# What Hurried Hands Reveal About "Tangled Tongues"*: A Neuropsychological Approach to Understanding Stuttering

W.G. Webster

## Introduction

Stuttering is usually characterized in terms of its most obvious manifestations: a speech disorder involving the repetition and prolongation of sounds (Andrews et al, 1982; Wingate, 1964).Common concomitants of dysfluency include orofacial and laryngeal tension, anxiety about and avoidance of social situations, and an impending loss of speech control. These concomitants are usually viewed as secondary to the core speech dysfluency, although this is a matter of continuing debate (Perkins,1983, 1984). On the basis of recent research in our laboratory, we believe that stuttering may be secondary to a more general disorder of central nervous system (CNS) function related to motor and cognitive organization and planning.

The concept of a CNS basis for stuttering is certainly not new. In fact, one of the more influential contemporary theories of stuttering was proposed more than half a century ago by Orton (1928) and Travis (1931) and was highly neuropsychological. The theory attributed stuttering to "aberrant interhemispheric relations", specifically to a lack of normal hemispheric lateraliztion of speech mechanisms and to a consequent "mistiming of nerve impulses to the bilateral speech musculature" (Travis, 1978). The development during the past two decades of clinical and experimental neuropsychological techniques for assessing brain lateralization has made this general hypothesis the focus of considerable research. The literature, which now contains several comparisons of stutterers and fluent speakers using a diverse range of methods, has recently been reviewed and summarized elsewhere (Moore, 1984). The data bearing on the Orton and Travis hypothesis are conflicting and inconclusive but are consistent with the general idea that some stutterers have some form of aberration or peculiarity in interhemispheric relations that become apparent under certain conditions. Unfortunately, there is little in the literature about the nature of the peculiarity.

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Reprint requests to:
Dr. William G. Webster
Department of Psychology
Carleton University
Ottawa, Ont. K1S 5B6

We have recently undertaken a program of laboratory research designed to test several neuropsychological models of potential forms of aberrant interhemispheric relations in stutterers. Our emphasis has been on the underlying neural mechanisms of stuttering as inferred from behavioural performance. We have focussed on tasks that do not directly involve speech but that none the less have implications for understanding speech mechanisms.

## Sequential Finger Tapping Performance by Stutterers

Our initial study (Webster, 1985) was intended to test the Orton and Travis hypothesis through and indirect analuxix of right and left hand sequential finger-tapping by adult male stutterers. Finger tapping is typically reported to be better with the right than with the left hand (Kinsbourne and McMurray, 1975; Lomas and Kimura, 1976; Wolff et al, 1977), and this is interpreted as reflecting the specialized left hemisphere mechanisms for the control of movement sequences that involve position changes. What makes finger-tapping an interesting and relevant task is the evidence (Kimura, 1977, 1979, 1982; Kinsbourne and Hiscock, 1983; Ojemann, 1983) that the neural systems underlying such sequential movement control overlap those involved in speech and orofacial movements. Accordingly, anomalies in sequential finger-tapping in stutterers may suggest something about the nature of the "aberrant interhemispheric relations" hypothesized by Orton and Travis.

We used four telegraph keys mounted in a box and each wired to different channels of an event recorder. During each 15-second trial, the subject was to tap the keys in a specified sequence, where one was the index finger and four the little finger. These subjects were instructed to tap each sequence as rapidly but as accurately as possible. Testing of each sequence with each hand was done with both visual guidance and no visual guidance of the fingers, and the order of testing with different independent variables was appropriately counterbalanced across subjects.

The dependent variables for each 15 second trial in the study were the number of correct sequences, the number of key presses and the number of incorrect responses. Incorrect responses included extra key presses, key presses in incorrect order and omissions from the sequence of key depressions.

What was especially striking about this initial study was the similarity of results between the stutterers and the fluent speakers. Both groups had a similar number of correct sequences and key presses and both showed significantly better performance with the right hand than with the left. The two groups were equally influenced by visual guidance of the hand and had similar response rates for the sequences tested. In other words, group was not a significant effect, and there were no significant interactions involving group as a variable.

These results indicated that, first, stuttering does not reflect a general problem in the sequencing or timing of behaviour (Sheehan, 1970; Van Riper, 1971). Second, and relevant to the Orton and Travis Hypothesis, the data provided clear evidence that the neural mechanisms associated with sequential responding, and by implication with those underlying speech, are lateralized in stutterers in the same manner as in fluent speakers. Consistent with this conclusion and with the data of Records and associates (1977) we have found no evidence in other studies that the prevalence of right-handedness and the strength of hand preference in stutterers are any different from those in the general population (Webster and Poulos, in press).

There were three apparently minor aspects of the finger-tapping study that made us uneasy about accepting these conclusions. First, 2 of the 18 stutterers had been eliminated from the analysis because they were unable to perform the sequential finger-tapping tasks. This raised concerns about task sensitivity and about whether there were some subtle, undetected effects in the other subjects. Second, the stutterers made significantly more incorrect responses than the fluent speakers. Although the actual proportion of incorrect responses was very low in both groups (and so group differences did not emerge in the analysis of total correct sequences), this again raised concerns about task sensitivity. Third, the parallel between repetitive sequential finger-tapping and serially ordered aspects of speech appeared tenuous in light of the fact that the speech difficulty experienced by most stutterers is related more to the initiation of new utterances than to their repetition (the "adaptation effect") (Bloodstein), We therefore undertook a second study (Webster, 1986b) with these concerns in mind.

The first phase replicated the essential aspects of the first study to ensure that the same effects could be obtained with a new group of subjects.

The second phase compared the ability of the stutterers and fluent controls to reproduce rapidly and accurately unique sequences of finger movements rather than the same sequence of finger-tapping repeatedly.

In each trial of this sequence reproduction task a visual display panel of a new finger tap sequence was presented. At the sound of a tone the subject was required to tap the sequence on the telegraph keys as quickly and as accurately as possible for 5 seconds. Included were different combinations of four-element sequences (except those beginning with the little finger) without repeated elements. To introduce unpredictability, three- and five-element sequences, and four-element sequences with a repeated element were interspersed at random among the four-element sequences. However, only the four-element sequences were analysed. In addition to the same measures of response accuracy described earlier, the dependent variables included response initiation times (i.e., the time from the start tone to the first key press) and sequence execution times (i.e., the time to carry out the first complete sequence). Of particular interest were the initial sequences tapped.

There were two important sets of findings in this study. First, the stutterers had significantly longer response initiation times than the fluent speakers (Fig. 1, left). However, once a sequence was initiated, the sequence execution time was similar in both groups. (Fig. 1, middle).

Second, the stutterers had significantly fewer correct initial sequences than the fluent speakers (Fig. 1, right). In other words, considering just the first sequence of taps generated in each trial, the stutterers had a significantly higher probability of error occurring than the fluent speakers. They also had fewer overall correct sequences (Fig. 2, lefta) and made more errors (Fig. 2 middle).

These findings indicated that there is a sequencing problem associated with stuttering. However, the total number of key presses was not different from that for the fluent speakers (Fig. 2, right). In combination with the sequence execution times, this finding is consistent with the idea that there is no general motor slowing or coordination problem in stutterers. Rather, the data indicate a specific difficulty in stutterers to organize and initiate new patterns of nonspeech motor movements analogous to some of the difficulties with speech utterances. Once a sequence was initiated, however, it was carried out at a rate similar to that of fluent speakers.

These two studies have led us to three conclusions about neural mechanisms and stuttering.

First, there is clearly no general or gross impairment in motor skill or motor performance by stutterers, as shown by the similarity between the stutterers and the fluent speakers in repetitive sequential finger-tapping rates, total number of key presses, and the sequence execution times of the sequence reproduction task.

Second, the hand differences in the repetitive sequential finger-tapping task indicate that the neural systems mediating sequential movement, and by implication those mediating speech, are lateralized in stutterers in the left hemisphere just as they are in fluent speakers.

Third, the results of the sequence reproduction task show that the neural systems in stutterers, although lateralized as normal in the left hemisphere, are not as efficient as those in fluent speakers in organizing and initiating new sequences of movements, and presumably, speech movements.

This third conclusion is bolstered further by the significantly higher probability of incorrect key presses by the stutterers than by the fluent speakers in both the initial repetitive sequential finger-tapping study (Webster, 1985) and its replication (Webster,1986b). This finding suggested that these mechanisms may be unusually susceptible to interference from other on-going neural activities; hence, we began to explore potential mechanisms of interference.

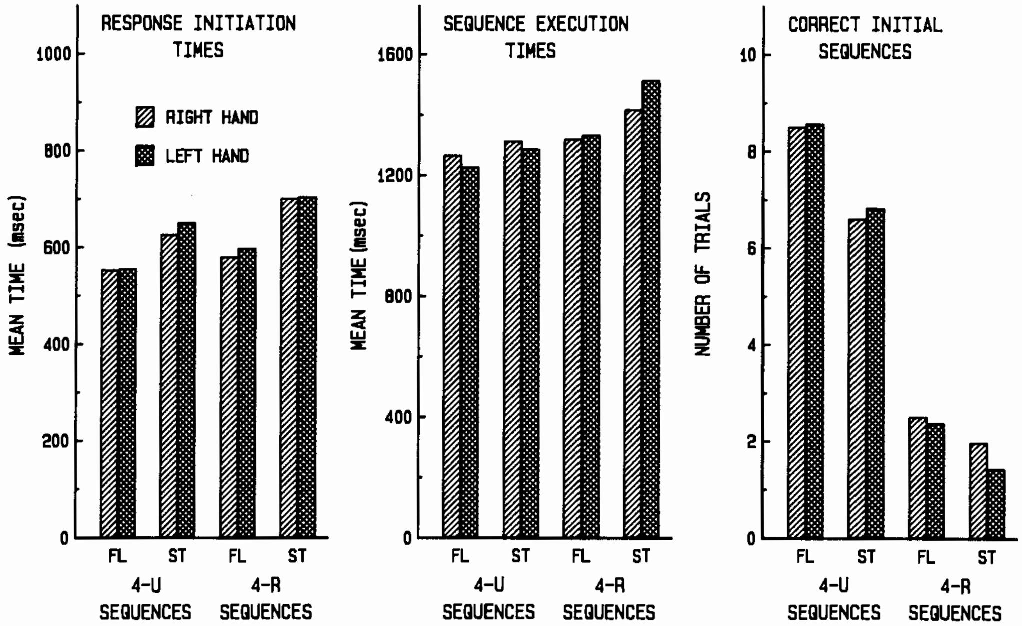


Fig. 1. Mean response initiation times (in msec) (left) and mean sequence execution times (in msec) (middle) for stutterers and fluent speakers correctly performing four-element sequences with (4-R) and without (4-U) a repeated element. Data are shown for each hand. Also shown is number of correct initial sequences (maximum of nine for 4-U sequences and three for 4-R sequences) (right).

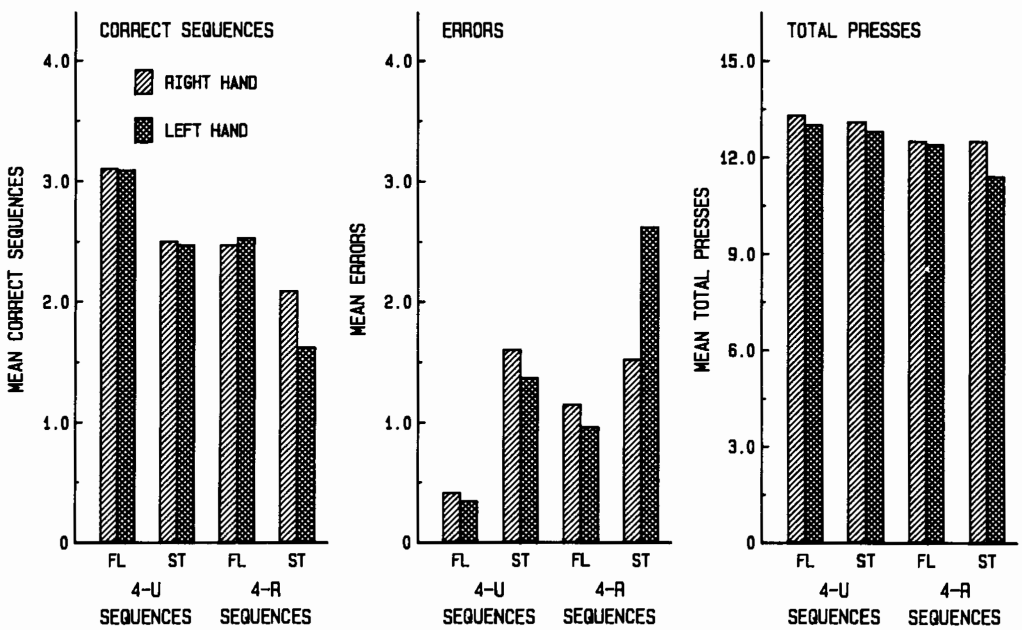


Fig. 2. Mean correct sequences (left), mean errors (middle), and mean total key presses (right) for stutterers and fluent speakers performing four-element sequences with (4-R) and without (4-U) a repeated element. Data are shown for each hand.

## *Mechanisms Underlying Neural Interference*

There is a small and provocative body of evidence to support the idea that stutterers strategically engage the right hemisphere when processing speech. The dichotic listening performance of stutterers is consistent with this idea (Moore, 1984), although clearer evidence is to be found in electrophysiologic activity recorded from the right and left hemispheres of stutterers. Not only do stutterers show anomalous right hemispheric electroencephalographic activation during verbal information processing (Moore and Haynes, 1980; Moore, 1986; Boberg et al, 1983), but also the pattern is reported to shift toward the more normal pattern of left hemisphere activation following successful therapy for stuttering (Boberg et al, 1983). These data do not indicate a reversed or bilateral representation of speech mechanisms in stutterers. They indicate only that stutterers engage the right hemisphere when processing speech; however, this is an ineffective strategy in that the right hemisphere does not contain the specialized neural systems required for such processing.

This concept of right hemisphere over activation, in combination with our earlier conclusions that neural mechanisms in stutterers are usually lateralized but unusually susceptible to interference, led us to the hypothesis that interhemispheric communication in stutterers may proceed in a relatively ungated or unregulated manner. The cerebral hemispheres are thought to be in a normal state of reciprocal inhibition, mediated by the corpus callosum, whereby activity in one hemisphere leads to a suppression of activity in the contralateral area (Kinsbourne, 1974; Moscovitch, 1977). Right hemisphere overactivation may reflect a dysfunction in these inhibitory mechanisms, an idea also suggested by Boberg and colleagues (1983). Unregulated collosal function may also permit the effects of this overactivation to "spill over" to the left hemisphere, thus interfering with the neural mechanisms of that hemisphere.

To explore this idea, we considered the fact that the left and right hemispheres have direct control over the contralateral hands, and developed two analogues of the children's game of rubbing the stomach with one hand while patting the head with the other. The degree of interference between these two activities should reflect the amount of communication between the hemispheres. Stutterers should have particular difficulty in doing two things with two hands at the same time. This is the converse of the situation in patients who have had the corpus callosum severed and who show a high degree of independence of bimanual movements (Preilowski, 19875; Zaidel and Sperry, 1977).

The first paradigm (Webster, 1986a) was built upon the repetitive sequential finger-tapping task described earlier, but now the subjects were required to carry out concurrently a second task with the other hand. One task required the subject to turn a vertically oriented knob back and forth in response to a brief tone that sounded every 2 seconds. The other required the subject to press and release a thumb button in response to the tone. Accuracy of performance on these concurrent tasks was quantified by determining the variance of the inter-response intervals.

Consistent with the hypothesis, right hand sequential finger-tapping was more interfered with by left hand concurrent task performance in the stutterers than in the fluent speakers. In other words, in a comparison with baseline performance involving only repetitive sequential finger-tapping, the stutterers showed a greater decrease in the number of correct sequences tapped when doing the concurrent task than did the fluent controls. Of critical importance for the interpretation of this effect is performance on the concurrent task. The stutterers may simply have attended more to the concurrent task at the expense of the finger-tapping task. Fortunately the interpretation is simplified by the fact that results of concurrent task performance were very similar in the two groups.

We have repeated this study using the sequence reproduction task with the right hand and the concurrent knob-turning task with the left hand (Webster, in press, b). Again the stutterers experienced more difficulty than the fluent controls in carrying out the two tasks together. They had poorer key-tap performance (correct initial sequences and response initiation times) as well as poorer concurrent knob-turning performance (initiation times and accuracy of response pacing).

While the data from these two studies are consistent with the hypothesis of unregulated callosal function, they are far from convincing. It is possible that stutterers are simply less adept than fluent speakers at doing two things at the same time (a possibility that is still interesting), regardless of which hemisphere is mediating the two tasks and of presumed callosal involvement. We are undertaking appropriate follow-up studies with tasks mediated by the same hemisphere (e.g., right hand sequential finger-tapping combined with right foot tone-responding). If the interference effects are related to callosal function, the groups should show similar interference during "intrahemispheric tasks", whereas during "interhemispheric tasks" the stutterers should show relatively greater interference than the fluent controls. On the other hand, if the effects we have found are related to attention, stutterers should show a similar degree of interference in both situations. The only evidence we have that the effects are not simply attentional comes from a control condition in the original interference study (Webster, 1986a), in which subjects performed sequential finger-tapping with the left hand and the concurrent task with the right. This is a neuropsychologically ambiguous condition, in that both hemispheres are directly involved in sequential finger-tapping. Under these conditions the two groups showed equivalent interference.

The second analogue we developed to test the callosal gating deficit hypothesis (Webster, in press, a) considered the fact that there is a natural tendency for the movements of one hand to be mirror-reversed with respect to those of the other (Corballis and Beale, 1982; Fog and Fog, 1963). In other words, if you turn one wrist clockwise there is a tendency for the other wrist to turn counterclockwise. Following the same logic underlying the initial interference study (Webster, 1986a), the callosal gating deficit hypothesis would predict a greater tendency among stutterers than among fluent speakers to have mirror image movements by the two hands. Indeed, there is evidence in the literature that this is the case (Fitzgerald et al, 1984), so we built upon that work using a task designed to be highly left-hemisphere dependent.

During each of 24 trials the subjects were read four single syllable words. As soon as they had repeated the words (speech blockages did not appear to be a problem for the stutterers), the subjects had to write the initial letter of each word as quickly as possible using both hands simultaneously. The writing surfaces were vertically oriented (fashioned after the"critical angle board" developed by Van Riper [1934] as a means of assessing handedness in his early research), and testing was carried out with the hands out of view behind a cloth screen.

Using five-point rating scales, each of the 96 letters written by the left and right hands was scored blindly for evidence of mirror-reversals and quality-of-letter formation independent of orientation. As well, the writing time for each trial was analysed (i.e., the time from when the last word was repeated to when the last letter was completed).

We included not only right-handed men, as we had in our earlier studies, but also left-handers and women because of the evidence that sex and handedness variables are related to callosal morphology (Witelson, 1985; de Lacoste-Utamsing and Holloway, 1983; de Lacoste-Utamsing et al, 1986). Consequently, there were eight groups formed by combining the independent variables of fluency, sex, and handedness. All groups but one had eight subjects. Unfortunately, only one left-handed female stutterer could be found for testing.

Consistent with the hypothesis, the stutterers showed significantly more mirror-reversed letters with the non-dominant hand than did the fluent speakers. The effects were the same for the right- and left-handers, and there were no differences between the men and the women. Very few of the subjects showed mirror reversals with the dominant hand, but all five who did so were male stutterers. The letters written by the stutterers (males and females, right- and left-handers) were also of significantly poorer quality than those written by the fluent speakers; this was the case with both the dominant and the non-dominant hands.

Although the stutterers made more mirror reversals and formed letters more poorly than the fluent speakers, this was not due to more rapid writing. Indeed, the male stutterers in particular were significantly slower to complete the trials than were the fluent controls. Not only does this indicate that a differential speed-accuracy tradeoff cannot account for the poorer letter writing of the stutters, but also it highlights the difficulties of the stutterers in bimanual coordination. Unfortunately we do not have any data on unimanual writing performance, and so it is still unclear whether these mirror reversal, letter quality and response time effects are due to a competing task situation involving the two hemispheres. Preliminary results of a study now being completed in our lab (Pole, in preparation) indicate that children who stutter have more mirror reversals and poorer quality of number formation than age-matched fluent children in unimanual writing performance. Clearly, many controlled studies with adults will be necessary to sort out these issues.

## *A Possible Locus for Interference*

Assuming that the interference hypothesis has validity and that the interference is mediated transcallosally, at least in part, one must ask where the hypothesized interference with sequencing and speech occurs. The data from the bimanual handwriting study (Webster, in press, a) point to the supplementary motor area (SMA) as being of special significance in this regard.

The SMA is located on the mesial surface of the hemisphere just anterior to the foot region of the primary motor contex and dorsal to the cingulate gyrus. There is an increasing amount of research, recently reviewed by Goldberg (1985), that indicates the importance of the SMA in the initiation and control of both speech and nonspeech sequential motor activities. For example, damage in this area, particularly if it involves the left hemisphere, results clinically in several speech difficulties including the initiation of propositional speech and the suppression of nonpropositional "automatic" speech (Jonas, 1981). It also causes bimanual coordination difficulties in both human and nonhuman primates (Brinkman, 1981). These include mirror-symmetric response by the two hands, similar to that we observed in the bimanual handwriting performance of stutterers (Webster, in press, a). This effect is at least partially reversed in nonhuman primates by subsequent section of the corpus callosum (Brinkman, 1982). Especially informative are the data from regional cerebral blood flow studies of SMA in humans (Larson et al, 1978; Roland, 1985) which have pointed to the significance of the SMA for both the mediation of propositional speech and the initiation of sequences of manual movements.

These observations parallel the difficulties of stutterers in speech initiation (Bloodstein, 1981), mirror-symmetric movements (Webster, in press, a), and organizing and initiating new nonspeech response sequences (Webster, 1986b), and lead directly to the hypothesis that the underlying neurological basis of stuttering is to be found, at least in part, in compromised SMA integrity. Such a hypothesis is fully compatible with ideas of "aberrant interhemispheric relations" (Travis, 1978) and with the earlier hypothesis that in stutterers the corpus callosum functions in a relatively ungated manner. There are very rich interhemispheric callosal connections between the SMAs of the right and left hemispheres (Goldberg, 1985), and usually the two SMAs operate in a highly coordinated manner. This is evidenced in the bilateral SMA activation reported in regional cerebral blood flow studies (Larsen et al, 1978), even with unilateral movements and contralateral activation of the primary motor cortex (Roland et al, 1982). It is important to bear in mind that the fibres comprising the corpus callosum originate and terminate in the cerebral cortex. A hypothesis of a callosal gating deficit is really one of a specific kind of cortical dysfunction. From this perspective, then, inefficient SMA processing and ungated interhemispheric communication could well be one and the same or have the same underlying basis.

We have now moved into the realm of speculation, as there is not evidence at this time that bears directly on the hypothesis. One implication of the SMA hypothesis, however, and indeed it is an implication of all of our research findings and hypotheses, is that speech dysfluency is only one of a wide range of motor and cognitive manifestations of stuttering. Although other effects may be subtle and clinically insignificant, they become evident as increasing demands (e.g., time pressure or stress) are placed on the system. We have started to explore some potential nonspeech cognitive concomitants by observing the performance of stutterers on a rapid letter transcription task (Webster, in press, c), in which the subject transcribes letters to paper that are being read to them very rapidly. We have found that stutterers do poorly on this task, even with short lists (i.e., 4 or 5 letters) that do not exceed the normal memory capacity. We are presently analysing the effects further with respect to memory demands, speeded response demands and demands with respect to organizing output while monitoring input (a dual-task situation of a cognitive nature). Following from the SMA hypothesis, we expect to find that stutterers will have difficulties with the aspects of the task that involve functions mediated by the SMA or the callosum.

## Subgroups

Many clinicians who work with stutterers are struck by the variation in presenting symptoms (e.g., interiorized v. overt stuttering, stuttering v. cluttering) and in short- and long-term responsiveness to treatment (Boberg, 1981). Riley and Riley (1980) have identified a basis for subgrouping children who stutter, although efforts to do so with adults have not been encouraging (Preus, 1981).

In our research, we have used unselected (except with respect to known history of neurological disorders) and self-defined stutterers recruited from Carleton University and the broader Ottawa community. They have therefore varied in age, education, treatment history and (in largely unknown ways) stuttering characteristics and apparent severity of stuttering. We have found evidence suggestive of subgroups; for example, in the initial repetitive sequential finger-tapping study (Webster, 1985) there was a small proportion of stutterers (10% to 15%) who were unable to finger tap with any degree of proficiency, and to the extent that they could, their performance was better with the left hand. In combination with dysfluency, this pattern is suggestive of a left hemisphere dysfunction not found in most stutterers. In the bimanual handwriting study (Webster, in press, a), we found an anomalous subgroup comprised of 5 of 25 stutterers who showed instances of mirror-reversed letters with the dominant hand.

Generally, in all our studies we found the performance of stutterers to be more variable than that of fluent controls. The significant group effects were not due to all stutterers being impaired. Indeed, many stutterers had scores that were well within the distribution of fluent speakers. This was, for example,with 56% of the stutterers in the bimanual handwriting study (Webster, in press, a) for non-dominant-hand mirror-reversal scores.

### Several issues become apparent

First, would the stutterers who had extreme scores in one of our studies also have extreme scores in other studies? In other words, does someone with poor sequential finger-tapping skill also show a high frequency of mirror-reversed movements in bimanual writing or a high level of interference in a concurrent task situation? Because different participants were used in different studies, we do not know the answer to this question, but to the extent that the tests assess related underlying neurological processes and that there are subgroups differing in those processes, we would, of course, expect such clustering.

Second, if stutterers can be subgrouped on the basis of motor and cognitive performance, are there meaningful differences between the subgroups for speech and speech-related variables? These might include dysfluency characteristics and severity, family history of stuttering, time of onset of stuttering, evidence of head injury or related trauma, incidence of covert versus overt stuttering, psychological aspects of stuttering, such as expectancy and avoidance, and so forth. The related and clinically more significant issue is how the supposed subgroups would differ in response to various kinds of contemporary stuttering treatment.

A third issue concerns stutterers whose motor and cognitive performance scores fall within the normal range. Does their performance disintegrate more readily than that of fluent speakers as time and information processing demands are made increasingly complex or intense beyond levels used in our current tasks, or is their performance in fact indistinguishable from that of fluent speakers? If the latter, what neural mechanisms might underlie their dysfluency?

These are three specific issues that we wish to address in our research in the near future. What we stress at this time, however, is that the group effects we have reported do not invariably or necessarily reflect the performance of all stutterers.

## A Concluding Comment

We believe that some progress has been made in identifying neural mechanisms underlying stuttering. Although much research remains to be done, especially with different methods to ensure converging evidence, our working hypothesis at this time is that the basic mechanism relates to a callosal gating deficit that originates in, and mediates neural inference in, the SMA. This hypothesized deficit is seen to underlie a general cognitive difficulty. It is premature to speculate on the possible implications for treatment of our research or of the conceptualization of stuttering as being comprised of a CNS dysfunction related to motor and cognitive organiztion and planning. Similarly, it is too soon to speculate on whether or how different aspects of successful stuttering therapy affect cognitive and motor organization and planning strategies. Once some of the issues related to potential subgroups are addressed, the treatment implications should become somewhat clearer.

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