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I am submitting herewith a thesis written by Mary Rhodes Robbins entitled “The Effect of Stuttering and Fluency-enhancing Conditions on a Manual Movement Task.” I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Arts with a major in Speech Pathology.

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THE EFFECT OF STUTTERING AND FLUENCY-ENHANCING CONDITIONS ON A MANUAL MOVEMENT TASK

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Abstract

The present study investigated the possibility of finding and quantifying correlates of stuttering behaviors outside of the speech production system. One female and six male adults who stutter (aged 22-49) drew continuous circles on a digital x-y pad under seven conditions: 1) while silent, 2) while reading alone, 3) while reading under choral speech, 4) while reading under frequency altered feedback (FAF) shifted up one-half octave, 5) while reading under FAF shifted down one-half octave, 6) while reading under delayed auditory feedback (DAF) of 100 milliseconds (ms), and 7) while reading under DAF of 200ms. Normalized jerk (NJ), a measure of motor disfluency, was measured during the drawing tasks. In addition, the proportion of stuttered syllables was computed for all reading tasks. Seven age and gender matched non-stuttering participants were also tested to examine group differences in NJ measures. Participants in the stuttering group displayed higher levels of mean NJ than controls in all reading conditions, but not for the silent condition. For the stuttering group, mean NJ measures were lowest in the silent (non-reading task), and showed a 49% increase for the unassisted (solo) reading condition. In terms of stuttering frequency, solo reading, the condition in which NJ measures were the highest, was also the condition which produced the highest mean proportion of stuttered syllables (0.13). During the choral condition, in which stuttering was reduced by 95% to its lowest level (0.01), the NJ measures were reduced by approximately 20%, more than any other reading task. The FAF and DAF conditions resulted in 58-75% decreases in stuttering frequency, and NJ values that were lower than solo reading, but higher than the choral condition. For the control subjects, the mean NJ
values remained relatively stable across conditions. In conclusion, for the stuttering group, under conditions in which stuttering frequency was high, NJ measures were high, and under fluency-enhancing conditions which lowered the stuttering frequency, NJ measures also decreased. Thus, it appears that stuttering can produce quantifiable disfluent effects on motor systems beyond the speech motor system and that reductions in overt stuttering are related to reductions in measures of normalized jerk.
Preface

Stuttering is a dynamic involuntary communicative disorder that is overtly characterized by intermittent disruptions of speech, namely part-word repetitions and prolongations of sounds. In more severe cases, stuttering can also result in silent “postural fixations,” in which the flow of speech is completely blocked while the face assumes a tense articulatory posture (Bloodstein, 1995; Peters & Guitar, 1991; Silverman, 1996; Starkweather, 1987; Van Riper, 1973). Incipient developmental stuttering symptoms begin to develop in children between the ages of two and six years old. However, approximately 80% of children who are identified as having incipient stuttering experience complete spontaneous recovery, with or without therapeutic intervention (Finn, Ingham, Ambrose, & Yairi, 1997; Kalinowski, Dayalu, & Saltuklaroglu, 2002; Yairi & Ambrose, 1999; Yairi, Ambrose, & Niermann, 1993). For children who do not recover, the pathology becomes progressive in nature. That is, the severity of the overt behaviors usually increases, as evidenced by an increase in the frequency and duration of stuttering events as well as an increase in the visible struggle associated with speech (Peters & Guitar, 1991). The progression in severity is accompanied by the emergence of the covert symptoms of stuttering which are invisible to an observer, but salient and real to the person who stutters. These include compensatory strategies for hiding the pathology (e.g. sound and word substitutions) and negative reactions to previous and anticipated stuttering behaviors (e.g. fear, shame and anxiety) (Sheehan, 1970). Further evidence that stuttering may be becoming more severe is the appearance of ancillary, non-speech “struggle” behaviors, which are overt symptoms of stuttering consisting of
unusual movements of the head, hands, arms, or legs (Bloodstein, 1960; Conture & Kelly, 1991; Kraaimaat & Janssen, 1985; Riley, 1972; Van Riper, 1982; Wingate, 1964), and which can include, but are not limited to, eye blinking, facial grimacing, head jerking, gasping, rapid expulsion of breath, and fist clenching (Bloodstein, 1993). Ancillary behaviors are only produced when the person who stutters speaks, and are most likely to occur during stuttered speech (Kraaimaat & Janssen, 1985; Mulligan, Anderson, Jones, Williams, & Donaldson, 2001). Thus, these non-speech behaviors provide clear evidence that stuttering influences motor systems outside of the speech periphery (Bloodstein, 1960, 1993; Conture & Kelly, 1991; Kraaimaat & Janssen, 1985; Mulligan et al., 2001; Van Riper, 1982). However, objective data quantifying the effects of stuttering on other motor systems are limited, a deficit which the current study aims to rectify by examining the influence of stuttering and fluency-enhancing conditions on the smoothness of a manual motor task by using a measure of motor disfluency known as normalized jerk.
Table of Contents

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Review of the Literature</td>
<td>1</td>
</tr>
<tr>
<td>2. Summary</td>
<td>17</td>
</tr>
<tr>
<td>3. Methods</td>
<td>19</td>
</tr>
<tr>
<td>4. Results</td>
<td>24</td>
</tr>
<tr>
<td>5. Discussion</td>
<td>32</td>
</tr>
<tr>
<td>List of References</td>
<td>43</td>
</tr>
<tr>
<td>Vita</td>
<td>57</td>
</tr>
</tbody>
</table>
1. REVIEW OF THE LITERATURE

An Overview of Stuttering

The developmental progression of stuttering has been described by various researchers as a series of stages (Bluemel, 1957), tracks (Van Riper, 1973), or phases (Bloodstein, 1960). Bloodstein’s system of four phases of stuttering is a useful way to describe the development of stuttering, in that it is typical of the progression of symptoms common to people who stutter, in spite of the fact that there is considerable overlap between the phases and they may occur at different ages for different people (Bloodstein, 1995). In Bloodstein’s phase one, incipient stuttering is characterized by easy-flowing, tension-free syllable repetitions that tend to occur at the beginning of sentences. During this phase, stuttering is evenly distributed across grammatical categories (e.g. nouns, verbs, articles, conjunctions, etc.). Depending on the severity of stuttering at this stage, it can be difficult to distinguish these overt stuttering behaviors from the normal childhood disfluencies that most children experience. For a child who stutters in this early phase, the pathology will be episodic, meaning that he or she will experience periods of time of up to several months in which the stuttering disappears, only to return later. Generally, no covert symptoms manifest at this incipient stage. The child may or may not be frustrated by his or her difficulty in communicating, but is usually not significantly concerned by the disfluencies themselves, and does not have a self-identity as a stutterer (Bloodstein, 1995).

In Bloodstein’s phase two, which typically begins during elementary school, stuttering changes from an episodic to a persistent (i.e. unremitting) disorder. While the
beginning of the sentences continues to be the most common loci of stuttering, the child begins to stutter in the middle and at the end of sentences as well. Most of the stuttered sounds occur on content words (e.g. nouns, verbs, adjectives) rather than on function words (e.g. pronouns, conjunctions, articles), in contrast to phase one in which the stuttered sounds can occur in any word. It is in phase two that severity begins to increase in terms of increased tension and struggle, longer prolongations, as well as the possible emergence of postural fixations and ancillary behaviors (Peters & Guitar, 1991). The child at stage two is also likely to identify him- or herself as a “stutterer”, but despite this awareness, does not typically show significant levels of concern about stuttering (Bloodstein, 1995). In other words, the child’s covert reactions to stuttering are limited to a self-identity as a stutterer and vague anticipation of future communication breakdowns related to stuttering.

Bloodstein’s phase three can begin anywhere from eight years old to adulthood, but typically begins while the child is in middle school. During this phase, the child begins to stutter with greater frequency in some speaking situations then others. For example, it is typical for children in this age group to have difficulty maintaining fluency during classroom presentations. In this phase, children who stutter develop fears associated with sounds and words which have previously shown a propensity for eliciting stuttering. Thus, a repertoire of feared sounds and words is developed that helps to create an anticipation of stuttering. This may lead to the use of covert strategies such as substitution (exchanging words to avoid feared sounds) and circumlocution (providing many additional statements to avoid saying a certain word). In other words, the child begins to develop patterns of stuttering relating to the anticipation of stuttering on certain
words or in certain situations. The child who stutters may be irritated by his or her stuttering, but usually will not develop negative reactions such as fear, shame, or anxiety. Young people at this stage do not tend to avoid any speaking situations, even though they may stutter quite severely (Bloodstein, 1995). By the time the child reaches phase three, stuttering is likely to have become ingrained or “hard-wired” into the brain, as most children who continue to stutter into this phase generally do not recover. Simply put, as a child gets older, the chances for natural recovery decline and by phase three the chances of recovery are minimal (Andrews, Craig, Feyer, Hoddinott, Howie, & Neilson, 1983; Yairi & Ambrose, 1999).

Bloodstein’s fourth and final phase of developmental stuttering represents a complete stuttering “syndrome.” Not every person who stutters reaches this stage, but those who do usually develop fearful anticipation of stuttering, as well as salient fears of certain speaking situations, sounds, and words. Typically, there is an increase in word substitutions and circumlocutions, and the person who stutters may begin avoiding certain people or speaking situations. Additional covert symptoms include negative emotional reactions to the stuttering, such as shame, fear, and anger (Bloodstein, 1995).

Although the overall development of stuttering that has been described is a general progression, each person who stutters will develop overt and covert behaviors in a pattern of stuttering that is unique to his or her own experiences and ways of coping with the disorder. In other words, as stuttering progresses, one person may produce more prolongations than repetitions, while another continues to display mostly repetitions, and a third experiences frequent postural fixations and ancillary behaviors.

While the true distal etiology of stuttering remains unknown, convergent data
indicate that it has a central neurophysiological origin (Bloodstein, 1995; Ingham, 2001; Kalinowski & Saltuklaroglu, 2004; Ludlow & Loucks, 2003; Saltuklaroglu, Dayalu, & Kalinowski, 2002; Sommer, Koch, Paulus, Weiller, & Buchel, 2002; S. V. Stager, Jeffries, & Braun, 2003; Wu, Maguire, Riley, Fallon, LaCasse, Chin, Klein, Tang, Cadwell, & Lottenberg, 1995) and is involuntary in nature (Fox, Ingham, Ingham, Hirsch, Downs, Martin, Jerabek, Glass, & Lancaster, 1996; Sommer et al., 2002). A recent model for understanding stuttering is one that proposes that people who stutter are afflicted by an involuntary block somewhere in the brain, which is directly or indirectly responsible for all overt and covert symptoms of stuttering. Thus, the symptoms manifest outward from the central block (Guntupalli, Kalinowski, & Saltuklaroglu, 2006). The “central” block is thought to directly cause the overt disruptions of speech (part-word repetitions, prolongation and postural fixations) and directly cause the ancillary behaviors visible in the speech periphery and in other motor systems of the body, as well as be indirectly responsible for all covert reactions (compensatory strategies and negative reactions). Thus, unlike other theories of stuttering, this “minimalist” view sees all stuttering symptomatology to result from a simple neural “hitch” (Guntupalli et al., 2005). Because stuttering is an intermittent and highly variable pathology, not all symptoms will be seen at all times, or to the same degree in different people.

In the model of stuttering described above, the central involuntary block also causes a third type of stuttering symptom which has been called “sub-perceptual stuttering” (Armson & Kalinowski, 1994). Although the symptoms of stuttering described above have been categorically designated as either overt or covert, this third type of symptom represents a middle ground in what may actually be a continuum of
symptoms ranging from overt to covert. Simply put, sub-perceptual stuttering can be found in the perceptually-fluent speech of those who stutter, as evidenced by kinematic features associated with stuttered speech that are only detectible using sensitive instrumentation. Support for the existence of this third category of stuttering was provided by Armson and Kalinowski (1994), in a survey of the literature comparing the speech motor behaviors of stutterers and non-stutterers (under the Speech Motor Dynamics movement of the 1970s, 80s and early 90s). A host of studies falling under the Speech Motor Dynamics paradigm found differences in acoustic measures (e.g. pause time, voice onset time, reaction time for initiation of phonation, segment duration, articulatory rate) in the “perceptually fluent” speech of stutterers relative to normals (Adams & Hayden, 1976; Agnello, 1975; Borden, 1983; Colcord & Adams, 1979; Cross & Luper, 1979; Di Simoni, 1974; Healey & Gutkin, 1984; Hillman & Gilbert, 1977; Love & Jeffress, 1971; Ramig, Krieger, & Adams, 1982; Starkweather, Hirschman, & Tannenbaum, 1976; Starkweather & Meyers, 1979; Watson & Alfonso, 1983, 1987). Other studies found differences in kinematic measures (e.g. movement duration, amplitude, velocity, reversals in the sequencing of articulators) in the “perceptually fluent” speech of stutterers relative to normals (Caruso, Abbs, & Gracco, 1988; McClean, Kroll, & Loftus, 1990; Story & Alfonso, 1989; Watson & Alfonso, 1987). Under this Speech Motor Dynamics paradigm, these differences were interpreted as evidence that stutterers have inherent differences in their speech motor system. However, Armson and Kalinowski (1994) argued that the Speech Motor Dynamics paradigm failed to separate the cause of stuttering from its effect, because the “perceptually fluent” segments were extracted from longer speech segments that contained stuttering. They argued that the
stuttering in the larger speech segment is likely to influence or “contaminate” the perceptually fluent segments within the segment in several ways. First of all, motoric changes and compensations for stuttering are likely to change the acoustic and kinematic properties of adjacent speech segments. Another way that the perceptually-fluent speech of the people who stutter can be influenced is if they have received therapy in the past, because in that case they may consciously or unconsciously prolong sounds, slow their rate, or use other strategies that will change the kinematic and acoustic properties of speech. Thirdly, severity is a factor, because for an individual whose stuttering is more severe, it is more likely that stuttered segments will exert an influence over adjacent, perceptually-fluent speech segments than for someone whose stuttering is milder. Finally, age will be a factor because, given the developmental history of stuttering, it would be expected that people who have more experience with stuttering will have more instances of sub-perceptual stuttering due to years of reacting to, and compensating for stuttering (Armson & Kalinowski, 1994). In conclusion, the speech of those who stutter, though not overtly disrupted, may never be free from the influence of stuttering, a notion that may extend to other motor sequences produced while speaking.

The recognition of sub-perceptual stuttering allows for the separation of the cause of stuttering from its effect when interpreting stuttering research. For example, searching for generalized motor deficits in people who stutter based on perceptually fluent speech can be misleading if the supposedly fluent segments are in fact influenced by stuttering. Thus, any observed motor differences may simply be the result of the influence of the central stuttering block on the speech motor system during speech, resulting in motor differences which manifest on a sub-perceptual level, but never producing overt stuttering
symptoms. The same possible confound must also be considered when evaluating the results of brain imaging studies which have sought to identify factors causal to stuttering. Abnormal activations during stuttering have been found relative to normals in the supplemental motor area (Curio, Neuloh, Numminen, Jousmaki, & Hari, 2000), superior lateral premotor region (SLPrM), the primary auditory cortex (Fox et al., 1996; Fox, Ingham, Ingham, Zamarripa, Xiong, & Lancaster, 2000), the anterior insula (De Nil, Kroll, Kapur, & Houle, 1998; Fox et al., 1996; Fox et al., 2000), and the cerebellum (Fox et al., 1996). The only way to determine whether these aberrant activations are unique to stutterers or are simply a result of the disruptive motor patterns created by stuttering, and the negative emotional responses that occur during stuttering, would be to test stutterers under conditions in which they are speaking but not producing disfluencies. Interestingly, under choral speech conditions (i.e. another speaker speaking in unison), which allows people who stutter to immediately speak fluently (Kalinowski & Saltuklaroglu, 2003a), all abnormal activations identified during stuttering are relatively normalized (Fox et al., 1996). Ingham et al. (2001) found that there were no differences between stutterers and non-stutterers, in terms of cerebral blood flow values, when they were not speaking. Furthermore, when the stutterers in the study were asked to remain silent, but to imagine that they were stuttering, they were determined to have activation patterns similar to those which occur during stuttered speech (Ingham, 2001). Finally, there is some evidence to suggest that non-stutterers speaking with pseudo- or fake stuttering show cerebral activation patterns which are similar to those evident in people who stutter when they are speaking and stuttering (Ingham, 2002). All of this evidence suggests that aberrant brain activations during stuttered speech cannot be assumed to be
causal to stuttering and are more likely to be a neural “reflection” of stuttering.

**Fluency-enhancing Conditions**

Any technique or condition that reduces the overt and covert manifestations of stuttering is thought to have “inhibited” the central involuntary block (Hreljac, 1993; Kalinowski, Dayalu, Stuart, Rastatter, & Rami, 2000; Kalinowski & Saltuklaroglu, 2003b; Kalinowski, Saltuklaroglu, Guntupalli, & Stuart, 2004; Saltuklaroglu et al., 2002; Saltuklaroglu, Kalinowski, Dayalu, Stuart, & Rastatter, 2004). The most potent inhibitor of stuttering, choral speech, in which the person who stutters speaks in unison with another person, has been shown to allow people who stutter to immediately produce fluent and natural-sounding speech without any training or motoric strategies (Kalinowski & Saltuklaroglu, 2003a). The inhibition of stuttering that can be achieved using choral speech ranges from 90-100% (Bloodstein, 1995; Cherry & Sayers, 1956; Johnson & Rosen, 1937; Saltuklaroglu et al., 2002), and is impervious to changes in audience size, speech rate, or situation (Armson, Foote, Witt, Kalinowski, & Stuart, 1997). Because choral speech is so effective in reducing stuttering, and normalizing brain function, it can be considered the “gold standard” of all fluency-enhancing conditions, representing a system-wide inhibition of stuttering in which the speech of the person who stutters is indistinguishable from a normal speaker from the central nervous system outward. Not only are the overt symptoms of stuttering eliminated, but because the chance of stuttering has been substantially limited, choral speech also frees the speaker from the covert reactions to stuttering (Kalinowski & Saltuklaroglu, 2003a). On the other hand, the choral speech “effect” ends as soon as the second speech signal is
removed, and stuttering almost immediately returns. It is as if the use of choral speech is analogous to a switch that can turn stuttering “on” and “off” (Ingham, 2001).

Altered auditory feedback (AAF), including delayed auditory feedback (DAF), and frequency altered feedback (FAF), have also proven to be powerful methods of increasing fluency. Like choral speech, speaking while using AAF also requires no training or motoric control, and as such AAF may be considered a permutation of choral speech (Hargrave, Kalinowski, Stuart, Armson, & Jones, 1994; Howell, El-Yaniv, & Powell, 1987; Kalinowski, Armson, Roland-Mieszkowski, Stuart, & Gracco, 1993; Kalinowski & Stuart, 1996; Stuart, Kalinowski, Armson, Stenstrom, & Jones, 1996; Zimmerman, Kalinowski, Stuart, & Rastatter, 1997). Delayed auditory feedback consists of hearing one’s own voice with a slight temporal delay, which sounds like an echo. DAF has a long history in stuttering research and treatment, and was recognized as early as the 1950’s to be a fluency-enhancing condition for stutterers at delays of 200 ms and greater (Goldiamond, 1962, 1965; Naylor, 1953; Webster, Schumacher, & Lubker, 1970). At this delay rate, which was the shortest allowed by the technology in the 1950s and 60s, a speaker naturally slows his or her speech rate. As a result, the early interest in the impact of DAF on the auditory system of those who stutter (Cherry & Sayers, 1956) was later eclipsed by the claims of some researchers (Costello Ingham, 1983; Wingate, 1969, 1970) that the fluency-enhancing effect was due solely to decreased speaking rate. As such DAF was perceived by many to be only a tool for motoric retraining (i.e. using prolonged speech to decrease stuttering). Recent improvements in technology that allow for shorter delays have led to a resurgence of interest in the effects of DAF on the auditory system. If decreases in stuttering under DAF were in fact due to a decreased
speaking rate, then fluency levels should not improve in those who stutter while speaking at fast rates under DAF. However, several studies have demonstrated that people who stutter can speak fluently under DAF at both normal and fast rates of speech, as well as when employing shorter delays (25, 50 and 75ms) (Hargrave et al., 1994; Kalinowski et al., 1993; Kalinowski & Stuart, 1996; Kalinowski, Stuart, Sark, & Armson, 1996). Thus, the improvement in fluency can be attributed to the direct impact on DAF on the auditory system, and may occur because the slight temporal displacement in perceiving the echo is analogous to perceiving another speaker, speaking in unison (i.e. creating a choral effect).

In contrast to people who stutter, when normally-fluent speakers speak while experiencing DAF, they tend to become disfluent. The disfluency types include phoneme, syllable and word disfluencies, changes in speech rate, prolonged voicing, and changes in breathing patterns (Black, 1951; Fukawa, Yoshioka, Ozawa, & Yoshida, 1988; Langova, Moravek, Novak, & Petrik, 1970; Mackay, 1968; S. Stager, Denman, & Ludlow, 1997; S. Stager & Ludlow, 1993). It has been suggested by some researchers that the effects of DAF in normally fluent speakers is to create artificial stuttering (Black, 1951; Cherry & Sayers, 1956; Lee, 1951; Van Riper, 1982; Yates, 1963) However, when the issue was examined using a variety of temporal delays (Stuart, Kalinowski, Rastatter, & Lynch, 2002), normals experiencing DAF showed an increase in disfluencies at a long delay (200ms), but not at short delays (25 or 50 ms). However, these disfluencies sounded as if the speakers were “tripping over words”, and were produced without struggle or tension, unlike the disfluencies produced by people who stutter. The disfluencies may have been due to the fact that the delay of the feedback (200ms) exceeds the length of time it takes for a speaker to hear what he or she has just said. In
conclusion, disfluencies experienced by normals under DAF are not likely to be representative of true stuttering (Stuart et al., 2002), as would be expected since they do not have a central involuntary block (Guntupalli, 2005). As such, these behaviors are not indicative of the pathology of stuttering and are unlikely to coincide with the aberrant findings in other motor systems that are expected in true stuttering.

Frequency altered feedback (FAF), is another form of auditory feedback in which a person’s own speech is perceived with a shift in pitch. It is another powerful fluency enhancing condition that has been demonstrated to effectively and immediately decrease stuttering (Hargrave et al., 1994; Howell et al., 1987; Kalinowski et al., 1993; Kalinowski, Stuart, Wamsley, & Rastatter, 1999; Macleod, Kalinowski, Stuart, & Armson, 1995). Studies have confirmed that FAF produces fluency enhancing effects in the order of an 80% inhibition of stuttering at both normal and fast rates of speech. (Hargrave et al., 1994; Kalinowski et al., 1993). Interestingly participants describe its effect as sounding as if another person was speaking at the same time (Hargrave et al., 1994), which typically sounds like Mickey Mouse when the frequency is shifted up, and Darth Vader when it is shifted down, again making FAF a homolog of choral speech. One clear drawback exists to using DAF and FAF to inhibit stuttering. They require an endogenous (i.e. self-generated) source of speech in order to create their fluency-enhancing effects, in contrast to choral speech which is produced exogenously (i.e. from an outside source), and so is independent of the user who is benefiting from its effects. As a result, some users may not receive as powerful stuttering inhibition as when under true choral speech. For example, some people experience silent blocks, in which the altered feedback loop is interrupted by periods of silence as a result of the stuttering, thus
temporarily removing the choral effect.

The Influence of Stuttering on Hand Movement

Manual systems and the speech motor system appear to be related in several ways. For example, there is evidence to support the existence of “stuttering-like” behaviors in handwriting. The handwriting of people who stutter has been found to have an excess of strokes extending above and below the line of script and tremor when making loops (Roman-Goldzieher, 1929). Schenck (1932) examined the handwriting of people who stutter and identified excessive pressure, small overlapping letters, and instances of concurrent disfluencies in speech (although the author was careful to point out that these features of handwriting are not exclusive to stutterers). Fagan (1932) also identified examples of disfluencies which occurred in both stuttered speech and handwriting. Other studies have confirmed generally poorer quality of writing in people who stutter (Fitzgerald, Cooke, & Greiner, 1984; Greiner, Fitzgerald, & Cooke, 1986).

There also appears to be an interconnectivity between the hand and the speech motor system that relates to communicative function. Like speech, handwriting has been described as a goal-directed and symbolic communication system (Fischer, 2001). Interestingly, the early literature on stuttering provides some evidence that writing while speaking improves fluency (Glassburg, 1923, 1927, Schulmann, 1933) by as much as 50% (Bloodstein, 1949), possibly via an endogenous choral effect. Mayberry, Jaques and Dede (1998) studied the manual gestures of people who stutter and found that compared to normally-fluent speakers, they produced fewer manual gestures overall, yet rarely produced a manual gesture while stuttering. In other words, participants spoke and
gestured at the same time until they produced a speech disfluency, at which time their hand would stop moving until the stuttered moment was over. These behaviors may be interpreted as instances of “stuttering” or disruptions in manual gesturing that may correspond with speech disruptions. Hand gestures often accompany speech and may represent a symbolic correspondence between the speech periphery and the hand, formed as a result of the evolution of language from manual gestures (Rizzolatti & Arbib, 1998). There is evidence to support a functional connection between the hand motor area in the brain and the left hemisphere regions responsible for language processing (Choi, Na, Kang, Lee, & Na, 2001; Hermsdorfer, Goldenberg, Wachsmuth, Conrad, Ceballos-Baumann, Bartenstein, Schwaiger, & Boecker, 2001; Meister, Boroojerdi, Foltys, Sparing, Huber, & Topper, 2003; Rizzolatti & Arbib, 1998; Seyal, Mull, Bhullar, Ahmad, & Gage, 1999; Tokimura, Tokimura, Oliviero, Asakura, & Rothwell, 1996). Meister et al. (2003) used transcranial magnetic stimulation (TMS) to compare the excitability of the primary hand motor area and the leg motor area, during a reading task. While the participants were reading aloud, there was an increase in excitability in the hand motor area of the language-dominant hemisphere only, and these changes appeared to coincide with the duration of speech. The excitability of the leg motor cortex did not change during reading (Meister et al., 2003). Terao et al. (2001) found that preparation for vocalization seems to cause unilateral activation of the hand motor cortex in the dominant hemisphere. These results suggest that speaking or preparing to speak may be associated with activations in the hand motor cortex.
Normalized Jerk

Disfluencies in hand movement (e.g. lack of control, sudden changes in direction, tremor, difficulty initiating movement, slow and rigid movements) have been studied in the handwriting of elderly persons and patients with Parkinson’s Disease using a measure called normalized jerk (Contreras-Vidal, Teulings, & Stelmach, 1998; Teulings, Contreras-Vidal, Stelmach, & Adler, 1997; van Gemmert, Teulings, & Stelmach, 1998). As a movement is made from point a to point b, there is a displacement, and corresponding changes in velocity, which is the first derivative of displacement or the change in displacement over time. Acceleration is the second derivative of displacement, or the change in velocity over time, and it is a measure that reflects how fast the movement is speeding up or slowing down. In a smooth movement, acceleration is predictable and steady, based on the needed trajectory of the movement. For example for a straight line drawn from point a to point b, the tip of the pen will steadily accelerate until it has reached the midpoint between a and b (velocity will be at a maximum), and then acceleration will become negative so that the tip of the pen can slow down and stop at point b. Jerk, the third derivative of displacement or the change in acceleration over time, is a measure that has been used to measure the disfluency in handwriting (Flash & Hogan, 1985; Hogan & Flash, 1987), in arm movements in humans (Schneider & Zernicke, 1989; Yan, Thomas, Stelmach, & Thomas, 2000), in lifting movements in humans (Puniello, McGibbon, & Krebs, 2000), and in reaching movements in cats (Kitazawa, Goto, & Urushihara, 1993). A movement that is not smooth will be characterized by many changes in acceleration, and hence, high levels of jerk. Conversely, a smooth movement is the result of steady acceleration, or no acceleration,
and will yield low jerk levels. Normalized jerk is a unit-free measure in which the change in acceleration is normalized by the following formula:

$$\sqrt{\frac{1}{2} \int dt \ j^2(t) \times \text{duration}^5 / \text{length}^2}$$

In which $j$ is the jerk, or the third derivative of displacement. As a result, it does not depend on the direction, duration, or the size of the motor movements (Hirano, Kojima, Naito, Honjo, Kamoto, Okazawa, Ishizu, Yonekura, Nagahama, Fukuyama, & Konishi, 1997). With this measure, the fluency in movements that have different displacements and durations can be compared. It can be assumed that normalized jerk is minimal when movements are smooth (Kitazawa et al., 1993; Teulings et al., 1997), (Hogan & Flash, 1987).

Teulings et al. (1997) found that relative to normal controls, patients with Parkinson’s disease exhibited higher levels of normalized jerk in a circle-drawing task. Similarly, the handwriting movement of elderly participants display higher normalized jerk scores than the young subjects (Contreras-Vidal et al., 1998). When the mental and motor load is increased to a moderate level by asking a participant to repeat numbers that have be auditorily presented (which is roughly equivalent to reading while drawing circles), normalized jerk increases for patients with Parkinson’s disease, but not for elderly or young subjects (Van Gemmert, Teulings, Contreras-Vidal, & Stelmach, 1999). Given the evidence that stuttering permeates other motor systems and the functional relationship between the hand and the speech mechanism, an increase in normalized jerk would be expected in a smooth movement task (like drawing circles) if it were performed while the subject was speaking and stuttering. If this effect can be demonstrated, then it
may also follow that fluency enhancing strategies which decrease speech disfluencies may also decrease normalized jerk. Choral speech, as the most potent fluency enhancer, would be likely to result in the largest decrease in normalized jerk, probably bringing it close to baseline, due to the almost complete inhibition of the central block. DAF and FAF would be predicted to have a significant effect as well, but to a lesser degree than choral speech due to the slightly less potent inhibitory effects over stuttering. If normalized jerk can be demonstrated to be a sensitive measure of the disfluencies resulting from the central block in the hand, then the relative effect of different conditions which appear to have an inhibitory effect on the block can be compared and studied.
2. SUMMARY

Rationale for Experiment

Stuttering is thought to manifest outward from a central involuntary block, resulting in overt speech disruptions and ancillary behaviors, as well as covert reactions such as avoidances and negative feelings. It is likely that some speech disruptions manifest on a sub-perceptual level, but cannot be overtly observed. If stuttering permeates other motor systems, then we can expect to detect its influence in a smooth motor task using a measure of disfluency such as normalized jerk. If a correlation between the frequency of stuttering in the speech task and the level of normalized jerk in a manual task can be demonstrated, and if speech-based inputs (choral speech, DAF, FAF), known to reduce stuttering in the speech periphery can be shown to have an inhibitory effect on normalized jerk in the hand as well, then the acquired data would support the theory that these inputs inhibit stuttering on a central level. In addition, normally-fluent speakers are likely to experience more speech disfluencies when speaking with DAF of 200ms, but may not be expected to experience disfluencies in the hand as well, since their disfluencies are not attributed to the same source as stuttering.

Experimental Questions

1. Does stuttering exert an influence on the smoothness of a manual circle-drawing task, and if so, can it be detected using a measure of normalized jerk?

2. Do people who stutter show any inherent differences in circular drawing fluidity as compared to normally communicating individuals (i.e. during silence)?
3. Does the influence of speech-based auditory feedback exert an inhibitory influence on motor disfluencies in the hand during circle drawing task? If so, what are the relative inhibitory powers of choral speech, DAF at 100 and 200 ms, and FAF shifted up \( \frac{1}{2} \) octave and down \( \frac{1}{2} \) octave?

4. Will normally-fluent speakers, speaking under altered auditory feedback, display increased disfluencies in speech and/or in hand movements during a circle-drawing task?
3. METHODS

Participants

The experimental group consisted of seven right-handed adults who stutter (six men and one woman, whose ages ranged from 22 to 49). Participants were only included in the stuttering group if they displayed at least 3% stuttered syllables in a reading task. Participants were excluded from the group if they presented with any other diagnosis of speech, language, or hearing disorder, aside from stuttering. The control group was comprised of seven right-handed, non-stuttering controls (six men and one woman, whose ages ranged from 23 to 50). Control subjects did not present with any diagnoses of speech, language or hearing disorders. The handedness portion of the Lateral Preference Inventory (LPI) was administered to each participant prior to data collection to ensure right-handed dominance (Coren, 1993).

Instrumentation and Stimuli

Participants drew on a digitizer x-y display (Wacom Intuos II) that was connected to a Dell™ personal computer (Dimension 3000, 2650, 1.6 GHz, 384MB RAM, and 20 GB hard drive). The digitizer used a sampling rate of 101 Hz with a spatial error of .05 mm. The full display (28 cm x 23 cm) of the digitizer was used to record movement information and it was oriented on a table according to the preference of each participant. The reading passages used were non-standardized and of fifth to seventh grade reading level, as determined by the Flesch-Kincaid reading scale (Flesch, 1974). These passages have been previously used in other published research (Dayalu et al., 2001; Kalinowski,
The DAF and FAF conditions were created by the participants speaking into a Cardioid microphone, and the signal was fed through a Digitech Studio S100 digital signal processor, routed to a Mackie DFX-6 mixer, and delivered to the participant’s ear using Ear Tone model ER-1 earphones. The microphone was held with a boom on a stand approximately five cm from the participant’s mouth. The two FAF conditions consisted of either a shift in frequency up one-half octave, or a shift in frequency down one-half octave. The DAF conditions consisted of either a delay of 100ms or a delay of 200ms. The output to the earphones was calibrated to approximate real ear average conversation sound pressure levels of speech outputs from normal-hearing participants. Speech samples from each participant were recorded with a videocamera (Sony DCR-HC30).

Conditions

Each participant drew continuous circles clockwise on the digitizer under a control condition and six experimental conditions. In the silent condition, participants drew the continuous circles without performing a simultaneous reading task. In the solo reading condition, participants read a passage while drawing continuous circles on the digitizer. In the choral reading condition, participants read a passage in unison (chorally) with the experimenter while drawing the continuous circles. During the DAF conditions, participants read a passage while experiencing a delay of 100ms and 200ms, respectively, while drawing the continuous circles. During the FAF conditions, participants read a
passage while experiencing auditory feedback that has been shifted up and down one-half octave, respectively, while drawing the continuous circles. During each condition, participants were asked to draw the continuous circles at a comfortable size and speed. A different reading passage was used for each reading condition, and the order of the passages was randomized by a computer program for each participant (http://www.randomizer.org).

Procedure

Prior to data collection, participants practiced drawing circles on the x-y pad to get accustomed to writing on its surface (Teulings et al., 1998). They also listened briefly to all of the auditory conditions, and practiced reading while drawing circles. Stuttering participants were asked to avoid the use of any therapy techniques during the reading tasks. The order of condition presentation was randomized by the data collection and analysis software, Movalyzer 3.0 (Neuroscript LLC, 2004). Each condition was presented in 10 trials. For each five second trial, the participants drew continuous circles, which were recorded by the digitizer, while reading the passage (except for the silent condition) until instructed to stop. They were then asked to begin both tasks again for the next five second trial, requiring the initiation of speech for each trial. The number of trials and the time for each recording by the digitizer was adapted from Teulings et al. (1997), who used blocks of either four, eight or, 16 trials and found five seconds of recording time during each trial to yield representative normalized jerk values for each trial. In this study, the onset of each trial was signaled by a 1000 Hz tone presented for 100 ms, at which time the participants were orally instructed to begin. In the control
condition, participants were asked to start drawing on the digitizer as soon as instructed, and were asked to remain silent throughout the trial. During the reading conditions with DAF and FAF, participants were asked to begin reading and drawing at the same time as soon as instructed to begin. During the choral reading condition, the experimenter began reading and the participant was asked to begin drawing and reading in unison immediately thereafter. The time interval between consecutive trials was approximately five seconds, and a two-minute rest period was given between consecutive experimental conditions.

Analysis

The recording of the continuous circles on the digitizer was analyzed using Movalyzer 3.0 (Neuroscript LLC, 2004) software, which is specifically designed for the kinematic analysis of handwriting. The recordings were low pass filtered at 7 Hz (Teulings & Maarse, 1984) and the normalized jerk values were calculated by the software according to the formula:

\[ \sqrt{\frac{1}{2} \int dt \, j^2(t) \times \text{duration}^5 / \text{length}^2} \]

In which \( j \) is the jerk, or the third derivative of displacement. In order to determine differences in normalized jerk between conditions and groups (i.e., stuttering versus control), the normalized jerk values were averaged across trials for each participant under each condition. A small number (less than 3%) of spurious data points were removed because they reflected extraneous movements resulting from difficulty initiating and/or
coordinating the reading task and the drawing task. A 2-factor (7 conditions x 2 groups) mixed ANOVA was then conducted using SPSS 13.0 statistical software.

The proportion of stuttered syllables was analyzed using an operational definition of stuttering which includes only the following: syllable repetitions, audible prolongations, and silent postural fixations (inaudible blocking on speech sounds). Frequency counts were collected while watching the audio-video recordings of all participants. Proportions of stuttered syllables were calculated in relation to total syllables produced. Ten percent of the frequency data was also analyzed by the experimenter and a trained research assistant. Inter-judge reliability, as indexed by Cohen’s kappa (Cohen, 1960) was .92. Kappa values above .75 represent excellent agreement above chance (Fleiss, 1981).
4. Results

The mean NJ values for the stuttering group and the non-stuttering group are listed in Table 1, along with the standard errors. The values are graphically displayed in Figure 1.

Upon first examination of the data, Mauchley’s Test of Sphericity \((p < 0.0001)\) revealed that the sphericity assumption was violated (Keppel, 1991). However, in this data set, the mean NJ measures are proportional to the standard deviations, therefore a log transformation was appropriate (Fleiss, 1986). After a log transformation, sphericity was improved, but still not met \((p < 0.006)\). Because the derived epsilon value was greater than 0.75, a Huynh-Feldt correction was appropriate (Keppel, 1991) and was used in the inferential statistics. A mixed ANOVA (2 groups X 7 conditions) revealed statistically significant main effects for condition \([F (2, 72) = 5.77, \text{Huynh-Feldt } p < .01, \eta^2 = .325, \Phi = 1.00]\), and group \([F(1, 12) = 4.76, p = .05, \eta^2 = .28, \Phi = .52]\). However, the interaction between condition and group was not significant \((p = .21)\). For the stuttering group, there was a significant main effect for condition \([F (6, 36) = 3.99, \text{Huynh-Feldt } p < .01, \eta^2 = .40, \Phi = .89]\), but for the non-stuttering group there was not \([F (6, 36) = 2.10, \text{Huynh-Feldt } p = .077, \eta^2 = .26, \Phi = .68]\). Within- and between-group contrasts were examined to determine the sources of these main effects, and are summarized in Table 2.

For both the stuttering and the non-stuttering group, the proportion of stuttered syllables, relative to total syllables produced, was calculated for each reading condition. There was a significant main effect of condition for the stuttering group \([F (5, 30) = \)
Table 1: Mean normalized jerk values (unit-free) and standard errors for the stuttering and non-stuttering group

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mean NJ</th>
<th>Std. Error</th>
<th>Mean NJ</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solo Reading</td>
<td>17.06</td>
<td>3.62</td>
<td>9.57</td>
<td>.30</td>
</tr>
<tr>
<td>Silent</td>
<td>11.44</td>
<td>1.97</td>
<td>8.67</td>
<td>.13</td>
</tr>
<tr>
<td>Choral Reading</td>
<td>13.73</td>
<td>2.19</td>
<td>9.27</td>
<td>.28</td>
</tr>
<tr>
<td>DAF 100 Reading</td>
<td>14.49</td>
<td>2.25</td>
<td>9.59</td>
<td>.43</td>
</tr>
<tr>
<td>DAF 200 Reading</td>
<td>15.37</td>
<td>2.86</td>
<td>9.78</td>
<td>.40</td>
</tr>
<tr>
<td>FAF + ½ Reading</td>
<td>14.90</td>
<td>2.87</td>
<td>9.51</td>
<td>.35</td>
</tr>
<tr>
<td>FAF – ½ Reading</td>
<td>14.52</td>
<td>1.89</td>
<td>9.56</td>
<td>.39</td>
</tr>
</tbody>
</table>
Figure 1. Mean Normalized Jerk by condition for the stuttering and non-stuttering groups.
Table 2: Sources of statistical differences in normalized jerk measure across conditions.

<table>
<thead>
<tr>
<th>Within-subject Contrasts</th>
<th>df</th>
<th>F</th>
<th>p</th>
<th>η²</th>
<th>Φ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silent vs. all reading conditions</td>
<td>1, 6</td>
<td>8.34</td>
<td>.03*</td>
<td>.58</td>
<td>.67</td>
</tr>
<tr>
<td>DAF reading vs. FAF reading</td>
<td>1, 6</td>
<td>.19</td>
<td>.68</td>
<td>.03</td>
<td>.07</td>
</tr>
<tr>
<td>Choral reading vs. all AAF (DAF and FAF)</td>
<td>1, 6</td>
<td>10.69</td>
<td>.02*</td>
<td>.64</td>
<td>.78</td>
</tr>
<tr>
<td>Choral reading vs. solo reading</td>
<td>1, 6</td>
<td>2.48</td>
<td>.17</td>
<td>.29</td>
<td>.27</td>
</tr>
<tr>
<td>silent vs. all AAF (DAF and FAF)</td>
<td>1, 6</td>
<td>8.37</td>
<td>.03*</td>
<td>.58</td>
<td>.68</td>
</tr>
<tr>
<td>DAF 100 reading vs. DAF 200 reading</td>
<td>1, 6</td>
<td>.77</td>
<td>.41</td>
<td>.11</td>
<td>.12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Within-subject Contrasts</th>
<th>df</th>
<th>F</th>
<th>p</th>
<th>η²</th>
<th>Φ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silent vs. all reading conditions</td>
<td>1, 6</td>
<td>9.27</td>
<td>.02*</td>
<td>.01</td>
<td>.72</td>
</tr>
<tr>
<td>Solo reading vs. all AAF (DAF and FAF)</td>
<td>1, 6</td>
<td>.05</td>
<td>.83</td>
<td>.01</td>
<td>.39</td>
</tr>
<tr>
<td>Choral reading vs. all AAF (DAF and FAF)</td>
<td>1, 6</td>
<td>3.93</td>
<td>.10</td>
<td>.40</td>
<td>.39</td>
</tr>
<tr>
<td>DAF reading vs. FAF reading</td>
<td>1, 6</td>
<td>.14</td>
<td>.72</td>
<td>.02</td>
<td>.06</td>
</tr>
<tr>
<td>DAF 100 reading vs. DAF 200 reading</td>
<td>1, 6</td>
<td>.39</td>
<td>.56</td>
<td>.06</td>
<td>.08</td>
</tr>
<tr>
<td>Solo reading vs. silent</td>
<td>1, 6</td>
<td>9.88</td>
<td>.02*</td>
<td>.62</td>
<td>.75</td>
</tr>
</tbody>
</table>

*Significant at p<0.05; effect size indexed by η²; and power indexed by Φ at a α of 0.05
### C) Between-group Comparisons of NJ (Stuttering vs. Non-stuttering Participants)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>df</th>
<th>t</th>
<th>p</th>
<th>$\eta^2$</th>
<th>$\Phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solo Reading</td>
<td>12</td>
<td>-2.17</td>
<td>.05*</td>
<td>.28</td>
<td>.51</td>
</tr>
<tr>
<td>Silent</td>
<td>12</td>
<td>-1.48</td>
<td>.17</td>
<td>.15</td>
<td>.28</td>
</tr>
<tr>
<td>Choral Reading</td>
<td>12</td>
<td>-2.08</td>
<td>.06</td>
<td>.27</td>
<td>.48</td>
</tr>
<tr>
<td>DAF 100 Reading</td>
<td>12</td>
<td>-2.15</td>
<td>.05*</td>
<td>.28</td>
<td>.51</td>
</tr>
<tr>
<td>DAF 200 Reading</td>
<td>12</td>
<td>-2.07</td>
<td>.06</td>
<td>.26</td>
<td>.48</td>
</tr>
<tr>
<td>FAF + ½ Reading</td>
<td>12</td>
<td>-2.00</td>
<td>.07</td>
<td>.25</td>
<td>.45</td>
</tr>
<tr>
<td>FAF – ½ Reading</td>
<td>12</td>
<td>-2.57</td>
<td>.02*</td>
<td>.36</td>
<td>.66</td>
</tr>
</tbody>
</table>

*Significant at $p<0.05$; effect size indexed by $\eta^2$; and power indexed by $\Phi$ at an $\alpha$ of 0.05.
13.876, Huynh-Feldt $p < .01, \eta^2 = 0.70, \Phi = 1.0$, but not for the non-stuttering group $[F(5, 30) = .733 \text{ Huynh-Feldt } p = 0.60, \eta^2 = 0.11, \Phi = 0.23]$. The mean proportion of stuttered syllables in the stuttering group was 0.13 (SE = 0.02) for solo reading, 0.01 (SE = 0.004) for choral reading, 0.04 (SE = 0.01) for DAF 100, 0.06 (SE = 0.02) for DAF 200, 0.03 (SE = 0.01) for FAF $+\frac{1}{2}$ reading, and 0.04 (SE = 0.02) for FAF -one-half reading (see Figure 2). These changes represent a decrease in stuttering rate that ranges from 58% to 95% across conditions, with the greatest reduction occurring during the choral reading condition. Single-$df$ within-subject contrasts were explored and are reported in Table 3. For the control group, based on the operational definition for stuttering, a very small increase in speech influences was observed under DAF conditions. However, these differences did not reach the level of statistical significance.
Figure 2. Proportion of stuttered syllables by condition for the stuttering group
Table 3. Sources of statistical differences in proportion of stuttered syllables in the stuttering group across conditions.

<table>
<thead>
<tr>
<th>Within-subject Contrasts</th>
<th>df</th>
<th>F</th>
<th>p</th>
<th>$\eta^2$</th>
<th>$\Phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choral reading vs. all AAF (DAF and FAF)</td>
<td>1, 6</td>
<td>9.09</td>
<td>.02*</td>
<td>.60</td>
<td>.711</td>
</tr>
<tr>
<td>DAF reading vs. FAF reading</td>
<td>1, 6</td>
<td>3.113</td>
<td>.13</td>
<td>.34</td>
<td>.319</td>
</tr>
<tr>
<td>DAF 100 reading vs. DAF 200 reading</td>
<td>1, 6</td>
<td>24.47</td>
<td>&lt;.01*</td>
<td>.80</td>
<td>.98</td>
</tr>
<tr>
<td>FAF + $\frac{1}{2}$ reading vs. FAF – $\frac{1}{2}$ reading</td>
<td>1, 6</td>
<td>.82</td>
<td>.40</td>
<td>.12</td>
<td>.12</td>
</tr>
<tr>
<td>Solo reading vs. all AAF and choral reading</td>
<td>1, 6</td>
<td>26.61</td>
<td>&lt;.01*</td>
<td>.82</td>
<td>.99</td>
</tr>
</tbody>
</table>

*Significant at $p<0.05$; effect size indexed by $\eta^2$; and power indexed by $\Phi$ at an $\alpha$ of 0.05.
5. Discussion

Stuttering Frequency

The major findings in the current study are two-fold. First, we demonstrated again the powerful effect of choral speech and two forms of altered auditory feedback (DAF and FAF) on stuttering frequency. During the unassisted (solo) reading task, the proportion of stuttered syllables was 13% of all syllables, but under the choral reading condition the mean stuttering frequency was reduced by 95% (to 1% of all syllables). Under conditions of altered auditory feedback (DAF and FAF) stuttering frequency was reduced between 58% and 75% (i.e. to 3%-6% of all syllables). These levels of stuttering inhibition are consistent with the previous literature on the effect of choral reading (Kalinowski & Saltuklaroglu, 2003), and altered feedback on stuttering frequency (Armson, Foote, Witt, Kalinowski, & Stuart, 1997; Hargrave, Kalinowski, Stuart, Armson, & Jones, 1994; Kalinowski, Stuart, Wamsley, & Rastatter, 1999; Macleod, Kalinowski, Stuart, & Armson, 1995; Saltuklaroglu, 2004). Choral reading was demonstrated to be the most powerful inhibitor of stuttering, an effect that was seen despite the fact that one subject showed an unusual lack of reduction of stuttering for choral speech, probably partially due to the fact that his stuttering severity was very mild (i.e. only 3% stuttered syllables in unassisted reading). Considering the 95% reduction in stuttering seen in this study, and the robust levels of inhibition reported in the literature (Bloodstein, 1995; Cherry & Sayers, 1956; Johnson & Rosen, 1937) when a person who stutters reads with another person, his or her speech is essentially normalized, in that the his or her speech is indistinguishable from the speech of a non-stutterer. In other words,
it is produced with ease, without disfluencies, and in a very natural way (Kalinowski et al., 2004). The other speech-based auditory inputs in this study, FAF and DAF, also demonstrated consistent stuttering inhibition. It is important to note that this stuttering inhibition occurs under choral and altered auditory feedback without the use of any motor control or techniques. Thus, their effects are attributed to the added auditory input. The effects of DAF and FAF, in addition to showing dramatic effects on the overt symptoms of stuttering, have an enormous impact on the experiential nature of the pathology.

When one subject was asked about his speech under the DAF and FAF, he replied “I just knew that I wasn’t going to stutter!” This may suggest that not only were the overt symptoms removed, but the covert symptoms (i.e. the anticipation of stuttering) were removed as well.

Non-stuttering control subjects, when speaking under conditions of DAF and FAF, displayed a number of speech disruptions, such as whole word repetitions and the insertion of extraneous sounds, and generally “tripped over their words.” However, in terms of the operational definition of stuttering (repetitions, prolongations or silent postural fixations), this group showed no significant differences between solo reading and any of the altered auditory feedback conditions. This is contrary to the findings of Stuart et al. (2002), who found that when non-stutterers read under conditions of a 200ms delay, they showed a small increase in disfluencies matching the above definition of stuttering. In the Stuart et al. (2002) study, participants read passages of 300 syllables, with a duration that ranged from approximately 53 to 71 seconds, and it is possible that the current study did not show comparable speech disruptions because the considerably shorter, five-second trials did not allow time for the delayed auditory input to disrupt
speech. The inability to show stuttering speech disruptions in non-stutterers is consistent with the analysis of Stuart et al. (2002) that the speech disruptions noted in non-stutterers during altered auditory feedback conditions are not true analogs of stuttering. In summary, in contrast to the participants in the stuttering group, who benefited from DAF and FAF in terms of lowering stuttering frequency, the non-stuttering controls showed no significant changes in speech fluency for those conditions.

The “normalization” of stuttered speech that occurs during choral speech, appears to be reflected at the neural level as well. Neuroimaging studies have found atypical brain activation patterns in people who stutter while they are speaking and stuttering (Fox et al., 1996, 2000, Ingham, 2001; Salmelin et al., 2000). However, when those participants spoke under choral conditions, their speech became fluent, and the brain activation patterns closely resembled those of a non-stuttering person. The central involuntary block, thought to be the source of stuttering, may be inhibited under choral speaking conditions, allowing speech to be produced more fluently (Kalinowski et al., 2000; Kalinowski & Saltuklaroglu, 2003; Saltuklaroglu, Kalinowski, & Guntupalli, 2004). If the stuttering block is inhibited by choral speech, resulting in a removal of the overt symptoms in the speech periphery, than other symptoms which normally result from the block should be inhibited as well. If this is the case, any effect that stuttering has over other motor systems, such as the hand, should also be normalized by speaking under choral conditions. These effects may be detected in the hand motor system, if an appropriate measure can be identified. Normalized jerk appears to be a valid measure of motor disfluency in hand movements, and appears to be sensitive to the effects of stuttering and other fluency-enhancing conditions.
Normalized Jerk

The second major finding of the current study relates to normalized jerk. To our knowledge, this study is the first to show a quantifiable effect of stuttering and various forms of altered auditory feedback on motor disfluencies outside the speech motor system. The measure of normalized jerk appears to be a stable and valid means of quantifying the motor disfluencies in the hand that and thus may be considered appropriate for measuring the impact of stuttering beyond the speech system. During stuttering, the effects of the central involuntary block spread outward to the speech periphery in the form of stuttering behaviors (Guntupalli et al., 2005). It appears that the effects of this block also spread outward to other motor systems, such as the hand, as suggested by the presence of ancillary behaviors (e.g. eye blinking, fist pounding, leg jerking) and the findings of the current study. Thus, the findings indicated that in the stuttering group, mean NJ measures in the solo reading task showed a 49% increase when compared to the silent (non-reading task) (i.e. 17.06 vs. 11.44) and other conditions. In the choral reading condition, in which stuttering was reduced to its lowest level in speech, the mean NJ measures were reduced the most (to 13.73). NJ measures for the DAF and FAF conditions were also reduced, but to a slightly lesser degree (ranging from 14.49 to 15.37). It appears that stuttering can exert an influence on hand movements as evidenced by the increase in NJ in an otherwise “fluid movement” task. By extension, choral speech and other feedback conditions, somehow lower the stuttering frequency (perhaps by inhibiting the central stuttering block), and appear to have the effect of decreasing the mean NJ in the manual task.
To provide a reference for the NJ measure, it is important to note that it is a unit-free measure which allows for comparison of movements that may vary in duration, displacement and orientation (Kitazawa et al., 1993; Teulings, 1996; van Gemmert et al., 1998). Thus, comparisons of various movement can be made for the purposes of quantifying motor disfluencies. First, the differences between mean NJ in the stuttering and the control group in the silent condition (11.44 and 8.67) were not significant and were consistent with the NJ levels measured during other smooth motor tasks in young adults (Contreras-Vidal et al., 1998; van Gemmert et al., 1998). In circle-drawing tasks similar to the current study, elderly (aged 53-78) and mild Parkinsonian participants displayed NJ values of 16.9 and 23.1 respectively (Teulings et al., 1997). The current study was able to demonstrate NJ levels in the hand movements of people who stutter which are comparable to NJ levels in the hand movements of populations such as mild Parkinsonianism, whose members possess permanent and pervasive motor disfluencies. This is important, because stuttering is an intermittent pathology. Our participants who produced only 13% of stuttered syllables in unassisted reading, demonstrated levels of NJ comparable to populations whose motor instabilities are constantly present, suggesting that the central stuttering block can have a relatively strong impact on other motor systems. Since in the stuttering group NJ levels are being detected in hand movements during speech tasks that are significantly higher than during the silent task, it would appear that stuttering behavior is associated not only with disruptions in the speech periphery, but disruptions in the fluency of the hand motor system as well.

By comparison, the normal participants showed significantly lower levels of NJ than the stuttering group, and these levels remained relatively unchanged across speaking
conditions. However, the slight decrease in NJ for the silent condition is probably due to
the very tight distribution of values in this population. One important comparison that
needs to be addressed is the comparison of NJ between stuttering and control participants
when the speaking task was removed. A significant difference may suggest that those
who stutter have inherent motor differences relative to normal individuals. However the
$p$-value of 0.17 is only approaching significance and the presence or absence of inherent
motor difficulties in those who stutter cannot be adequately determined from these data.

In the stuttering group, the addition of any speaking task increased the NJ values.
It is also important to note that previous studies examined the effect of increasing the
motor load by imposing a mental task, and found no increase in NJ for young adults (van
Gemmert, et al., 1998). Therefore the increases in normalized jerk seen in the stuttering
group is not likely to be due to the increase in motor load imposed by the reading task. In
the current study, when there is no speech task, there is no significant difference in NJ for
the stuttering group (as compared to normals). When a speech task is imposed, the NJ
increases. The elevated NJ levels are evident, even when participants speak under DAF
and FAF conditions in which the overt stuttering behaviors are low. Even choral speech,
which reduces stuttering to 1% of stuttered syllables, generated NJ measures that were
significantly greater than the silent conditions. A possible explanation for this finding is
the presence of sub-perceptual stuttering.

Sub-perceptual stuttering is posited to emanate from the central involuntary block,
and affect the speech motor system in subtle ways that do not manifest overtly as
stuttering behaviors (Guntupalli et al., 2005). It consists of changes in speech production
that may manifest at acoustic, kinematic levels and neuromuscular levels (Armson &
Kalinowski, 1994) but not be observable in overt speech behaviors. For example, Freeman and Ushijima (1978) detected laryngeal muscular discoordination just prior to initiation in otherwise fluent utterances. Participants in the current study, during the choral conditions, while benefiting from auditory input being provided, were still forced to initiate every utterance on their own. Since 90% of stuttered sounds occur on the initial syllable of a word (Johnson & Brown, 1935; Hahn, 1942b; Taylor, 1966a, Sheehan, 1974, & Weiner, 1984b, as cited in Bloodstein, 1995), initiation of an utterance would be a likely loci for sub-perceptual stuttering as well. If sub-perceptual stuttering occurred during initiation of utterances in the current study, then it may be detected by NJ, even though it did not result in an overt stuttering behavior. If NJ can help quantify the influence of sub-perceptual stuttering, then differences between the “perceptually-fluent” speech of stutterers and the speech of non-stutterers can be examined. This would open up many avenues of study which could shed light on the presence or absence of inherent motor differences between stutterers and non-stutterers.

When looking only at stuttering participants, the NJ levels of choral reading and DAF and FAF reading appear to be decreased relative to solo reading, but these differences only approach statistical significance. The reasons appear to be two-fold. First, a small sample size was used and it is suspected that the addition of more subjects will allow the differences to become statistically significant. Secondly, the overall severity of the tested population was relatively mild in the solo reading condition. A reading task is essential to the quantification, and control of variables, needed for this type of study, but often elicits speech from even moderate to severe stutterers that does not necessarily display high levels of stuttering behaviors. With milder levels of
stuttering in the solo reading condition, a smaller degree of reduction of stuttering frequency is observed in the choral condition, and smaller effect sizes are generated.

An examination of Figure 3 confirms the inhibitory power of speech-based auditory inputs over stuttering, with reductions ranging from 58% for DAF at 100 ms to 95% for choral speech. It appears that these same auditory conditions also decrease NJ during a circle-drawing task. In single-df comparisons of NJ in the stuttering group, the difference between NJ in solo reading and in choral reading approached significance. Choral reading was the most powerful inhibitor of stuttering, and in this condition, NJ was decreased the most, in that the difference between choral reading and all other forms of AAF was statistically significant. DAF was not significantly different from FAF, and DAF at 100ms was not significantly different from DAF at 200ms. In looking at the effects of condition on both speech and NJ, it seems likely that the inhibitory power of choral speech, responsible for the enhancement of fluency, is also responsible for the reduction of NJ seen in that condition. With more research, it may also be possible to detect statistically significant reductions in NJ that parallel the significant reduction in stuttering under altered feedback conditions. Findings such as these would support the theory that these inputs inhibit stuttering on a central level, because the effects of stuttering and fluency-enhancing conditions would be demonstrated on two separate, peripheral motor systems during the same task.

An examination of the graphical representations of NJ and stuttering frequency (see figures one and two) reveals a compelling similarity in the trends of these measures taken during speaking tasks. When stuttering frequency is high (solo reading condition), NJ is high. When speaking under choral speech, stuttering frequency is decreased, and
NJ is lowered. When speaking under conditions of altered feedback, there is a lesser degree of stuttering inhibition, and NJ appears to be lowered somewhat. The presence of stuttering and the level of NJ appear to be related. Thus, the relationship between overt stuttering and disruptions in a smooth motor manual task in clearly suggested.

A direct correlation between NJ and the proportion of stuttered syllables in the 5 second trials was not found. There are several possibilities that may account for this. First of all, the speech and the hand motor systems appear to be related to each other, but they remain separate motor systems. Also, the proportion of stuttered syllables is not an adequately sensitive measure to capture the severity of overt stuttering behaviors. Because it is a categorical measure, each syllable is judged to be stuttered or not stuttered. This tends to overestimate the severity of the milder symptoms displayed under DAF and FAF. For example, a very severe silent postural fixation just prior to a syllable and a mild, barely noticeable silent postural fixation, are both counted as a stuttered syllable, despite the fact that one indicates a more severe symptom of the stuttering central block. NJ, on the other hand, is a continuous measure, and is likely to be more sensitive to the severity of the disfluency being produced by the central stuttering block, because it can record measures along a continuum. Milder blocks are likely to be reflected as lower NJ, and harder blocks may produce higher levels of NJ. In the current study, there were several participants whose proportions of stuttered syllables was high, but the severity of those stuttering moments was much milder under DAF and FAF conditions, making a correlation with the NJ values impossible, because NJ may be reflective of the actual severity of the stuttering and as such will not correlated well with the “inflated” measure of the proportion of stuttered syllables. Another possible way to
explain the lack of correlation between NJ and the proportion of stuttered syllables is that NJ is sensitive enough to detect the effect of the stuttering block on a sub-perceptual level, in that the speech may appear fluent, but the hand motor system may be experiencing the effect of the central stuttering block in the form of motor disfluencies which can be detected by NJ.

The impact of auditory inputs on the stuttering frequency indicates that these externally presented speech signals somehow inhibit the central stuttering block and decrease the occurrence of overt stuttering symptoms. Because stuttering inhibition is thought to occur at the level of the brain, it is very difficult to directly test the mechanism. It appears that NJ is a measure sensitive enough to detect the effect of stuttering as well as the effect of altered auditory feedback, and as such is a valuable tool in this line of study. The hand and the speech periphery are different motor systems, but they both appear to be impacted by the central involuntary block during stuttering. Looking at NJ in hand movements, we may be able to demonstrate the relative impact of various forms of altered auditory feedback on the block. Larger sample size and participants with more severe forms of the pathology may help reveal relative differences between the impact of DAF and FAF on the stuttering block. Other effects known to reduce stuttering can be studied to see if they also reduce NJ, which would give us a clue as to how they are influencing the central involuntary block. For example, behavioral therapy techniques (e.g. prolongations, gentle onsets) can be tested alone or in combination with altered feedback, to see if they result in reduced NJ in a smooth drawing task. The effects of DAF and FAF have been used in self-contained devices which appear to be effective in providing stuttering inhibition (Kalinowski et al., 2005).
The next generation of self-contained devices could be tailored to the individual wearer to deliver new forms of altered auditory feedback, such as sustained vowels or an on-demand signal. The use of the measure of NJ may allow for the study of the relative inhibitory effects of these additional types of altered feedback, before they are added to the capacities of the devices. Finally, there is much controversy in the field of stuttering regarding the presence or lack of acoustic and kinematic differences in the perceptually fluent speech of people who stutter. If normalized jerk is indeed a sensitive measure of the resultant effects of the central stuttering block on the motor system of the hand, then it may prove to be an important tool in clarifying these issues. By helping to determine when a person who stutters in being effect by the stuttering block, NJ may be used to identify speech that is truly fluent, and allow for comparisons in the speech of people who stutter and people who do not.
LIST OF REFERENCES
REFERENCES


Vita

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