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Research Article

Control and Prediction Components of Movement Planning in Stuttering Versus Nonstuttering Adults

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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 9 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 nonorofacial 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.

A large body of evidence has suggested that stuttering is a movement disorder involving deficiencies in fundamental sensorimotor processes (see Bloodstein & Bernstein-Ratner, 2008). On the basis of kinematic studies of speech production in stuttering and nonstuttering individuals, researchers have reported between-groups 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, because 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; Howell, Sackin, & Rustin, 1995; Loucks & De Nil, 2006, 2012; Max et al., 2003). We should note that some studies have failed to find such between-groups differences or have found differences that were restricted to certain experimental conditions (Cooper & Allen, 1977; De Nil, 1995; Jancke, 1994; Jancke, Kaiser, Bauer, & Kalveram, 1995; Janssen, Wieneke, & Vaane, 1983; Wieneke, Eijken, Janssen, & Brutten, 2001); however, the preponderance of evidence has suggested 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 have indicated 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 versus nonstuttering individuals have been found in a large variety of finger movement tasks (Bishop, Williams, & Cooper, 1991; Borden, 1983;

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Cross & Luper, 1983; Hand & Haynes, 1983; Max et al., 2003; Starkweather, Franklin, & Smigo, 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, 1990, 1997; Webster & Ryan, 1991). 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 has been 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 that 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, 2000; Neumann et al., 2003; Sakai, Masuda, Shimotomai, & Mori, 2009; Watkins et al., 2008). Generally, these studies have indicated that stuttering individuals, 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-groups 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, 2011).

Given the combined results of these behavioral and neuroimaging studies, one can conclude 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, Guenther, Gracco, Ghosh, & Wallace, 2004; Neilson & Neilson, 1987, 1991). This perspective is based on empirical, theoretical, and computational work suggesting that, 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 the accuracy of both the initial aiming direction and 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. For this purpose, we determined the correlation between the horizontal force (typically referred to as the *tangential force*) that the participant applies to slide the object across the table surface and the vertical force (typically referred to as the *normal force*) that the participant 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 (because 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 (viz., 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 compared with the control participants.

Method

Participants

Participants were nine right-handed male stuttering adults ranging in age from 20 to 46 years ($M = 32.67$ years) and nine right-handed male nonstuttering adults ranging in age from 19 to 44 years ($M = 32.60$ 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. The nonstuttering participants were recruited through the participant pool. Interested individuals were first screened for eligibility by phone or e-mail and then, if eligible, invited to participate. The first nine eligible stuttering individuals and the first nine eligible nonstuttering individuals participated in the study, and no attrition of participants occurred 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, 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 on age (±3 years), sex, and self-reported handedness. All participants were naive to the purpose of the study and gave informed consent before participation.

Apparatus

The experimental set-up was based on one previously described by Flanagan and 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 lightweight air sled (303 g) that allowed near-frictionless motion over a glass work 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 the 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). The top surface of the object was covered with medium sandpaper (220 grit). We used an electromagnetic motion tracking system (Liberty, Polhemus) 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

Before the experiment, seat height was adjusted such that the angle between the participant's upper arm and trunk was approximately 90° (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° (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° 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 s. 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

Table 1. Individual participant information for the stuttering group.

Participant	Age, years	Sex	Handedness	L1	SSI–4 score	SSI–4 severity	Stuttering frequency	Treatment
1	20	Male	Right	English	22	Mild	5.49	5 years prior
2	21	Male	Right	English	19	Mild	3.25	3 years prior
3	28	Male	Right	Kannada	36	Severe	9.50	No treatment
4	31	Male	Right	English	17	Very mild	5.6	3 years prior
5[a]	31	Male	Right	English	25	Moderate	9.34	6 years prior
6	33	Male	Right	English	19	Mild	3.25	21 years prior
7	42	Male	Right	English	28	Moderate	13.05	No treatment
8	44	Male	Right	English	28	Moderate	6.72	16 years prior
9	46	Male	Right	English	23	Mild	5.44	3 years prior

Note. L1 = native language; SSI–4 = Stuttering Severity Instrument—4th Edition; stuttering frequency = mean percentage of syllables stuttered across SSI–4 speaking and reading tasks; treatment = time since most recent stuttering treatment.

[a] For Participant 5, no recording of the reading task was available; Participant 5's SSI–4 score, SSI–4 severity, and stuttering frequency are based on the speaking task only.

visual feedback of the movement trajectory for 1 s. 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 premovement 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 premovement 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, $t(16) = 0.086$, $p = .774$, $\eta^2_p = .005$. Thus, any effects of individual variability in premovement force were negligible.

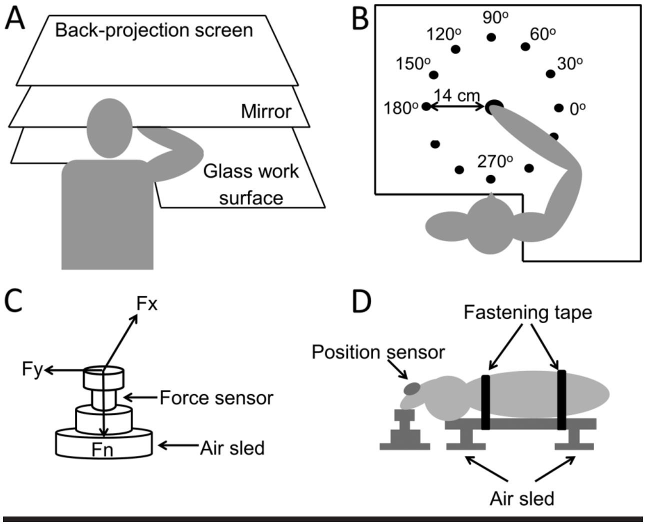


Figure 1. Participants performed arm movements in a horizontal plane toward visual targets presented in a virtual display system (A). Twelve visual targets were used, radially oriented at 30° intervals and 14 cm from the start position (B). The test object was instrumented with a force sensor (C). The 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.

We also tested for a between-groups 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 (two 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, we calculated a coefficient of friction 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, $t(16) = -0.665$, $p = .516$, $\eta^2_p = .027$. Therefore, we do not consider these coefficient of friction data further.

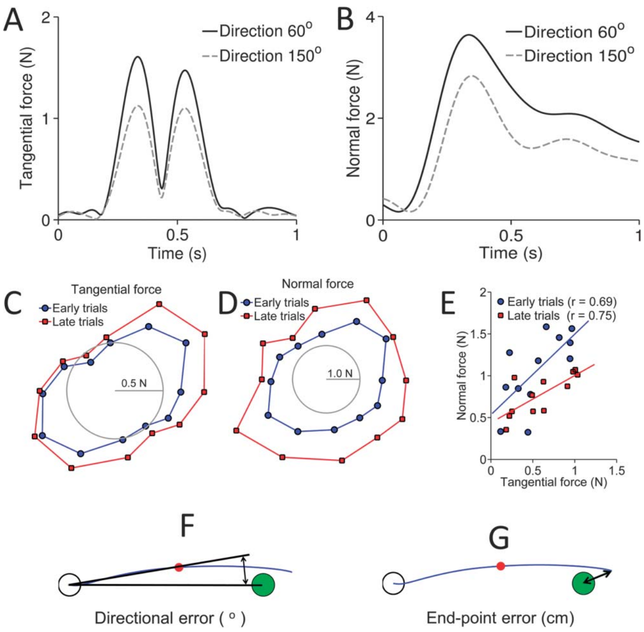
Signal Conditioning

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. We then calculated the tangential velocity (hereinafter termed *velocity*) as $V = \sqrt{V_x^2 + V_y^2}$. From the six-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. We used these two orthogonal forces 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. Last, we computed the rate of change in F_t and F_n using a central difference equation.

We defined the onset time for all signals 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 s after the target appeared, (b) the velocity profile was not bell shaped, (c) peak F_n was more than 3 standard deviations 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 1,000 ms from movement onset. We included these criteria 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. It is important to note that the number of excluded trials was not statistically significantly different between the stuttering and nonstuttering groups, $t(16) = .304$, $p = .211$, $\eta^2_p = .092$.

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. We used directional error (F) and end point error (G) as the measures quantifying the control component of movement planning.



Dependent Variables

We included as dependent variables quantifying the movement planning control component two kinematic measures of accuracy. 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 centimeters) 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, we extracted the peak F_t value as well as the F_n value at the time of peak F_t. We then used correlational analyses (see below) to determine the strength of the coupling between these two forces.

To determine whether the stuttering and nonstuttering participants differed on any general movement parameters, we extracted a number of additional kinematic and kinetic measures. 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 at which velocity was higher than 0.5 cm/s.

Statistical Analyses

We conducted all statistical analyses with IBM SPSS version 19 using repeated-measures analysis of variance 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).

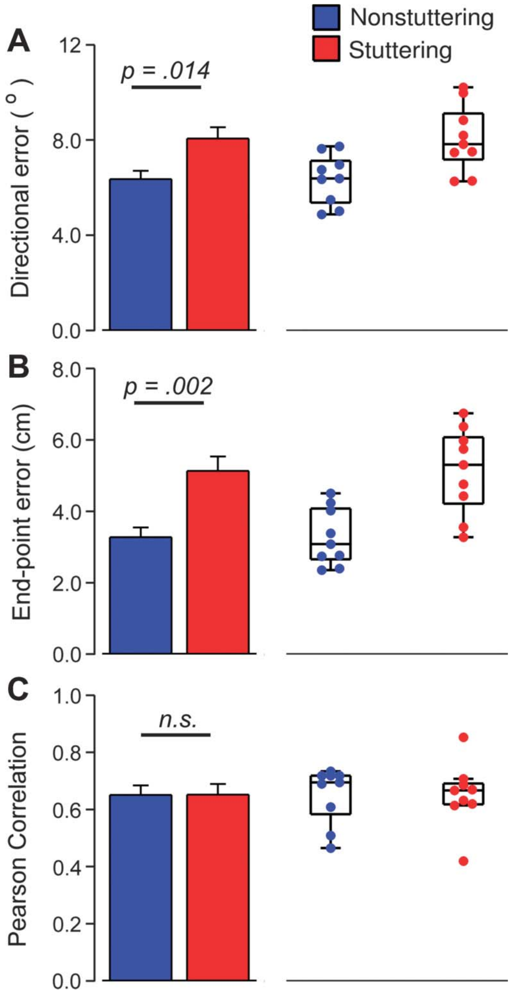
To quantify the strength of direction-dependent coupling between F_n and F_t for each participant, we determined the correlation between peak F_t and F_n at the time of peak F_t across the 12 movement directions (Figure 2E). The Pearson correlation coefficient was calculated separately for the set of 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). We used repeated-measures analysis of variance with group as a between-subjects factor and time (two levels) as the repeated measure to statistically compare the calculated correlation coefficients. Last, we also used Pearson correlation coefficients to investigate the relationship between each of the dependent variables and the stuttering participants' mean stuttering frequency (in percentage of syllables stuttered) across the conversational and reading speech samples of the SSI–4. All significance levels were set at $\alpha = .05$, and η^2_p was calculated to estimate effect sizes.

Results

Movement Accuracy

The group main effect was statistically significant for both directional error, $F(1, 16) = 7.540$, $p = .014$, $\eta^2_p = .320$, and end point error, $F(1, 16) = 13.911$, $p = .002$, $\eta^2_p = .465$. 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. We also found a statistically significant main effect of direction, but not time, on both directional error, $F(7.884, 126.147) = 10.907$, $p < .001$, $\eta^2_p = .405$, and end point error, $F(4.254, 68.062) = 4.348$, $p = .003$, $\eta^2_p = .214$. Descriptively, the between-groups 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 × 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 × Group, Time × Direction × Group) were also not statistically significant for either directional or end point error ($p > .200$).

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 toward 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.



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 × Group interaction ($p > .380$; note that we calculated the correlation coefficients across movement directions and, thus, this analysis of variance 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

We found a statistically significant main effect of direction on peak F_t, $F(3.594, 57.497) = 4.117$, $p = .007$, $\eta^2_p = .205$; peak F_t latency, $F(5.295, 84.715) = 4.704$, $p = .001$, $\eta^2_p = .227$; F_n at the time of peak F_t, $F(4.249, 67.985) = 2.561$, $p = .043$, $\eta^2_p = .138$; peak F_n, $F(4.958, 79.329) = 2.596$, $p = .032$, $\eta^2_p = .140$; peak F_n latency, $F(5.814, 93.026) = 3.127$, $p = .008$, $\eta^2_p = .163$; peak velocity, $F(6.296, 100.729) = 6.507$, $p < .001$, $\eta^2_p = .289$; 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 × Group, Direction × Group, Time × Direction, and Time × Direction × Group) were statistically significant for any of the kinetic and kinematic variables ($p > .081$).

Correlation Between Dependent Variables and Stuttering Frequency

We found 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 this 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 because 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, end point error, or both), 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 toward the visual targets. Both directional errors and end point errors were statistically significantly larger for the adults who stuttered than for the adults who did 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 are 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-groups difference in accuracy when moving the jaw to remembered somatosensory targets; Daliri et al., 2013). However, the strength of the correlation between peak tangential force and 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 because 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 the 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-groups 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 neuromechanical 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 this 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, this paradigm examined only the prediction of movement consequences that need to be accounted for during movement planning, but that are then compensated for 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 also be important to investigate how stuttering versus nonstuttering individuals modulate task-relevant sensory systems on the basis of 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, one could argue that the observed general sensorimotor deficit is unlikely to play an important role in the mechanisms underlying stuttering itself because 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 of or substitution for feared words, physical struggle, and so forth. 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, which may be affected, in turn, by the participant being familiar versus unfamiliar with the research staff and the research environment. Last, 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, neurochemical, 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.

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