. Individual participant data show that approximately 50% of stuttering individuals performed outside the range for nonstuttering individuals. Both groups performed similarly in scaling normal force in

anticipation of direction-dependent changes in tangential force. Error bars indicate standard errors. n.s. = nonsignificant.

Individual participant information for the stuttering group (*L1* = native language; *SSI-4* = Stuttering Severity Instrument 4th Edition; *Stuttering frequency* (%SS) = mean percent syllables stuttered across *SSI-4* speaking and reading tasks; *Treatment* = time since most recent stuttering treatment).

Table 1

	Age	Sex	Handedness	L1	SSI-4 score	SSI-4 severity	Stuttering frequency (%SS)	Treatment
S1	20	male	Right	English	22	mild	5.49	5 years prior
S2	21	male	Right	English	19	mild	3.25	3 years prior
S3	28	male	Right	Kannada	36	severe	9.50	no treatment
S4	31	male	Right	English	17	very mild	5.6	3 years prior
S5 ^a	31	male	Right	English	25	moderate	9.34	6 years prior
S6	33	male	Right	English	19	mild	3.25	21 years prior
S7	42	male	Right	English	28	moderate	13.05	no treatment
S8	44	male	Right	English	28	moderate	6.72	16 years prior
S9	46	male	Right	English	23	mild	5.44	3 years prior

^aFor participant S5, no recording of the reading task was available; S5's *SSI-4* score, *SSI-4* severity, and stuttering frequency are based on the speaking task only.