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Timing in finger tapping and speech: A comparison between stutterers and fluent speakers *

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Abstract

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Stutterers, even in their fluent utterances, seem to be less able than nonstutterers to time speech motor activity precisely. The question addressed in this study is whether this timing inability is caused by a deficient central timing mechanism or whether it is caused by a more variable motor output process. To this end, twelve adult stutterers and twelve control subjects were asked to perform several variants of a rhythmic keytapping task and a speaking task in which they were asked to utter a vowel or a short word at regular intervals.

The results were remarkably similar for both groups. This was true for conditions requiring finger movements, speech movements, or coordination of two simultaneous activities. Only on one measure – the ability to synchronize speech and tapping with a rhythmic tone – did the stutterers show larger variability than the nonstutterers. In contrast to the rhythmic performance, the simultaneous measurements of lip EMGs showed strong group differences. The order of upper lip and lower lip peak EMGs was different in stutterers and in nonstutterers, and the length of the time interval between these EMG peaks was also more variable in stutterers than in nonstutterers. In addition, the duration of lip EMG from peak to acoustic onset was longer in stutterers. It is argued that stutterers do not have a large general timing deficit. Rather, they have coordination disabilities which result in the EMG irregularities.

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One of the motor activities that places a particularly great demand on the sequencing and timing of movements is speech. It is not only the high output rate of speech – five syllables per second or fifteen speech sounds per second (Starkweather 1987; Levelt 1989) – that is demanding, but also the requirement for the optimal coordination of movements within and across three different systems – respiration, phonation and articulation – which makes it a difficult task to perform. In view of these considerations it is not surprising that some people show a deficit in speech control, perhaps the best known example being stuttering.

Since Zimmermann's (1980) seminal paper entitled 'Stuttering: A disorder of movement' many studies have shown differences between stutterers and nonstutterers in speech motor control. For example, stutterers, compared to nonstutterers, perform alternating movements (so-called diadochokinetic movements) at a slower rate, have longer acoustic and physiological reaction times, a slower and more variable rate of speaking, increased speech muscle activity, and different speech movement patterns even in perceptually fluent utterances (see Peters and Hulstijn (1987) for a collection of papers; and Starkweather (1987) for a review). Recently, Peters et al. (1989) found that the onset of muscle activity related to liprounding and the onset of muscle activity in the laryngeal area – onsets which in normal speakers occur closely together in time – occur at a much larger and more variable interval in stutterers. More importantly, the inter-articulator timing, i.e. the intervals between upper lip, lower lip, and jaw movements or between tongue and jaw movements, were found to be more variable or atypically sequenced in stutterers (Caruso et al. 1988; Alfonso 1991; Hulstijn et al. 1991). These findings suggest that stutterers have a deficit in the coordination of speech movements.

According to Summers and Burns (1990), in a review of the timing of fast motor actions, problems in coordination may be the result of an inability to time movements precisely. It has been suggested that incoordination may reflect deficiences in some central timing mechanism or clock. Research by Keele and Ivry (1987) and Ivry and Keele (1989) with normal subjects, with patients having lesions in different parts of the motor pathway (e.g. Parkinson's disease patients and cerebellar patients), and with clumsy children (Williams et al. 1990) has provided evidence that deficits in a central clock or timing module may in fact exist.

The hypothesis tested in the present study is that stuttering also reflects a deficit of the central time keeping mechanism. This hypothesis is tested against its alternative, which ascribes observed timing irregularities to an imperfect or more variable output process. By using a rhythmic tapping task, and by applying the two-process model developed by Wing and Kristofferson (1973), the variability of the central clock as well as the variability of the motor output process can be estimated separately. It is therefore possible to determine whether stutterers can be characterized more adequately either by a less precise central clock or by a less precise (i.e. more variable) motor output. If the second alternative is supported, then the question arises whether this holds only for speech output or for all motor activity. To address the latter question, we compare rhythmic tasks involving the production of simple speech sounds with rhythmic finger tapping tasks.

In addition to these hypotheses about timing, three questions about coordination will be asked. The first is whether the previously reported difference between stutterers and nonstutterers in the time relation between upper lip and lower lip muscle activity can be replicated. The second issue is whether stutterers are less precise in coordinating speech and other motoric activity, such as pressing a key with the dominant hand. The third question asks whether stutterers are less accurate in the coordination of nonspeech activities, like simultaneous keypressing with the two hands.

Method

Subjects and design

Twelve adult male stutterers and twelve control subjects of approximately the same age and educational level participated in the experiment. Subjects were classified as stutterers by two certified speech pathologists. One subject in each group was left-handed.

Task

There were six variations of the rhythmic task. Three conditions involved repetitive tapping with one or both index fingers (called tapping tasks) and three conditions involved repetitive production of a voiced sound (either [i] or [pip]): the latter conditions were called speaking tasks). Each trial of each condition started with a series of short (50 ms), clearly audible (1000 Hz) tones, presented with a stimulus onset asynchrony of 400 ms. As soon as the subjects felt ready, they tried to synchronize their response with the tones. After 13 synchronization responses the tones stopped and the subjects continued responding until an additional 31 (tapping) or 21 (speaking) intervals were recorded. The end of a trial was signalled by a long tone, after which feedback was given about the means and standard deviations of the twelve synchronization intervals as well as the final 20 or 30 continuation intervals. Subjects were instructed to tap or speak at a constant rate and to produce a mean interval as close as possible to the desired 400 ms. The order of conditions was randomized across subjects within a group.

Conditions

In the three tapping conditions the subjects had to tap with the index finger of one hand – the dominant hand ('domhand') and the nondominant hand ('nondomhand') – and with the index fingers of both hands simultaneously ('both-hands'). The latter condition was included to measure the subjects' ability to coordinate two activities. Tapping with the nondominant hand was added as an extra control. Subjects performed ten trials in each task. The last 10 synchronization intervals and the last 30 continuation intervals were analyzed.

The three speaking conditions had only 21 continuation (20 for analysis) intervals, since pilot work had shown that 21 plus 12 synchronization intervals could be produced in one breath. To compensate for the shorter trials the number of trials was increased to 14 in the speaking conditions. The simplest condition required the subjects to utter repeatedly the vowel [i]. The second condition, the repetitive production of the syllable [pip] was included because it was originally thought to be a more complex task than simply saying [i], and to allow for the recording of lip muscle activity in lip closing. The third condition required the coordination of speech production with manual activity. In this condition the subjects had to synchronize the beginning of the syllable with pressing a key with the index finger of the dominant hand ('[pip] + hand'). In the two tasks requiring simultaneous responding ('both-hands' and '[pip] + hand') the subjects were specifically instructed to produce both responses synchronously, but they were given feedback about one response only (the dominant hand in the 'both-hands' condition, and the [pip] production in the '[pip] + hand' condition).

Procedure

Before the start of the experiment all six conditions were practised until at least one error-free trial was produced. An error was defined as the production of an interval shorter than 200 ms or longer than 600 ms. Conditions were given in blocks of five (tapping) or seven (speaking) trials. Tapping and speaking were alternated. Each of the twelve subjects in a group was given a different order of conditions. After a pause of a few minutes the six conditions were repeated in the reverse order. The entire experiment took about one hour.

Apparatus

Subjects' tapping responses were recorded by means of special keys that needed a force of about 120 g and a displacement of 2 mm to be depressed. The speech responses were recorded using a condenser microphone (AKG, type 451 E) connected to a laboratory-built high sensitivity voice key, which was connected to an IBM PS2/30 computer, equipped with an interface that allowed the measurement of intervals with a precision of 0.1 ms.

Electromyographic (EMG) activity of the Orbicularis Oris Inferior and the Orbicularis Oris Superior was recorded by means of silverball electrodes (San-ei Sokki, Inc.) and Honeywell amplifiers and integrators (see Peters et al. (1989) for more detail). The output of the EMG amplifiers was rectified and integrated with a time constant of 40 ms. The amplified, as well as the integrated, EMG was recorded on tape and written on polygraph paper (Siemens, Mingograph) set at a paper speed of 50 mm/s.

Results

Mean intervals

The mean continuation intervals for each condition are presented in table 1. In the 'both-hands' condition the data were derived from

Table 1
Performance in the tapping and speaking conditions of stutterers (S) and nonstutterers (N). Means and *SD*'s are given in ms.

Variable	Group	Condition					
		Tapping			Speaking		
		Non-dom-hand	Dom-hand	Both hands	[i]	[pip]	Dom hand + [pip]
Mean	S	390.4	391.5	390.8	399.4	391.2	393.1
	N	394.0	394.5	391.4	400.2	393.0	393.6
SD-total	S	19.1	18.2	17.5	24.3	19.1	20.8
	N	18.7	18.3 [c]	15.5	23.7 [c]	19.4 [c]	21.8
SD-clock	S	13.6	12.2	9.3 [a]	11.3	8.8	10.6
	N	10.4	10.8 [c]	5.5	7.9	9.8	9.4
SD-motor	S	7.5	7.9	9.1	13.5	10.7	11.3
	N	9.9	8.8	9.5	14.9 [c]	10.4 [b]	12.7
$r < 0.50\%$	S	9.2	9.2	35.0	25.6	10.7	25.0
	N	11.7	11.7	50.0	21.4	22.6	32.7
$r > 0.00\%$	S	18.3	15.8	10.8	7.1	7.1	3.0
	N	5.8	8.3	5.8	8.3	4.2	7.1
SD-sync	S	19.7	22.1	21.3	24.2	21.8	25.8 [a]
	N	18.0	19.5	17.7	20.3	16.9	18.2

[a] Difference between group S and group N significant ($p < 0.05$).
[b] Difference between horizontally adjacent conditions significant at $p < 0.05$; [c] $p < 0.01$.

the intervals produced with the dominant hand. In the '[pip] + hand' condition only the '[pip]' or speech interval data are presented. In all six conditions the behavior of the two groups was very similar. For each condition, *t*-tests on the mean intervals showed no significant group differences. During the synchronization phase the mean intervals were very close to the required 400 ms, ranging from 402 ms to 397 ms across subjects. However, in the continuation phase the means exhibited drift. To assess the drift, the 20 or 30 intervals per trial were averaged over successive groups of 10 intervals. ANOVA's performed on these 10-interval averages showed a slight (−1.4 ms) but nonsignificant drift ($F(2, 44) = 2.86$, $p < 0.10$) in the three tapping conditions, and a somewhat larger (−2.3 ms), significant ($F(1, 22) = 17.13$, $p < 0.001$) drift in the three speaking conditions.

Variability

The two-process model developed by Wing and Kristofferson (1973) assumes that the variability in the production of equal intervals is composed of two independent processes. The first process is assumed to be related to a central clock that emits pulses at a more or less regular interval. These pulses then trigger the associated motor output, which leads to a recordable response after a certain delay. Both the central clock and the motor delay are assumed to have their own independent variability. According to this model, the variance of the motor delay equals the covariance of adjacent intervals (the lag-1 autocovariance). The total variance is viewed as the sum of the clock variance, which is unknown, and twice the motor delay variance, which can be estimated from the lag-1 autocovariance. If the mean interval gradually drifts away from the original value, then the variability will be overestimated. Since drift was found to be small but non-negligible, an attempt was made to remove it by calculating the linear regression line over the 20 or 30 continuation intervals per trial and using the residual variance (see Wing et al., 1989). The total variances (*SD*-total), as well as the clock variances (*SD*-clock) and the motor delay variances (*SD*-motor) obtained in this way are presented in table 1, expressed as standard deviations. Wing and Kristofferson's model predicts that the correlations between adjacent intervals should fall between $r = 0.00$ and $r = -0.50$. On a number of trials the correlations fell outside this range. Table 1 presents the percentages of too high and too low correlations. Note that these violations of the model amounted to more than half the trials in the 'both-hands' condition of the nonstutterers. These aberrant correlations made the estimates of clock and motor delay variability less reliable. Since clock or motor delay variances cannot be negative, they were set at zero on trials in which the lag-1 autocorrelation was outside its theoretical limits.

Inspection of table 1 reveals that the *SD*s of the stutterers came very close to the *SD*s of the nonstutterers. This held for *SD*-total, *SD*-clock and *SD*-motor. With only one exception, *t*-tests on the group differences in each of the six conditions were nonsignificant. The exception was the 'both-hands' condition, in which *SD*-clock showed a significant difference between stutterers and nonstutterers ($t = 2.28$, $df = 22$, $p < 0.05$). However, this was also the condition in which the estimates of clock and motor delays were least reliable, so the difference must be accepted with caution.

In contrast to the group differences, most of the differences between conditions were significant. Since the six conditions were quite diverse, they were tested in a pairwise fashion: 'nondomhand' vs. 'domhand', 'domhand' vs. 'both-hands', [i] vs. [pip], and [pip] vs. '[pip] + hand'. Tapping with the nondominant hand was about as regular as tapping with the dominant hand. However, tapping with two hands differed from single-hand tapping. Unexpectedly, the total variability of the dominant hand in the both-hands condition was smaller (by 2.4 ms) than in the comparable single-hand condition ($F(1, 22) = 8.38$, $p < 0.01$). One might guess that this difference could be attributed to the motor delay variability, but the difference in *SD*-motor was not significant, while *SD*-clock did differ ($F(1, 22) = 14.80$, $p < 0.01$). In contrast, the effect of an extra response in the [pip] + hand condition increased the variability as expected (by about 2.1 ms for *SD*-total, $F(1, 22) = 8.64$, $p < 0.01$). Only *SD*-motor reflected this increase ($F(1, 22) = 5.77$, $p < 0.05$). Another unexpected outcome was the higher variability in the [i] condition compared to the [pip] condition (4.7 ms for *SD*-total, $F(1, 22) = 13.77$, $p < 0.01$; *SD*-clock: ns, *SD*-motor: $F(1, 22) = 10.72$, $p < 0.01$).

Coordination

The additional hypotheses concerned the ability to coordinate two responses. Means and standard deviations were calculated, per trial, for the time intervals between the two hands and between the [pip] reaction and the key press of the dominant hand. The averages of these means and standard deviations are given in table 2. The dominant hand led the nondominant hand by an average of 4 to 5 ms in the both-hands condition. In the [pip] + hand condition the mean difference between the verbal and manual response is about 50 ms. This is about the average duration of the [p] sound. Subjects probably tried to synchronize the [p] with the key press, but since the [p] has a very low and quite variable acoustic energy, the trigger level of the voice key was set at such a height that the [p] sound was always skipped in favor of the [i]. Both groups showed almost equal means and averaged variability (*SD*). None of the four *t*-tests produced a significant result.

Table 2
Means and averaged variability (*SD*) – in ms – of the time intervals between synchronized responses, between upper lip and lower lip EMG, and between upper lip and acoustic onset of stutterers (S) and nonstutterers (N).

Condition	Group	Mean	*SD*
Right–left hand	S	−4.2	13.3
	N	−5.4	12.7
[pip]–right hand	S	51.9	23.5
	N	48.1	27.8
Upper lip–lower lip EMG	S	−32.4 [a]	41.1 [b]
	N	6.9	16.1
Upper lip–acoustic onset	S	165.3 [a]	19.6
	N	131.8	22.1

[a] Difference between group S and group N significant at $p < 0.05$; [b] $p < 0.01$.

Synchronization

An extra test for the hypothesis that stutterers are less talented in response coordination is to measure how well they perform in synchronizing their responses with an external stimulus. This was done in the synchronization phase of each trial in all six conditions. The averages of the standard deviations of the tone-response intervals during synchronization (*SD*-sync) are presented in table 1. Stutterers had a larger standard deviation, but this difference was significant only in the most difficult condition, the condition in which speech and hand movements had to be synchronized with the tones ($t = 2.32$, $df = 22$, $p < 0.05$).

EMG

The EMG activity of the upper and lower lip was assessed from the paper recordings. The integrated EMG activity showed one clear peak before each single [pip]-speech sound. As EMG onset was more gradual, the peaks were used for analysis. The interval between upper and lower lip peak EMG was determined for the second [pip] utterance of the synchronization phase and the first [pip]-utterance in the continuation phase. The data for synchronization and continuation were quite similar; in table 2 the average values are given. Both the means ($t = 2.23$, $df = 22$, $p < 0.05$) and the *SD*'s ($t = 3.24$, $df = 22$,

$p < 0.01$) differed significantly between the groups. Stutterers seemed to respond with their lower lip first (10 out 12 subjects) while this was not the case for nonstutterers (5 out 12 subjects).

In addition, the time interval between peak EMG and speech onset was measured from the paper recordings. The average values are given in table 2. In stutterers this interval was larger than in nonstutterers ($t = 2.22$, $df = 22$, $p < 0.05$), but it had the same variability.

Discussion

The results can be summarized by noting that stutterers did not differ from nonstutterers in their performance in the rhythmic tasks. Also, their results in synchronizing the movements of both hands, and in the coordination of speech and tapping, were as good as that of nonstutterers. Only in one condition, where both speech and tapping had to be synchronized with the tones, did stutterers perform more poorly than nonstutterers. In contrast to these results, the groups differed in most of the EMG measures. Stutterers showed a different order of upper lip and lower lip muscle activity, as well as a more variable interval between lip EMG's. Also, the period between peak EMG and speech onset was longer in stutterers.

The present study followed the line of research developed by Keele and Ivry (1987; Ivry and Keele 1989) in using a simple repetitive tapping task. The lack of group differences in the rhythmic tasks of the present experiment may be due to the fact that these tasks may have been too simple to detect a more subtle timing disability than the disability shown by the patient groups studied by Keele and Ivry. The only condition in which stutterers showed a larger variability was probably the most difficult one. In a recent study by Webster (1990) stutterers and controls did not differ in simple one-hand finger tapping, but group differences were obtained in bimanual 2 : 1 tapping, in which the right hand tapped twice as frequently as the left hand. Unfortunately, Webster (1990) did not measure individual time intervals but only the overall tapping rate, so no assessment of the timing variability of stutterers was obtained. Nevertheless these findings suggest that future tests of the hypothesis that stutterers are deficient in the precise timing of their movements should use more difficult tasks. A range of intervals should be tested, not just a single interval, like the 400 ms used here. It would also be interesting to study the timing ability of stutterers by using more complex rhythms.

The EMG findings of the present experiment agree with the EMG data reported in earlier studies (for references, see Introduction). First, stutterers' longer preacoustic EMG duration suggests that they need more time, or that they use a strategy to take more time, for the closing and release of the lips in [p] production. This explanation implies that stutterers will run into problems if they have to produce much shorter intervals, e.g. 200 ms, or if they have to produce the [pip] sounds in a legato rather than staccato fashion, with the interruption of the [i] by the [p] as short as possible. The second finding – the different order of upper lip and lower lip EMG in stutterers – may be explained by an inability to coordinate separate movements. This explanation is in line with the third EMG result of a larger variability of the interval between upper and lower lip EMG. However, the explanation conflicts with the finding – in the same ([pip]) condition – that the onset of the acoustic output of stutterers was produced with equal interval variability. Probably, EMG activity has greater timing variability than does acoustic onset. This agrees with data reported by Gracco (1988) on normal speakers, who found the same sequence of kinematic events in lip closing for the [p] in all normal subjects, but different sequences of the onsets of the muscles involved.

It is not clear whether the greater variability shown by stutterers in the EMG time measures reflects an inherent timing disability, which causes the disorder, or whether it is the result of a different way of making articulatory movements. For instance, during the experiment it was sometimes observed that stutterers made larger lower lip and jaw movements than did controls, possibly as a strategy to improve the production of equal intervals. This could have induced the 'abnormal' sequence of reacting with the lower lip first. Clearly, research that combines the measurements of EMG with movement kinematics and with speech is needed to evaluate this hypothesis more fully.

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