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From Planning to Articulation in Speech Production: What Differentiates a Person Who Stutters From a Person Who Does Not Stutter?

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The main purpose of the present study was to differentiate between people who stutter and control speakers regarding their ability to assemble motor plans and to prepare (and execute) muscle commands. Adult males who stutter, matched for age, gender, and educational level with a group of control speakers, were tested on naming words and symbols. In addition, their ability to encode and retrieve memory representations of combinations of a symbol and a word, was tested in a recognition task, using manual reaction times and sensitivity scores, as defined in signal detection theory, as performance measures. Group differences in muscle command preparation were assessed from electromyographic recordings of upper lip and lower lip. Results indicated no interaction between group and word size effects in choice reaction times or a group effect in the ability to recognize previously learned symbol-word combinations. However, they were significantly different in the timing of peak amplitudes in the integrated electromyographic signals of upper lip and lower lip (IEMG peak latency). Findings question the claim that people who stutter have problems in creating abstract motor plans for speech. In addition, it is argued that the group differences in IEMG peak latency that were found in the present study might be better understood in terms of motor control strategies than in terms of motor control deficits.

KEY WORDS: speech motor control, stuttering, motor planning, speech physiology

One of the main interests in stuttering research concerns the difficulties persons who stutter may have in the planning of speech. This general notion has a long history in stuttering research and treatment (e.g., Van Riper, 1982). A popular way to investigate planning aspects in speech production is to use a reaction time paradigm, in which the time between the presentation of the stimulus and the onset of speech is influenced by the nature of the verbal response (Klapp et al., 1979; Sheridan, 1981; Sternberg, Monsell, Knoll, & Wright, 1978). In stuttering research word size is one of the main factors of interest, since people who stutter are known to stutter more often on longer words compared to shorter words (Soderberg, 1966; and Starkweather, 1987, for a review). The influence of word size on reaction time is assumed to be related to the fact that longer words have more units (e.g., syllables or phonemes), which will affect the time needed to prepare the whole sequence in advance (Klapp, 1977; Monsell, 1986; Shaffer, 1984). For normal speakers, evidence in favor of such an assumption was found in both simple (e.g., Dembowski & Watson, 1991; Peters, Hulstijn, & Starkweather, 1989; Sternberg et al., 1978; Sternberg, Wright, Knoll, & Monsell, 1980; Watson & Alfonso, 1982; Watson, Freeman, & Dembowski, 1991) and choice reaction time studies (e.g., Klapp, 1974; Klapp, Anderson, & Berrian, 1973; Peters et al., 1989; Rosenbaum, Gordon, Stillings, & Feinstein, 1987; Van Lieshout, Hulstijn, & Peters, 1996).

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The fact that word size can influence both simple and choice reaction times is interesting, since it is argued that simple reaction times do not reflect influences of speech planning as such (e.g., Klapp et al., 1979; Sheridan, 1981). In fact, a simple reaction time task is often used to avoid influences that are related to speech planning (cf. Hulstijn, 1987; Klapp et al., 1979; Ludlow, 1991; Sternberg et al., 1978; Watson & Alfonso, 1983, 1987). How then to explain the effect of word size on both simple and choice reaction times? The answer to this question may be found in the assumption that word size effects in simple and choice reaction times have their origin at different stages in speech production (cf. Levelt, 1989; Verwey, 1994).

Based on the model of Sternberg et al. (1978), Levelt (1989) proposes four different stages in speech production (see Table 11.2, p. 421) that follow the retrieval of word form information from the mental lexicon. In the first stage a detailed abstract motor (or phonetic) plan is assembled and (if necessary) stored in a short term motor buffer (the Articulatory Buffer). In an earlier version of the model, this stage only included phonological encoding, but in a more recent version of the model (see Levelt & Wheeldon, 1994) a phonetic encoding substage was added, in which the end-product of phonological encoding (a phonological word) is used to retrieve motor templates (gestures) stored as syllabic units in a long-term motor memory (the *syllabary*, as it was called by Levelt & Wheeldon, 1994). A similar distinction between a phonological and phonetic processor can be found in Kent (1990). For practical reasons, this paper will address the phonological and phonetic encoding substages as one stage, called the *motor plan assembly stage* in accordance with the use of the same concept in a previous paper (Van Lieshout et al., 1996). The effects of word size in choice reaction time studies are believed to have their origin mainly at this stage (Levelt, 1989), since longer words have more syllables, which, according to the model, will take more time to encode phonologically and also to find all the corresponding motor templates (stored as syllabic units) in the syllabary.

Following this motor plan assembly stage, there are two stages in which first, the motor plan units are retrieved on a one-by-one basis (retrieval stage), and second, these units have to be unpacked to make the individual muscle commands available for their final parametrization and execution (unpacking or muscle command parametrization stage). The processes at the muscle command parametrization stage determine the final output characteristics of muscle activity in order to produce adequate patterns of force to generate movement sequences. Since the retrieval and muscle command parametrization stages are both involved in setting up the muscle commands prior to their execution, they will be referred to as one stage in this paper, the *muscle command preparation stage*,[1] in accordance with the same concept used in a previous paper (Van Lieshout et al., 1996). Word size effects found in simple reaction times are assumed to have their origin at the muscle command preparation stage, since longer words have more muscle commands[2] and this will affect the time to complete the unpacking and muscle command parametrization substages (Levelt, 1989).

The fourth and final stage involves the execution of the muscle commands, starting at the initiation of muscle activity, which is (normally) followed by the onset of an articulatory movement. In the present study this stage is referred to as the *execution stage*.

For people who stutter, the model as described above would predict that if they have problems in processing information at the motor plan assembly stage (cf. Bosshardt, 1990, 1993; Hubbard & Prins, 1994; Postma & Kolk, 1993; Wijnen & Boers, 1994), the increase in planning demands for longer words would increase the differences in choice reaction time between themselves and those who do not stutter. Or, in other words, choice reaction time would show an interaction between group and word size effects. This interaction effect was found in a study by Peters et al. (1989). They compared choice reaction times of a group of people who stutter and matched control speakers for monosyllabic words, polysyllabic (3/4 syllables) words, and sentences. Both groups showed a significant increase in choice reaction time for the polysyllabic words and sentences, but especially for the polysyllabic words the increase was clearly stronger for the subjects who stutter.

To replicate and extend the significance of this finding, a study by Van Lieshout et al. (1996) contrasted monosyllabic words with polysyllabic words (2/3 syllables) in two different choice reaction time tasks. One task was a word-naming task of the same type used in Peters et al. (1989) in order to replicate their finding most directly. The other task was a nonstandard picture-naming task, in which subjects had to learn a fixed combination between a picture and a word. This way, reading time differences as related to the size of a word (Eviatar & Eran-Zaidel, 1991; Naveh-Benjamin & Ayres, 1986) could be eliminated, making the relation between changes in reaction time as a function of word size and planning more evident. The results showed that despite a clear word size effect in the word-naming task, there was no significant interaction between group and word size effects for this task. For the picture-naming task there was no main effect of word size and neither was there a significant group by word size interaction effect. Together, these data did not provide evidence in favor of the hypothesis that people who stutter have problems at the stage of motor plan assembly.

One reason that might account for not finding the interaction between word size and group effects in the study of Van Lieshout et al. (1996) was the manipulation of word size, in particular for the picture-naming task. For that task, all three-syllable words were formed by adding grammatical suffixes to bisyllabic words to indicate a plural form of these

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[1] Roughly, the processes that relate to the motor plan assembly stage can be referred to as "motor planning," whereas the processes that relate to the muscle command preparation stage can be referred to as "motor programming" (cf. Van Mier, 1992). However, since these terms have been used in many other definitions, they have become rather ambiguous. To avoid confusion, in this paper (and in a previous one, Van Lieshout et al., 1996) descriptive terms are chosen that identify their relationship to the stages as addressed in Levelt (1989).

[2] Of course, when the motor plan consists of more than a single word (stress-group), the muscle command preparation stage will also take more time because more units in the motor plan will increase the time to search the short-term motor buffer (Levelt, 1989; Sternberg et al., 1978).

words. This method facilitated the choice of pictures, but due to the high usage frequency of these suffixes in Dutch, it might have diminished the demands on the planning of these words. In addition, in the study of Peters et al. (1989), word size was varied along a somewhat wider range contrasting monosyllabic words with three- to four-syllable words. So, it is possible that a wider range in number of syllables within a word than used in Van Lieshout et al. (1996) would be more successful in eliciting the potential problems people who stutter may have in processing information at the motor plan assembly stage.

What about group by word size interaction effects as related to the muscle command preparation stage? According to the model described above, simple reaction time data could provide an answer to this question, since the motor plan can be assembled in advance and, after the signal to start speaking, subjects only need to retrieve the units of the motor plan stored in the short term motor buffer, unpack, and provide parameter values for the individual muscle commands before they are executed (Levelt, 1989; Sternberg et al., 1978). Findings that could indicate that people who stutter (children or adults) have problems in the muscle command preparation stage as shown by a greater simple reaction time difference than control speakers for longer (or more complex) words are reported in a number of studies (Bishop, Williams, & Cooper, 1991; Maske-Cash & Curlee, 1995; Reich, Till, & Goldsmith, 1981; Till, Reich, Dickey, & Seiber, 1983; Watson et al., 1991). On the other hand, there are also a number of studies that report negative or less clear findings in this respect (Dembowski & Watson, 1991; McKnight & Cullinan, 1987; Peters et al., 1989). Furthermore, it has to be noticed that the positive findings may be limited to stuttering persons with concomitant (linguistic) problems (Maske-Cash & Curlee, 1995; Watson et al., 1991). In general, the effects of word size on group differences may be more limited in simple reaction time studies as shown in the study of Peters et al. (1989). In using both simple and choice reaction time tasks, they only found a significant interaction between group and word size effects for their choice reaction time task. This indicates that group by word size interaction effects are most likely found in studies that include the processing of information at the motor plan assembly stage by using a choice reaction time paradigm.

If people who stutter are different from control speakers in the way they handle the preparation of muscle commands, it seems likely that group differences will also exist at the stage of muscle command execution, since the borderline between both stages is rather vague. Preparation and execution will follow each other very quickly and to some extent the execution of ongoing muscle commands will coincide with the preparation of the muscle commands next in line (cf. Abbeduto, 1985; Klapp & Wyatt, 1976; Sternberg et al., 1978; Verwey, 1994). Delays that arise at the muscle command preparation stage could thus hamper ongoing muscle command execution. As such, people who stutter may have significant delays in initiating speech (see Adams, 1985; Peters et al., 1989, for reviews) or speech-related motor activities (e.g., Peters et al., 1989; Watson & Alfonso, 1987). Or, as mentioned by Van Riper (1982), it may lead to stuttering, because "when a person stutters on a word, there is a temporal disruption of the simultaneous and successive programming of muscular movements required to produce one of the word's integrated sounds, or to emit one of its syllables appropriately or to accomplish the precise linking of sounds and syllables that constitutes its motor pattern" (p. 415). Given the above-mentioned problem in creating a meaningful temporal distinction between the preparation and execution of muscle commands, the present study addresses them both as a single "post-planning" stage, using the term *muscle command preparation/execution stage.*

If people who stutter are different from control speakers in the way they prepare muscle commands, this could also give rise to group differences in the time course of EMG signals (Almé & McAllister, 1987; Guitar et al., 1988; Hulstijn, Van Lieshout, & Peters, 1991; Van Lieshout, Peters, Starkweather, & Hulstijn, 1993; Van Lieshout et al., 1996) and/or their amplitudes (Freeman & Ushijima, 1978; Kalotkin, Manschreck, & O'Brien, 1979; Murray, Empson, & Weaver, 1987; Shapiro, 1980; Van Lieshout et al., 1993; but see Caruso, Gracco, & Abbs, 1987; McClean, Goldsmith, & Cerf, 1984; Smith, 1989; Smith, Denny, & Wood, 1991). This, in turn, may lead to group differences in kinematic characteristics of the resulting movement patterns (e.g., Alfonso, 1991; Caruso, Abbs, & Gracco, 1988; Van Lieshout, Alfonso, Hulstijn, & Peters, 1994; Van Lieshout et al., 1996; Zimmermann, 1980a, 1980b), and, indirectly, to group differences in the duration of acoustic events (e.g., Borden, 1983; Healey & Ramig, 1986; McMillian & Pindzola, 1986; Pindzola, 1987; Schäferskûpper & Dames, 1987; Starkweather & Meyers, 1979; Van Lieshout et al., 1996).

In the study described here, the main purpose was to look for evidence that persons who stutter may differ from control speakers either in their ability to assemble motor plans or in the way they prepare/execute muscle commands. As mentioned above, a proper test for the assumption that group differences exist at the motor plan assembly stage can be made in varying word size within a choice reaction time paradigm (cf. Colombo et al., 1995; Peters et al., 1989). More syllables affect the time demands on the phonological syllabification process and the retrieval of motor templates from the syllabary (Levelt & Wheeldon, 1994) at the motor plan assembly stage, as defined in this paper. In the theoretical perspective that is described above, the critical test for the assumption that people who stutter take (or need) more time than matched control speakers to complete the processes at the motor plan assembly stage rests on the finding of word size effects in combination with a significant interaction between group and word size effects. Therefore, in the present experiment, word size was varied systematically in number of syllables, ranging from one to four syllables. In comparison to the previous study (Van Lieshout et al., 1996) the range in number of syllables was extended, and, in addition, grammatical suffixes were not used.

Since the significant group by word size interaction effect in the study of Peters et al. (1989) was found in a word-naming task, the same type of task was used in this study in order to provide a basis for replicating their finding. Of course, using a choice reaction time paradigm in a word-naming task, there is a possibility that longer words will affect reading time too (Eviatar & Eran-Zaidel, 1991; Naveh-Benjamin & Ayres, 1986; but, see Hudson & Bergman, 1985; Rossmeissl & Theios, 1982, for data that suggest a parallel, in contrast to a serial processing, of the letters in visually presented words).

Therefore, next to word naming, another type of task was used, in which subjects had to learn to associate a word with a meaningless visual-graphic symbol composed of line patterns, which had no conceptual relationship to any of the words used in the experiment (cf. Brennan & Cullinan, 1976; Levelt & Wheeldon, 1994, for the use of a similar type of task). Although geometrically less complex, the use of these symbols can be compared to the use of lexigrams as described, for example, in Wilkinson, Romski, and Sevcik (1994). That is, a symbol becomes the equivalent of a word. There are two main reasons to use this type of task for naming. First, in contrast to the word-naming task, the effect of word size on the assembling of motor plans is no longer confounded by the physical appearance of the stimulus. In this sense, the symbol-naming task provides an unbiased estimate of word size effects on naming. Secondly, in contrast to a standard picture-naming task with normalized pictures (cf. Snodgrass & Vanderwart, 1980), there is no reason to limit the choice of words to those that can be depicted in a meaningful manner (Levelt & Wheeldon, 1994). Thus, for a symbol-naming task, more different words can be used, and more importantly, different words can be assigned to different symbols across subjects to minimize a systematic bias in naming time due to the visual complexity of a picture.

Of course, this task also forces subjects to elaborate on the coding strategies in order to memorize successfully the correct combination (cf. Kyllonen, Tirre, & Christal, 1991; Paivio, 1971, 1991). It has been suggested that people who stutter differ from controls in their ability to encode and retrieve linguistic information (Bosshardt, 1993; Carpenter & Sommers, 1987; Moore, 1986; Moore, Craven, & Faber, 1982; Rastatter & Dell, 1987). To test this assumption, the subjects in the present experiment performed a symbol-word recognition task, using manual reaction times as well as response measures as defined in signal detection theory (Green & Swets, 1966; McNicol, 1972) to evaluate their speed and sensitivity to detect previously learned symbol-word combinations. Manual and not speech reaction times were used to test recognition performance to exclude possible influences of naming processes. The most obvious limitation of the symbol-naming task is the number of combinations that can be learned within a session. In the present study a single naming session included four symbol-word pairs, which is in line with other studies (Levelt & Wheeldon, 1994; Van Lieshout et al., 1996).

To test more specifically for group differences in muscle command preparation/execution, electromyographic (IEMG) recordings of the upper lip and lower lip were taken. This could only be done for one half of the experimental stimuli, namely for those words that had a voiced bilabial onset (/b/ or /m/). The other words started with a voiced apico-alveolar onset (/n/ or /d/). From the integrated (I)EMG signals two measures were taken. The first measure is defined as the interval between the onset of upper lip and lower lip IEMG, which reflects the relative timing of the lip muscles for a bilabial closure. The order of synergistic muscle onsets for lip closure can be quite variable across (normal speaking) subjects (Gracco, 1988), but people who stutter have been found to show stronger delays in the onset of upper lip IEMG activity, compared to lower lip IEMG activity (cf. Hulstijn et al., 1991; Van Lieshout et al., 1996; see also Conture, Colton, & Gleason, 1988).

The second measure is defined as the interval between the onset of IEMG activity and the time of peak amplitude (IEMG peak latency). In an earlier study (Van Lieshout et al., 1993), a group of persons who stutter were found to show significant delays in lower lip IEMG peak latency in comparison to matched controls. The significance of this measure was addressed by Gracco (1988) in stating that "the temporal characteristics of the EMG activity (onset time to peak amplitude) are important variables in the coordination of the multiple articulators" (p. 4637).

As already mentioned, if people who stutter are delayed in the preparation and/or execution of muscle commands, it may (indirectly) affect the time to complete the verbal response (cf. Borden, 1983; McMillan & Pindzola, 1986; Pindzola, 1987; Postma, Kolk, & Povel, 1990), in particular for longer words (Van Lieshout et al., 1996). Therefore, in addition to the reaction time and IEMG measures, word duration was included in the present experiment as a general estimate of execution time.

In sum, the present study was designed to determine whether a group of persons who stutter would differ from a group of control speakers in

1. the assembly of abstract motor plans, as shown by a significant interaction in choice reaction time between group and word size effects for word naming and symbol naming. A recognition task was used to check for possible group differences in the building and retrieval of memory representations that could influence the choice reaction times in the symbol naming task;
2. later stages, that is, in the preparation/execution of muscle commands, as shown by larger interlip intervals and stronger delays in the interval between IEMG onset and peak amplitude for people who stutter. Such group differences are also expected to result in longer word durations for people who stutter. The group effects for these measures may be influenced by word size, showing greater differences for the longer words between people who do and who do not stutter.

Method

Subjects

In the experiment 12 adult males who stutter participated (mean age 24.2 years, *SD* = 3.4, range 19–31 years), matched for age (mean 23.3 years, *SD* = 3.1, range 19–30 years), sex, and educational level to 12 control speakers. All subjects had normal hearing acuity, normal language and voice quality, and normal vision. None of the persons who stutter had been in treatment over at least the last year preceding the start of the experiment. They were all selected from a clinical population of people who stutter known to the speech department of the ENT clinic of the academic hospital in Nijmegen.

Stuttering severity was determined by three experienced speech-language pathologists using the Stuttering Severity Instrument (SSI, Riley, 1972) scores on oral reading and conversational speech, which were both recorded on video prior to the experiment. Of the persons who stutter, 7 were classified as very mild, 4 as mild, and 1 as moderate. All subjects were volunteers paid for their participation.

Design and Procedure

Stimuli. See the Appendix for words and symbols that were used in the experiment. All words were low-frequency nouns (<10/million), based on 42 million tokens in CELEX, a computerized Dutch lexical database (Burnage, 1990). In total, 16 different words were used, which varied systematically along two dimensions, that is, in size (one, two, three, and four syllables) and consonant-vowel word onset (bilabial consonant: /biː/ and /meː/; alveolar consonant: /doː/ and /naː/). These 16 words were assigned to four different word sets. In each set the four words differed in consonant-vowel onset and number of syllables, and they were not semantically related to each other. These four word sets were used to form two fixed combinations of two word sets each in which the four levels of word size and the two levels of initial consonant sound category (bilabial vs. apico-alveolar) were fully crossed. Each subject was assigned to either of the combinations. The order of word sets within a fixed combination was balanced across subjects. The variation in word onset was used to prevent subjects from adopting a fixed a priori lip position. The voiced bilabials were used to include measures for lip IEMG activity. The mean number of graphemes was 4.0 (SD = 0.0) for the one-syllable words, 7.5 (SD = 0.6) for the two-syllable words, 10.0 (SD = 0.0) for the three-syllable words, and 14.5 (SD = 0.6) for the four-syllable words.

For the symbol-naming task, meaningless visual-graphic symbols composed of line patterns matched for complexity and size were used (see Appendix, Figure A). Only those symbols were selected that, according to a small panel of subjects (4 randomly chosen female graduate psychology students who did not participate in the experiment and were naive as to its goals), did not show a consistent association with a particular word of the experimental stimuli. In this way, all selected symbols were neutral with respect to the target words of the experiment and could be combined at random with any of them. Furthermore, the panel was asked to group symbols that to their accord were more or less similar. From the symbols that were consistently grouped together, and thus might get confused, the symbol that had the most distinctive features, as compared to the other symbols outside the group, was chosen. For the experiment, none of the selected 16 symbols was consistently paired with a particular initial phoneme-word size level combination across subjects. In sum, several steps were taken to minimize a systematic bias in reaction times as a function of the stimulus (symbol) that was used to cue the paired response word.

Procedure. Before the start of the experiment, the persons who stutter were asked to read aloud a standard text and subsequently they were engaged in a brief dialogue with the experimenter. These speech tasks were videotaped and used afterwards for estimating stuttering severity.

Subjects were informed about the use of surface EMG electrodes before they received written task instructions. Small surface EMG electrodes were attached bilaterally with flexible tape at the junction of the vermilion border for upper lip and lower lip, approximately 1.25 cm from the median raphe, which is a standard procedure at the Nijmegen research lab (cf. Peters et al., 1989; Van Lieshout et al., 1993). A microphone was placed at approximately 30 cm in front of the subject's mouth.

In general, three aspects were emphasized in the instructions. First, upon hearing the warning sound, a subject had to inhale through his mouth. Second, until the stimulus was presented, he had to keep his lips in an open position. In this way the initial upper and lower lip configuration was similar for all subjects. Third, when the stimulus was presented, simultaneously with a high-pitched tone, they had to respond as fast as possible, except in the learning session, where accurate responding was more critical than fast responding. Between two series of tasks, subjects could take a break. During the experiment, subjects were seated 1 m from a TV monitor on which the stimuli were presented. Subjects performed in the presence of one of two experimenters; the other experimenter controlled the equipment in an adjacent room.

Tasks. The experiment consisted of two series of three different tasks (and a learning session) in a fixed order, all using a choice reaction time paradigm. For each series of tasks, one of two sets of four different words each was used (see stimuli section for details about the way word sets were formed).

The first task was a *word-naming task*. The four words of a set were presented consecutively 24 times in a random order, yielding 96 trials, halfway interrupted by a short break. Following the successful completion of the word-naming task, the subjects were familiarized with four symbol-word pairs that had to be learned for the next tasks, by showing one by one the selected combinations of a word and a symbol on 10 by 15 cm index-cards.

Then a *learning session* started, which enabled the subjects to build associations between the symbol and the target word. During this learning session a symbol was presented on the screen for each trial. The subjects had to name the correct target word. After the response was given, the correct word appeared on the screen underneath the symbol. Each pair was presented 12 times in a random order. All subjects had to satisfy the criterion of naming the four correct verbal labels five times in a row before they could proceed to the next task (cf. Brennan & Cullian, 1976; Levelt & Wheeldon, 1994).

The next task was a *recognition task*. Subjects were shown simultaneously a symbol and, underneath it, one of the 4 target words. By pressing a button with their right or left index finger, they had to indicate whether or not the displayed combination was correct, that is, if it was one of the four pairs previously learned. Half of the combinations that were shown were correct, so the chance of making a correct response on the basis of a pure guessing strategy would be 50%. There were 48 trials in total, presented in a random order. Since it can be expected that the yes-response is faster than the no-response (e.g., Kroll & Potter, 1984), the yes-response was always given with the dominant hand, which, in general, is assumed to deliver the faster manual response (Bashore, 1981; Webster & Ryan, 1991).

Finally, in the *symbol-naming task*, the same four symbol-word combinations were used, but this time the subjects were asked to name as fast as possible the correct verbal label for the symbol that was presented on the screen. Similar to the word naming task, the four choices were presented consecutively 24 times in random order, yielding 96 trials, interrupted halfway by a short break.

In all these tasks, except the learning task, subjects were encouraged to respond as fast as possible. In the word-naming, recognition, and symbol-naming task this was emphasized by giving the subjects visual feedback on voice-key reaction times. These voice-key data were only used for feedback purposes and not for further analysis. In all tasks (including the learning session) a trial onset was signaled by a low frequency beep (500 Hz, 500 ms), followed by a 500 ms interval in which the subject was explicitly instructed to inhale. This instruction was meant to prevent a bias toward group differences in reaction times that actually reflect group differences in the onset of inspiration (Van Lieshout et al., 1996; Watson & Alfonso, 1987).

After the 500 ms silent interval a high frequency beep (2000 Hz, 100 ms) was presented simultaneously with the stimulus (word or symbol) to which the subject had to respond (manually or verbally) as fast as possible. After 2 s the stimulus disappeared from the screen. The next trial started after a silent intertrial interval (ITI) of 2 s during which visual feedback was given on reaction time (word naming, recognition, and symbol naming), or in which the correct target word was shown (learning session).

Before the start of the first task (word naming) subjects received 20 practice trials with stimuli that were not used in the experiment proper. These trials were not further analyzed. Symbols and words were presented in the central part of an 18 by 24 cm rectangular screen at a viewing distance of 1 m, using uppercase letters of about 1 cm height for the words.

Instrumentation. The presentation of the stimuli (words or symbols), the warning and reaction tones, the starting and stopping of the data-recording equipment, and the registration of voice-key reaction times, were under control of an IBM PS2/30 micro-computer, connected to two (monochrome) TV-monitors, one in front of the experimenter, the other in front of the subject.

Lip EMG activity was recorded using small (0.4 mm) silverball electrodes (San-ei Sokki, Inc.). For the EMG measurements a reference electrode was positioned on the skin covering the mastoid. EMG electrodes were connected to differential preamplifiers (Honeywell, EMG preamplifier). The output of the preamplifiers was fed to amplifiers (Honeywell, Accudata 135) set at a frequency range of 20–2500 Hz. The speech signal was recorded using an AKG (type 451 E) condenser microphone. All signals, including a pulse signal indicating the start and stop of a trial, were recorded on a 14-channel FM instrumentation recorder (TEAC) at a running speed of 9.52 cm/s (Frequency range 0–2500 Hz). Key press 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 (cf. Hulstijn, Summers, Van Lieshout, & Peters, 1992).

Fluency Criteria And Data Analysis

Only those utterances were analyzed that were judged to have been spoken fluently. This was done to prevent the measures from being contaminated with influences of stuttering events. As described in Peters et al. (1989), in order to be fluent, an utterance had to satisfy two criteria. First, there should be no visible signs of struggle in the subject's face or body just before or during the trial sequence. Every instance of such signs was noted during the experimental sessions. Second, the utterance should not contain audible hesitations, prolongations, repetitions, or any other perceptual sign of dysfluency. During the experimental sessions, dysfluencies were noted and checked afterwards by careful listening to audio recordings of the subject's speech. Next, all trials in which subjects made naming errors were excluded. In addition, for the EMG signals to be included, there had to be no signs of electrode movement artifacts or excessive activity (that might accompany behaviors that are not task related, like licking the lips, swallowing, yawning) of any kind. Stuttering subjects were not asked to indicate whether they experienced a subperceptual stutter that might have gone unnoticed by the experimenter. Such an instruction could have biased the results in creating a dual-task situation for the persons who stutter. That is, they would not only have to perform the experimental task, but in addition they would have to monitor carefully their (inner) speech to detect (c)overt dysfluencies. Such extra demands could easily increase reaction times and word durations. For the word-naming task in total 5.03% of the data for the controls, and 11.94% of the data for the persons who stutter were left out of the analysis. For the symbol-naming task the percentages were 14.93% for the control speakers and 19.31% for the persons who stutter. Clearly, the symbol-naming task induced more errors than the word-naming task. For the recognition task, errors (incorrect yes or no-response) were determined automatically by software. Together with the correct manual responses these error data were used to evaluate the recognition performance of the persons who stutter and their matched controls.

Speech and EMG signals from the FM instrumentation recorder were bandpass filtered (EMG: 20–500 Hz; Audio: 80–2500 Hz, all with 48 dB/octave) before being digitized at 2500 Hz (EMG) or 5000 Hz (Audio) and their gain was set to an optimized value (±5 V). The onset and offset of the speech signal were used as temporal markers to determine speech reaction time and word duration. For these measures it was possible to use a limited frequency band (80–2500 Hz) for the audio signal (cf. Watson et al., 1991). After being digitized, the EMG signals were software rectified and low pass filtered between 15 and 40 Hz. Both raw and integrated EMG signals were displayed during the analysis (see also Figure 1).

Speech and IEMG time measures were determined automatically using an algorithm in which the onset or offset (only for audio) of a signal was defined at a 5% level of the optimized range (±5 V) above a calculated noise level (mean + 3 × standard deviation) for a number of trials within a set of data for a given naming task (thus: onset = noise level + 50 mV). All automatically derived onsets were visually checked and corrected if necessary (see also Gracco, 1988). Once the onset of the IEMG signals was determined, an automatic algorithm was used to find the IEMG peak amplitude in the interval between IEMG onset and the onset of speech. In Figure 1 an example of a typical trial is shown, illustrating the temporal markers for the onset and offset of speech, the onset of upper lip and lower lip IEMG activity, as well as the temporal location of the IEMG peak amplitude for both lips.

Dependent Variables

Recognition task. To analyze the recognition task performance two measures were used that are derived from signal detection theory (Green & Swets, 1966; McNicol, 1972). The first measure is the nonparametric sensitivity score *P(A)*, which indicates how well subjects can make correct judgments while avoiding making incorrect ones. It is based on the probabilities of "*hits*" (recognizing the combination as previously learned and being correct) and "*false alarms*" (recognizing the combination as previously learned and being incorrect). The exact formula that was used to calculate the *P(A)* scores can be found in McNicol (1972, p. 115). With high levels of sensitivity, the distribution of this score will be skewed, which might affect the analysis of variance. Therefore, as recommended by McNicol (1972), all *P(A)* scores were transformed, according to the formula:

$$2 \arcsin \sqrt{P(A)}$$

A second measure for recognition performance is *bias*, that is "the extent to which the observer favors one hypothesis over another independent of the evidence he has been given" (McNicol, 1972, p. 11). The total number of "yes" responses was used as a nonparametric bias score. Both measures of recognition performance were also used by Bosshardt (1993), although he did not mention the transformation for the P(A) scores. Next to these recognition measures that indicate how well subjects can make a (correct) judgment, *manual reaction time* was used to determine how fast these judgments were given.

Word-naming and symbol-naming task. For word naming as well as for symbol naming, *choice speech reaction time* was used as an overall performance measure. It was based on the interval between the moment at which a stimulus was presented and the very first onset of speech acoustics (see Figure 1). Word size and group effects for this measure were used to test the first assumption mentioned at the end of the Introduction.

In addition, but only for the words with a bilabial consonant onset, two IEMG measures were calculated. The first measure is based on the interval between upper lip and lower lip IEMG onset (*interlip interval* = lower lip IEMG onset − upper lip IEMG onset; thus a negative value indicates that the lower lip came first). The second measure is based on the interval between (upper/lower) lip IEMG onset and the temporal location of the IEMG peak amplitude (*IEMG peak*

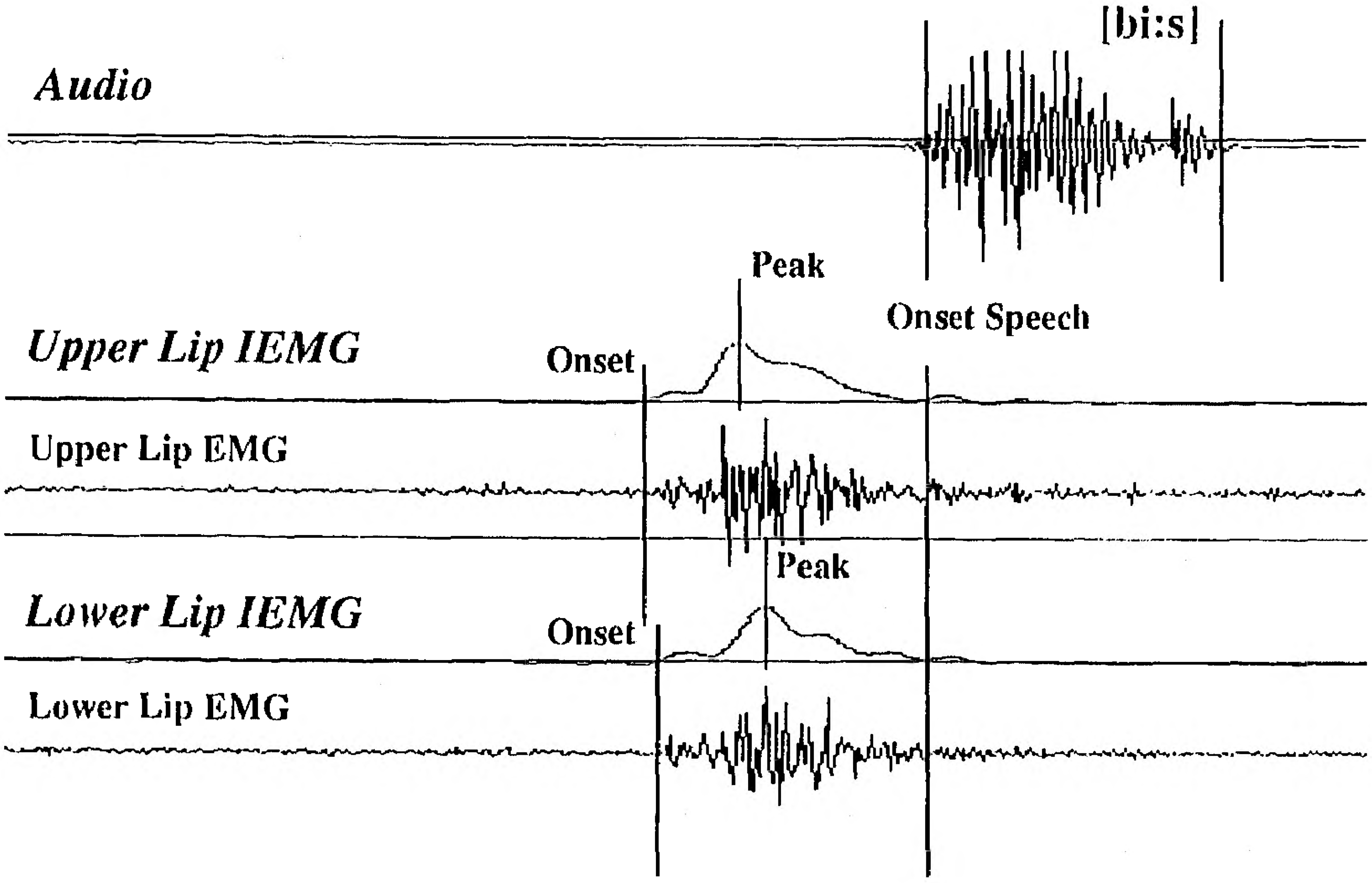

FIGURE 1. Typical example of acoustic and (I)EMG signals for one response, showing (a) onset of speech; (b) offset of speech; (c) onset of Upper lip IEMG; (d) temporal location of Upper lip peak IEMG amplitude; (e) onset of Lower lip IEMG; and (f) temporal location of Lower lip peak IEMG amplitude.

latency). As a more general estimate for group differences in speech execution, the interval between the onset and offset of speech acoustics (*word duration*) was included in the analyses. Group and word size effects for these measures were used to test the second assumption mentioned at the end of the Introduction.

Statistical Analysis

In order to reduce susceptibility to outliers in the data, separately for each subject and task the median values (Ferguson, 1984) were calculated across the repetitions of individual stimuli. For word naming and symbol naming the number of repetitions was 24. For the recognition task, the number of repetitions was 12 for either response type (yes/no). In case the median could not be calculated due to missing data, it was replaced by a value calculated according to a method described in Winer (1962, p. 282). This strategy was used 101 times out of a total of 36864 cells (=0.27%). The median values were used to calculate the group means for the factors of interest (group and word size).

For the recognition task, transformed P(A) scores, bias scores, number of hits (maximum of 6 per combination), and false alarms (maximum of 6 per combination) were analyzed in singular analyses of variance, with word size (four levels) as within-subject factor and group (persons who stutter vs. control speakers) as between-subject factor. For the manual reaction times the analysis of variance followed a three-factor design with repeated measures with group as between-subject factor and word size (four levels) and response type (two levels) as within-subject factors.

For the word-naming task as well as for the symbol-naming task, the analysis of variance followed a two-factor design with repeated measures on speech reaction times and word durations with group as between-subject factor and word size (four levels) as within-subject factor. Variations in the initial phonemes of a word can influence reaction times (cf. Dembowski & Watson, 1991; Peters et al., 1989), but the design of the present experiment was such (see above) that word size levels and initial phoneme were not confounded. Therefore, data were pooled across the words with alveolar and bilabial initial phonemes, except, of course, for the IEMG measures. For the latter, separate analyses of variance were performed on the interlip interval and on upper lip and lower lip IEMG peak latencies for the words with initial bilabial consonant following a two-factor design with repeated measures with group as between-subject factor and word size (four levels) as within-subject factor. *F*-values reported for word size main effects as well as for word size interaction effects are based on multivariate tests (Hotellings T^2) of significance (Rietveld & Van Hout, 1993).

For group main effects, additional information will be supplied to evaluate the power of that particular variable in differentiating on a more general level between people who do and who do not stutter, as well as to be able to compare the results of the present study more directly with the results of previous studies. The additional information includes two estimates of how much (in %) of the total variation for that particular measure is accounted for by group membership (Eta Squared, η^2 and Omega Squared, ω^2). Furthermore, 95% confidence interval (*CI*) information will be given to indicate the upper and lower limits of the size of the group difference. Finally, the percentage of proportion misclassified (*PM*) subjects will be given to indicate how well group membership can be predicted from the variable for which the group effect is reported. The latter index reflects the degree of overlap between the distributions for the persons who stutter and their matched counterparts; the higher the overlap, the more difficult it is to differentiate between members of the two groups using that particular variable. A more detailed account of using these indices to interpret the significance of group differences was recently given by Young (1994).

Word size effects are submitted to trend analysis, using orthogonal polynomial contrasts to qualify the nature of the size effect, that is, to test for a linear increase or possibly higher order (quadratic, cubic) effects (Ferguson, 1984). For all tests a significance level of 0.05 was applied.

Results

The results are presented in two major sections. The first section presents the data for the recognition task, and the second section presents the data for the word-naming and the picture-naming tasks. For the recognition task the sensitivity data will be given first, followed by the data of the manual reaction times. For the naming tasks, the acoustic data (speech reaction time and word duration) will be given first, followed by the IEMG data (interlip interval and peak latency).

Recognition Task

Sensitivity measures. Table 1 shows the means and standard deviations of the transformed sensitivity *P*(*A*) score, the bias score, the number of false alarms and the number of hits for group (persons who stutter and control speakers) and word size (four levels). On the *P*(*A*) score the persons who stutter and the controls were not found to be different, F (1, 22) = 1.21, p = .283, and contrary to expectations, the average value for the persons who stutter (2.72) was even slightly higher than the average value for the control speakers (2.63). Similarly, there were no group effects for bias, F (1, 22) = .84, p = .370, the number of false alarms, F (1, 22) = 1.85, p = .188, and the number of hits, F (1, 22) = .14, p = .709. Main effects for word size were not significant, although there was a trend for P(A), F (3, 20) = 2.68, $p < .08$. No other effects were found to be significant ($F < 2$).

Manual reaction time. Table 2 lists the means and standard deviations of the manual reaction times for group, response type (yes/no), and word size. Persons who stutter (798 ms) and controls (790 ms) did not differ from each other in their overall manual reaction times, F = .03, p = .867. In general no-responses (836 ms) took longer than yes-responses (751 ms), F (1, 22) = 33.51, $p < .001$. There was a trend for an overall main effect for word size, F (3, 20) = 3.06,

TABLE 1. Means (+*SD*) of transformed sensitivity index P(A), bias scores (Bias), number of false alarms (FA), and number of hits (Hits) of control speakers (CS) and persons who stutter (ST) for one (1 syl), two (2 syl), three (3 syl), and four (4 syl) syllable words.

	P(A) *CS*	P(A) *ST*	Bias *CS*	Bias *ST*	FA *CS*	FA *ST*	Hits *CS*	Hits *ST*
1 syl	2.59 (.32)	2.58 (.38)	5.92 (.82)	6.04 (.92)	.62 (.38)	.75 (.50)	5.29 (.28)	5.29 (1.08)
2 syl	2.72 (.28)	2.83 (.26)	6.42 (.70)	5.87 (.43)	.71 (.72)	.25 (.26)	5.71 (.40)	5.62 (.43)
3 syl	2.60 (.31)	2.64 (.25)	6.08 (.95)	6.33 (.65)	.67 (.72)	.67 (.49)	5.42 (.63)	5.67 (.39)
4 syl	2.62 (.30)	2.82 (.27)	6.17 (.78)	5.83 (.58)	.67 (.58)	.29 (.33)	5.50 (.60)	5.54 (.54)

$p < .06$, and, in addition, there was a group by word size interaction effect, $F(3, 20) = 3.63, p < .05$, showing a longer reaction time for persons who stutter in the one-syllable condition (800 ms) as compared to the control speakers (743 ms). For the polysyllabic words group differences were much smaller (two-syllable words: persons who stutter 8 ms faster; three-syllable words: persons who stutter 1 ms faster; and four-syllable words: persons who stutter 13 ms faster). Since a significant interaction between word size and response type (yes/no) was also found, $F(3, 20) = 11.87, p < .001$, simple main effects for word size were tested separately for the yes- and no-responses. For the yes-response there was a significant main effect for word size, $F(3, 20) = 9.07, p < .001$, which was not found for the no-response, $F(3, 20) = .97, p = .426$. A trend analysis on the main effect of word size for the yes-response revealed a quadratic component, $F(1, 22) = 26.1, p < .001$, denoting longer manual reaction times for the yes-response for two- (810 ms) and three-syllable (779 ms) words, in comparison to one- (700 ms) and four-syllable (710 ms) words. Neither for the yes-, nor for the no-response was there a first order interaction between group and word size. As can be seen in Table 2, the interaction between group and word size that was found when pooled across response type (see above), seems to be primarily based on the group difference (75 ms) found for the no-response in the monosyllabic condition. That is, for some unknown reason, people who stutter took more time than control speakers to decide that a particular one-syllable word did not belong to the displayed symbol.

Naming Tasks

Acoustic data: Word naming/reaction times. Figure 2A shows the means (and standard deviations) of the acoustic reaction times for group and word size. Persons who stutter (443 ms) had longer reaction times than their matched controls (418 ms), but this group difference was not significant, $F(1, 22) = .96, p = .337$. There was a main effect for word size, $F(3, 20) = 34.80, p < .001$, but no interaction with group, $F(3, 20) = .57, p = .641$, as can be seen in Figure 2A. Trend analysis on the main word size effect revealed a significant linear, $F(1, 22) = 89.11, p < .001$, and cubic component, $F(1, 22) = 14.40, p < .001$, showing an increase (26 ms) in speech reaction time between one- and two-syllable words and also between three- and four-syllable words (13 ms), but no clear difference between two- and three-syllable words.

Acoustic data: Word naming/word duration. Means (and standard deviations) for word duration are listed in Figure 2C. As a group, persons who stutter (469 ms) had longer word durations than their matched counterparts (436 ms). However, this group effect was not significant, $F(1, 22) = 3.16, p < .10$. There was a main effect for word size, $F(3, 20) = 338.06, p < .001$, but no interaction with group, $F(3, 20) = .36, p = .783$, as shown in Figure 2C. Trend analysis on the word size effect revealed a clear but trivial significant linear component, $F(1, 22) = 1065.00, p < .001$, but, in addition, there was a cubic component, $F(1, 22) = 43{,}56, p < .001$. The latter effect is based on the fact that

TABLE 2. Means (+*SD*) of manual reaction times of control speakers and persons who stutter for one (1 syl), two (2 syl), three (3 syl), and four (4 syl) syllable words.

	Control speakers YES	*Persons who stutter* YES	*Control speakers* NO	*Persons who stutter* NO
1 syl	681 (133)	720 (109)	806 (130)	881 (174)
2 syl	809 (178)	811 (139)	844 (195)	825 (150)
3 syl	788 (150)	770 (61)	816 (158)	832 (141)
4 syl	729 (131)	702 (60)	844 (147)	844 (156)

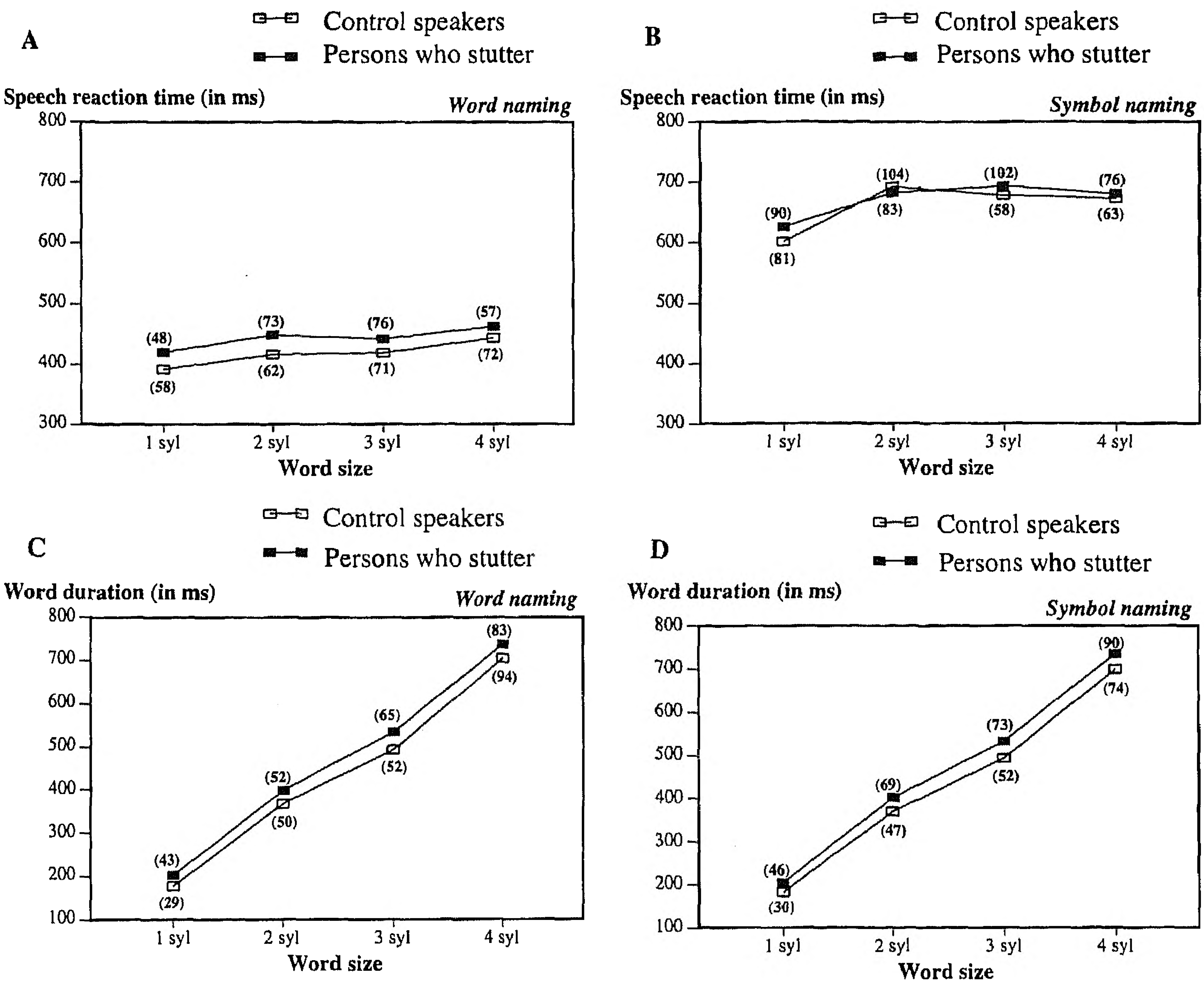

FIGURE 2. Speech reaction times (+*SD*) for control speakers and persons who stutter for word size (one-syllable, two-syllable, three-syllable, and four-syllable words) in word naming (A) and symbol naming (B); also word durations (+*SD*) for nonstutterers and stutterers for word size (one-syllable, two-syllable, three-syllable and four-syllable words) in word naming (C) and symbol naming (D).

the increase in word duration between two- and three-syllable words was smaller (130 ms) than the increase between one- and two-syllable words (193 ms) and three- and four-syllable words (207 ms). This finding seems to parallel the small difference in speech reaction time between two- and three-syllable words (see above).

Acoustic data: Symbol naming/reaction time. Means and standard deviations of acoustic reaction time for group and word size are shown in Figure 2B. Compared to the word-naming task average reaction times were slower in the symbol-naming task (430 vs. 666 ms). This is a well-documented effect for naming pictures (symbols) in comparison with naming words (Glaser, 1992; Smith & Magee, 1980; Theios & Amrhein, 1989). Persons who stutter were on average 8 ms slower than their matched controls, a group difference that was not significant, F (1, 22) = .08, p = .784. There was a significant word size main effect, F (3, 20) = 21.12, $p < .001$, but, again, as in word naming, there was no interaction with group, F (3, 20) = .45, p = .719, as shown in Figure 2B. A trend analysis on the word size effect revealed a linear, F (1, 22) = 27.35, $p < .001$, and a quadratic component, F (1, 22) = 23.31, $p < .001$. Speech reaction time increased between one- and two-syllable words (74 ms), remained practically the same (1.2 ms) for two- and three-syllable words, and showed a small decrease (9 ms) between three- and four-syllable words. In sum, there was a clear dichotomy in reaction times between monosyllabic words and polysyllabic words.

Acoustic data: Symbol naming/word duration. Means and standard deviations of word duration for group and word size are shown in Figure 2D. On average, group differences in word duration were the same as found for the word-naming task (control speakers: 437 ms; persons who stutter: 470 ms), but, again, the effect was not significant, F (1, 22) = 2.77, p = .110. As can be expected, there was a strong main effect for word size, F (3, 20) = 444.44, $p < .001$, but no interaction with group, F (3, 20) = .20, p = .897, as shown in Figure 2D. A trend analysis on the main effect

TABLE 3. Means (+*SD*) for the interlip interval (Interlip = lower lip IEMG onset − upper lip IEMG onset) and the IEMG peak latencies (Peak Lat) for upper lip (UL) and lower lip (LL) for control speakers (CS) and persons who stutter (ST) for one (1 syl), two (2 syl), three (3 syl), and four (4 syl) syllable words of the word-naming (WN) and symbol-naming (SN) task.

	CS Interlip	*ST* Interlip	*CS* Peak Lat -UL	*ST* Peak Lat -UL	*CS* Peak Lat -LL	*ST* Peak Lat -LL
1 syl/WN	18 (7.1)	21 (18)	59 (9.6)	75 (23)	50 (33)	61 (19)
2 syl/WN	19 (11)	26 (22)	63 (15)	93 (33)	60 (39)	77 (30)
3 syl/WN	16 (17)	22 (31)	64 (18)	83 (27)	70 (45)	92 (43)
4 syl/WN	15 (9.0)	15 (18)	58 (12)	80 (30)	55 (28)	72 (23)
1 syl/SN	17 (22)	11 (24)	68 (15)	80 (24)	59 (17)	76 (38)
2 syl/SN	27 (37)	22 (39)	65 (15)	101 (31)	60 (24)	87 (31)
3 syl/SN	21 (18)	.42 (55)	68 (25)	85 (21)	60 (28)	98 (39)
4 syl/SN	11 (21)	9.8 (36)	64 (21)	86 (34)	62 (32)	83 (33)

of word size showed the expected linear component, $F\ (1, 22) = 1430.00, p < .001$, and, similar to word naming, there was also a cubic component, $F\ (1, 22) = 29.12, p < .001$. The increase in word duration between two- and three-syllable words was smaller (128 ms) than the increase between one- and two-syllable words (192 ms) and between three- and four-syllable words (203 ms). So, for word naming and picture naming the word size effect on word duration was nearly identical, as were the absolute durations for each word size level (compare Figure 2C and 2D).

IEMG data: Word naming/interlip interval. Means (and standard deviations) of the interlip interval data for group and word size are shown in Table 3. Persons who stutter (21.0 ms) and matched control speakers (16.7 ms) showed no significant difference in size or sign of the interval, $F\ (1, 22) = .51, p = .481$. Word size had a significant effect on the interlip interval, $F\ (3, 20) = 3.70, p < .05$, but there was no interaction with group, $F\ (3, 20) = .58, p = .634$. The results of the trend analysis revealed a significant linear component, $F\ (1, 22) = 7.19, p < .05$, showing on average a decrease of the interval for longer words.

IEMG data: Word naming/peak latency. Means and standard deviations of IEMG peak latency for both lips for group and word size are shown in Table 3. A significant group effect (22 ms longer peak latency for persons who stutter) was found for the upper lip, $F\ (1, 22) = 7.98, p < .01$, $\eta^2 = 26.6$, $\omega^2 = 22.5$, $CI = 5.8–37.9$, $PM = 28.1\%$, but not for the lower lip, $F\ (1, 22) = 1.82, p = .191$, although the group difference was only slightly smaller (16 ms longer for persons who stutter). Word size had a significant effect on upper lip IEMG peak latency, $F\ (3, 20) = 4.35, p < .05$, and lower lip IEMG peak latency, $F\ (3, 20) = 8.44, p < .001$. These effects were similar for persons who do and who do not stutter, as shown by a nonsignificant group by word size interaction effect for upper lip, $F\ (3, 20) = 1.36, p = .284$, and lower lip, $F\ (3, 20) = .55, p = .65$. A trend analysis on the main effect of word size revealed a quadratic component, $F\ (1, 22) = 8.93, p < .01$, for upper lip, and a linear, $F\ (1, 22) = 10.43, p < .01$, and quadratic component, $F\ (1, 22) = 13.15, p < .001$, for the lower lip. For the upper lip, IEMG peak latencies for one- (67 ms) and four-syllable (69 ms) words were shorter than for two- (78 ms) and three-syllable (73 ms) words. For the lower lip, IEMG peak latencies showed a steady increase for two- (13 ms) and three-syllable (12 ms) words, but a decrease of 17 ms for the four-syllable words.

IEMG data: Symbol naming/interlip interval. Means and standard deviations of the interlip interval data for group and word size are shown in Table 3. Persons who stutter (10.8 ms) and control speakers (19.1 ms) showed no significant difference in size or sign of the interval, $F\ (1, 22) = .67$, $p = .421$. Word size did not have a significant effect on the interlip interval, $F\ (3, 20) = .95, p = .433$, as in contrast to the word-naming task, and neither was there an interaction with group, $F\ (3, 20) = .87, p = .473$.

IEMG data: Symbol naming/peak latency. Means and standard deviations of IEMG peak latency for group and word size are shown in Table 3. Significant group effects were found for upper lip, $F\ (1, 22) = 7.50, p < .05, \eta^2 = 25.4$, $\omega^2 = 21.3$, $CI = 5.3–38.5$, $PM = 28.8\%$, and lower lip, $F\ (1, 22) = 9.40, p < .01, \eta^2 = 29.9, \omega^2 = 25.9, CI = 8.3–42.8$, $PM = 26.4\%$, showing longer intervals for the persons who stutter (group difference for the upper lip: 22 ms; for the lower lip: 26 ms). There was no main effect for word size for the upper lip, $F\ (3, 20) = .85, p = .483$, or lower lip, $F\ (3, 20) = .78, p = .520$. Also, the interaction between word size and group was nonsignificant for both lips: upper lip, $F\ (3, 20) = 1.82, p = .176$; and lower lip, $F\ (3, 20) = .75$, $p = .536$.

Discussion

This study was set up to find evidence that people who stutter differ from control speakers in the way they process information at the stage of motor plan assembly or the stage of muscle command preparation/execution. In light of the first assumption (group differences at the stage of motor plan assembly) a group by word size interaction effect was expected for choice reaction times in word naming, as well as in symbol naming. These interactions, however, were not found, despite clear main effects of word size in both the word-naming and picture-naming task. In fact, there was not even a general group effect in both naming tasks. A recognition task to test the ability of building and retrieving memory representations for the symbol-word combinations also revealed no group differences or group by word size interactions.

Data that could have supported the second assumption (group differences at the stage of muscle command preparation/execution) showed mixed results. For the interlip interval there were no group effects or group by word size interaction effects. For IEMG peak latency, people who stutter showed, in general, longer delays compared to the matched control speakers. However, this effect seemed independent of word size effects, as shown most clearly in the word-naming task.

Group differences in word durations were not significant, although for word naming there was a statistical trend ($p < .10$) showing longer word durations for the persons who stutter. Word size had no influence on the size of the group effect. These findings and others will be discussed in more detail as regards their significance in providing positive or negative evidence for the assumptions that were mentioned at the end of the Introduction.

1. Do persons who stutter have problems in assembling abstract motor plans?

Group differences in speech reaction times. In this study it was expected that if persons who stutter need more time to assemble a motor plan, this should be most evident for the longer words, since they contain more syllables and thus put time demands on the phonological syllabification and syllabary retrieval processes (Levelt, 1989; Levelt & Wheeldon, 1994). Word size indeed affected naming latencies in word naming and symbol naming, but not in a simple linear way, which is in line with findings of other studies (cf. Klapp & Wyatt, 1976; Sternberg et al., 1978; Van Lieshout et al., 1996). Although there was always a clear difference in reaction time between monosyllabic and bisyllabic words, adding an extra syllable to a word that already has more than one syllable did not automatically increase choice reaction time. One way of explaining this observation is by assuming that for words with more than two syllables, the subjects could choose to start executing these first two syllables, whereas the remaining syllables are processed in parallel at earlier stages. Klapp & Wyatt (1976) already mentioned this possibility and, more recently, Verwey (1994) discussed this issue in great detail. As indicated by Verwey (1994), a clear indication for such on-line processing is a decrease in reaction time for longer sequences. The data from the present experiment showed examples of this effect, especially in the symbol-naming task. For word naming, the increase in speech reaction time for the four-syllable words, not found in symbol naming, could reflect an effect of reading time (Eviatar & Eran-Zaidel, 1991; Naveh-Benjamin & Ayres, 1986). Furthermore, as mentioned by Verwey (1994), practice could enhance this on-line processing, and the subjects in the present study had ample practice on only four different words for each series of tasks.

The most important aspect of this all is the fact that in the present study group differences and word size showed no significant interaction, neither in naming latencies, nor in word durations. Apparently, people who stutter processed the information for longer words in the same way and in the same time scale as control speakers. Thus, the present findings do not support the hypothesis that persons who stutter have a deficit in assembling motor plans (or speech planning), as was claimed by a number of authors (cf. Bosshardt, 1990, 1993; Hubbard & Prins, 1994; Peters et al., 1989; Postma & Kolk, 1993; Wijnen & Boers, 1994).

This replicates the findings of a previous study (Van Lieshout et al., 1996), in which persons who stutter and their matched controls also failed to show a differential effect for word size. However, as already mentioned, especially for picture naming, the size effect in that study seemed too restricted in its demands on motor plan assembling. That is why in the present study word size was varied along a wider range, but even with this manipulation there was no group by word size interaction effect.

A serious limitation in the significance of not finding a group by word size interaction effect may be found in the severity ratings for the stuttering subjects that were used in the present experiment. According to the SSI scores there was only one moderate rating and the other subjects had relatively mild ratings. In the previous study (Van Lieshout et al., 1996), the number of subjects with moderate ratings was higher (5), but, as in the present study, there were no stuttering subjects with high severity SSI-ratings, which might limit the scope of these findings. However, it has to be said that clinical severity scores, like the ones obtained using the SSI, have to be interpreted with much caution as regards their significance toward explaining the absence or presence of group effects in studies like the one presented here. For example, in the SSI physical concomitants in terms of coping and struggling behaviors have a very strong influence on the total outcome of the severity score. In Figure 3 the individual SSI scores for the stuttering subjects used in this experiment are shown for the job task, the reading task, the duration of disfluencies, and the presence of physical concomitants, expressed as a percentage of the maximum score for that part of the SSI. As can be seen, all subjects had relatively low scores on physical concomitants, despite sometimes relatively high scores on frequency of disfluency and duration of disfluencies. Therefore, it is questionable whether SSI scores in terms of stuttering severity allow clear predictions on the possibility of finding group differences in the measures as used in the present experiment (cf. Watson et al., 1992). Despite these objections, the fact that two studies with different stuttering subjects failed to provide evidence in favor of the assumption that people who stutter have problems at the stage of

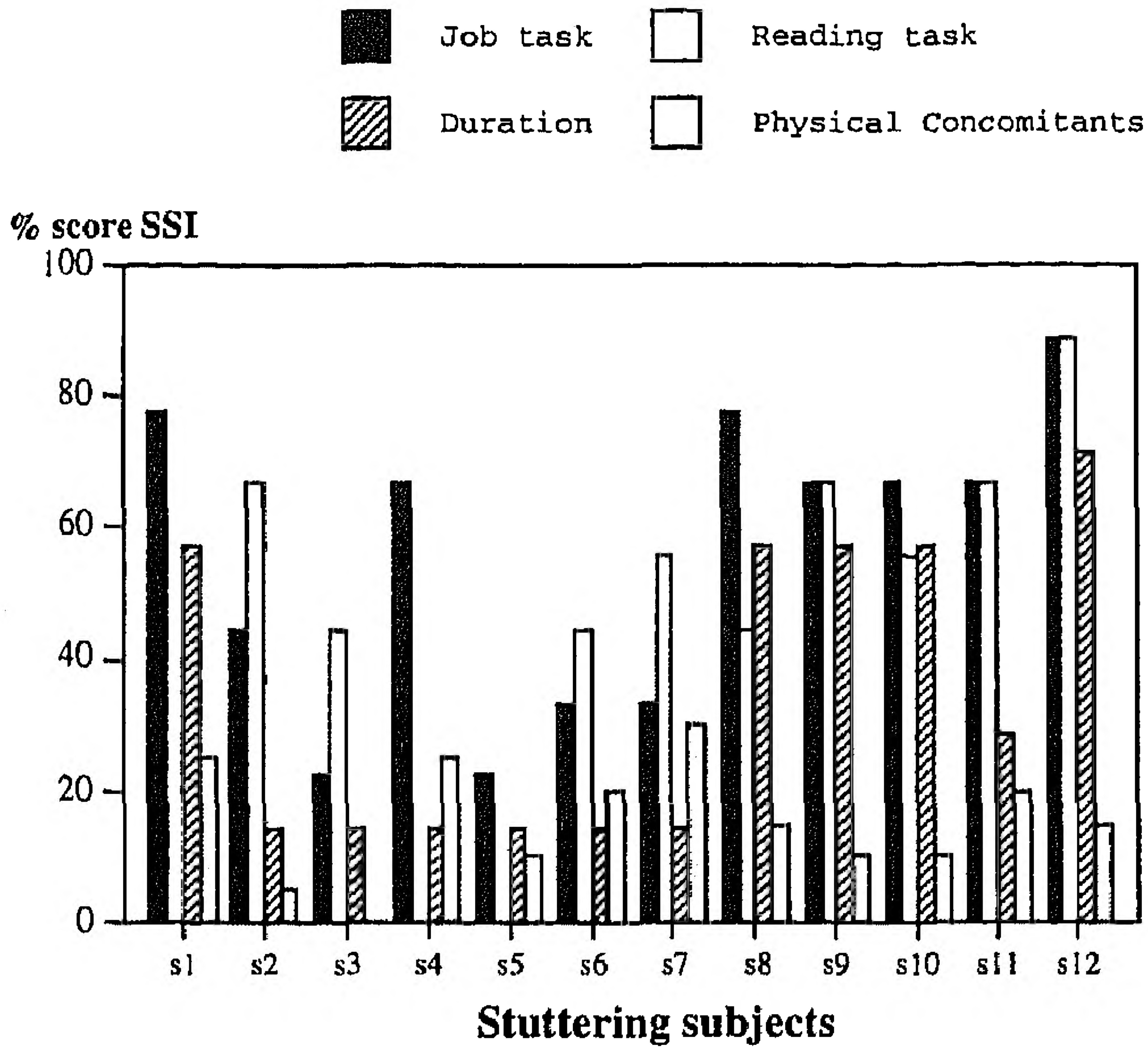

FIGURE 3. SSI subscores in percentage of maximum value for individual persons who stutter. Subjects are ordered from left to right according to their overall severity rating (s1 to s7 = very mild; s8 to s11 = mild; s12 = moderate).

motor plan assembly, either at the phonological or phonetic encoding process, can be taken as a serious threat to the generality of the claim.

Group differences in the recognition of symbol-word combinations. In the recognition task, the subjects had to indicate whether or not a displayed symbol-word combination was previously learned. To be able to do so, they had to learn to build associations between the stimulus (symbol) and the response (word). It has been claimed that persons who stutter have problems in memory encoding and retrieval of linguistic stimuli (Bosshardt, 1993; Carpenter & Sommers, 1987; Moore, 1986; Moore et al., 1982). In the present study, there was no support for this claim. Recognition performance, as measured by the same indices that were used by Bosshardt (1993), did not show that persons who stutter had more problems in recognizing the correct stimulus pairs than control speakers. On the contrary, they even had somewhat higher sensitivity scores, although the group effect was not significant.

The same was found for the manual reaction times. If persons who stutter have more difficulties in the encoding and retrieval of the appropriate associations between a symbol and a word, then it could be expected that they would take or need more time to decide whether or not the displayed combination was one of the four combinations previously learned. However, they did not. One could argue that the symbol-word combinations were perhaps too easy to elicit the potential problems persons who stutter may have in memory encoding and retrieval. However, such an explanation seems unlikely in light of the clear effects of word size on manual reaction time. Indeed, a study by Brennan and Cullinan (1976) showed that "long words as opposed to short words may be more difficult to learn as names [to a symbol] and more difficult to retrieve from storage" (p. 151). Furthermore, the use of abstract line patterns (cf. Nagata, 1986) and low frequency nouns can be expected to increase the load on memory encoding and retrieval.

But, even in the absence of group differences in recognition, it is possible that the combination of memory retrieval and naming, as required in the symbol-naming task, could generate a kind of processing overload situation for the persons who stutter, as can be inferred from the ideas expressed in a number of so-called "interference" theories (Nudelman, Herbrich, Hoyt, & Rosenfield, 1989; Peters & Starkweather, 1990; Webster, 1993). This might show in stronger group differences or even group by word size interaction effects for the symbol-naming task, compared to the word-naming task. The data from the present study do not support this theory. In fact, the group difference in symbol naming was smaller than the group difference found for word naming.

In sum, the data of the present study do not provide evidence that persons who stutter have problems in processing information at the stage of motor plan assembly, as it was called in this study. This also seems in line with the findings of a recent study by Throneburg, Yairi, and Paden (1994), in which stuttering children (with and without accompanying phonological deficits) showed no effect of phonological difficulty on their stuttering frequency.

2. Do persons who stutter have problems in the preparation of muscle commands?

Group differences in the interlip interval. In a previous study (Van Lieshout et al., 1996) a significant group difference in the interval between upper lip and lower lip IEMG onset was found for word and picture naming. The present study showed no such difference. In this respect it is important to note that in the previous study the interlip interval data were based on a mixture of lip-closing and lip-rounding gestures, whereas in the present study, only lip-closing activity was measured. As noted by Gracco (1988, 1994), different articulatory tasks (in his study lip closing and lip opening) may require different ways of coordinating muscle activity due to differences in biomechanical influences on these actions. It seems plausible to assume that if subjects are forced to alternate between two different lip gestures (closing and rounding) from trial to trial, as in the previous experiment (Van Lieshout et al., 1996), they need a certain amount of flexibility in changing muscle command parameters for the two lips that are used to execute the gesture that is required. Recently, it has been suggested that this type of flexibility in motor control may be reduced for (some) people who stutter (Kalveram, 1993; McClean, Levendowski, & Cord, 1994; Van Lieshout et al., 1994). On the other hand, with only one type of lip gesture (the alveolar phonemes do not require lip action), including a pre-specified lip position (open mouth before stimulus onset), as in the present experiment, the demands on flexibility in motor control are probably less (see also Zimmermann & Hanley, 1983), thus diminishing the probability of finding group differences in the relative timing of the onset of muscle activity for upper lip and lower lip.

Group differences in IEMG peak latency. In a recent study (Van Lieshout et al., 1993) it was shown that persons who stutter differed significantly from control speakers in the durations of the interval between IEMG onset and the temporal location of the IEMG peak amplitude. The present study replicated this finding in both naming tasks, although the effect was not significant for the lower lip in word naming. Taken together for both lips and tasks, the amount of variance for the IEMG peak latency variable that is accounted for by group membership is roughly around 25%, which is considerably less than the 48% calculated from the data reported in Van Lieshout et al. (1993). Also, the 95% confidence intervals of the group differences in the present study (taken together, roughly between 6 ms and 40 ms) are clearly smaller in size than the interval for the lower lip found earlier (roughly between 73 ms and 155 ms). This difference is also reflected in the percentage of subjects that would be misclassified as either a stuttering or nonstuttering subject (around 28% in this study vs. 16% in the 1993 study).

Both studies differed in a number of ways, but probably the most important difference[3] can be found in the diversity and complexity of the stimuli that were used. That is, in general, the subjects in the present study had more practice on the same items than the subjects in the 1993 study. So, it seems that with extended practice on a number of words the group difference for IEMG peak latency may become smaller, due to a decrease in the IEMG peak latency interval for stuttering subjects. This finding may be compared to a finding reported by Zimmermann and Hanley (1983), showing that practice "seems to be associated with an increased velocity of the articulators" (p. 39). If practice can decrease the size of the IEMG peak latency interval and, at the same time, increase movement velocities for people who stutter, one could speculate about a possible relationship between the two phenomena.

For single-joint movements Gottlieb, Corcos, and Agarwal (1989) provided data that differences in movement speed or time can be related to differences in the duration of EMG activity. Although their theory remains more or less silent about EMG peak latency (see the comment of Gottlieb et al. in paragraph 1.4h. in their response to open peer commentary), it is clear from some of their examples that differences in movement speed can affect this measure, showing longer peak latencies for slower movements (see Figures 4, 10A, 14, and, for a more schematic illustration, Figure 8A in Gottlieb et al., 1989; see also open peer commentary of Wallace & Weeks, 1989). A similar relationship between IEMG peak latency and movement speed can be found in Gracco (1988, Figure 11) for lip closing. Although these data are based on individual performances, it seems reasonable to assume that if two groups of subjects in general would differ in the speed of, for example, lip closing movements, this could lead to a group difference in IEMG peak latency. Of course, without movement data, this remains somewhat speculative. However, there are kinematic studies that do seem to indicate that people who stutter may move at a slower rate than control speakers in perceptually fluent speech (McClean et al., 1994; Zimmermann, 1980a; but, see Caruso et al., 1988).

Group differences in word duration. If people who stutter would show longer movement durations, this would affect their speech rate too. On the other hand, it has to be noticed that slower speech rates do not entail per definition longer movement durations (cf. Adams, Weismer, & Kent, 1993). With single word utterances, the measure of word duration that was used in the present experiment may serve as an estimate of speech rate. In the experiment described here, people who stutter in general showed slightly longer word durations (33 ms) in both naming tasks than control speakers. The effect, however, was not significant. In a previous study (Van Lieshout et al., 1996), the group effect for word duration was much stronger, although different in size for picture naming (86 ms) and word naming (127 ms). Both tasks in that earlier study differed in the number of different items that had to be named. In the picture-naming task, per subject only four different items were repeated 24 times, whereas in the word-naming task 32 different items were repeated only three times. Clearly, subjects had more practice on each item for the picture-naming task. In the experiment described here, both naming tasks used the same number of items and the same number of repetitions per item and there was no task difference in word duration.[4] Thus, it seems that, similar to IEMG peak latency, group differences in word duration are influenced by practice. As indicated by the data from Zimmermann and Hanley (1983), differences in movement speed for articulation may form the common factor on which these practice effects are based. Of course, if the longer IEMG peak latencies (and word durations) that are shown by the people who stutter, compared to the nonstuttering control speakers, reflect the use of a reduced movement speed, the question remains how this group effect can be explained, or in other words, why would people who stutter move their articulators at a slower rate? Surely, this question cannot be answered within the boundaries of the present experiment, but some hypotheses can be explored briefly.

The first hypothesis suggests that this group difference reflects a timing deficit for people who stutter at the substages of muscle command initiation/execution (cf. MacKay & MacDonald, 1985; Van Riper, 1982). Persons who stutter may have a functional impairment in controlling muscle force over time, which is not the same as a deficit in controlling muscle force alone (cf. Starkweather, 1995). For specific types of (speech) motor disorders Gracco (1991) discussed the possibility that a deficit in scaling muscle actions to a specific speech movement task may relate to a disturbed functioning of the supplementary motor area (SMA). The role of the SMA in stuttering has gained some interest recently (cf. Caruso, 1991; Dembowski & Watson, 1991; Watson et al., 1992; Webster, 1993) and perhaps the data of the present experiment are another (indirect) indication that

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[3] There were also different stuttering subjects in both studies, but since the stuttering severity scores across the studies are based on different methods, there is no clear way to relate stuttering severity to group differences in IEMG peak latency.

[4] Due to the fixed sequence of tasks for a given word set, the practice effect in symbol naming (last task) might have been stronger, compared to word naming (first task), but it seems that after the word-naming task there was no extra benefit from the additional practice given at symbol naming. This might reflect a kind of ceiling effect.

there is an SMA involvement in stuttering. But then, if a timing deficit underlies the delays in IEMG peak latency, it seems reasonable to assume that this would be accompanied by either more (cf. Janssen, Wieneke, & Vaane, 1983) or less (cf. McClean et al., 1994) variable interval durations. In comparing the average coefficient of variation (CV) of IEMG peak latency of persons who stutter and control speakers for upper lip (controls: 21.01%; persons who stutter: 25.1%) and lower lip (controls: 38.4%; persons who stutter: 23.1%), a clear group difference is not observed. Also, if group differences in IEMG peak latency are based on a neuromuscular timing deficit, the practice effect on IEMG peak latency would have to be accounted for as well. For example, as indicated by Ludlow (1991), the effect of practice on the speech output of neurologically based speech disorders may not always be as clear as with stuttering. Next to this "deficit" hypothesis, there is room for another hypothesis to explain why people who stutter might use slower movement speeds, compared to nonstuttering subjects.

In this hypothesis, which is also discussed in earlier publications (Van Lieshout et al., 1993, 1994, 1996), a group difference in movement speed could relate to a group difference in motor control strategy. For example, for single-joint movements Gottlieb et al. (1989) made a distinction between two different control strategies. In one type of strategy subjects want to exert explicit control over movement speed or time, whereas in the other type of strategy movement speed is not a control variable and a mere consequence of task conditions. The details of these strategies and their EMG and kinematic consequences as described by Gottlieb et al. (1989) may be quite different for speech, apart from the implicit suggestion that there is a possible relation between IEMG peak latency and movement time/speed (see above). However, the basic concept, that subjects may choose different ways of specifying muscle commands to perform a certain task, remains an interesting viewpoint, especially in its potential to provide a tentative explanation for why people who stutter may use slower movement speeds than control speakers in perceptually fluent speech. In such an explanation, the slower movement speed is a direct reflection of a control strategy in which people who stutter want to exert explicit control over movement speed in order to avoid situations in which the motor control system might get out of balance (cf. Zimmermann, 1980c). Such a strategy can also be induced by intensive speech treatment as was suggested by the data of a recent study by McClean et al. (1994). In this sense, longer movement durations can be seen as a kind of compensation behavior, but a compensation for what?

There are several possibilities, all of which are still highly speculative and without sufficient empirical support. Generally speaking, one could argue that whenever and for whatever reason people who stutter need more time to complete the processing of information at some stage during speech production, the increase in movement duration can enlarge the time window in which the task can be accomplished without interruption. For example, in terms of motor control, decreases in movement speed may indicate "that the motor control system shifts from a strategy that is predominantly open-loop at fast movement speeds to a strategy that is predominantly closed-looped at slow movement speeds" (Adams et al., 1993, p. 52).[5]

Differences in open-looped versus closed-looped control strategies may relate to motor skill (Van Lieshout et al., 1994; Van Lieshout et al., 1996; see also Neilson, Neilson, & O'Dwyer, 1992). In this view, persons who stutter are at the low end of the motor skill continuum and, in moving at a slower speed, they can put a stronger emphasis on using proprioceptive information to guide their actions. Or, as stated by Neilson (1989):

> A subject highly skilled at a task is likely to plan a fast response, whereas a subject who is unskilled, neurologically impaired, or just wanting to take it easy, is likely to plan a slow response. Adjusting the speed of a response in this way implies a trade-off between control effort and the error between desired and actual reafference signals. (p. 229)

The issue of speech motor skill in stuttering was also addressed in a longitudinal study by Kloth, Janssen, Kraaimaat, and Brutten (1995). In their study, Kloth et al. examined the linguistic and speech motor skills (using acoustic measures) of children at risk for stuttering who had no signs of stuttering at the start of the investigation. The main difference that was found between those children who, one year later, were classified as people who stutter and those who did not, was a higher pre-onset articulatory rate for the stuttering children. The authors concluded that this finding was in line with suggestions from a "Demands and Capacity" approach (cf. Adams, 1990; Starkweather & Gottwald, 1990) that the occurrence of stuttering is related to the fact that for these individuals their speech rate exceeds their speech motor skills. So, although speculative and in need of more empirical support, the data from the present study showing a group difference in IEMG peak latency might suggest that people who stutter move their articulators at a (slightly) slower movement speed in correspondence to a control strategy than seems appropriate within the constraints of a limited (but not necessarily impaired) speech motor skill.

Conclusions

In the present study a tentative answer was sought as regards the significance of various stages in speech production (motor plan assembly and muscle command preparation/execution) to explain differences between people who stutter and matched control speakers. The data that were presented do not show clear evidence that people who stutter in general have problems in assembling motor plans for speech production or in building and retrieving memory representations of symbol-word combinations. With respect to the stage of muscle command preparation/execution, the

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[5] In the study of Adams et al. (1993), slow speech rates (one quarter to half that of conversational speech) were characterized by more asymmetrical velocity profiles and multiple velocity peaks. Clearly, in the present study such strong decreases in movement speed were not found, and neither were the asymmetrical velocity profiles. However, the process of shifting from a more open-looped to a more closed-looped strategy may be a gradual one, with single narrow-peaked and broad multiple-peaked velocity profiles being extremes at each end of the continuum.

data show that people who stutter, compared to matched controls, have delayed IEMG peak latencies. The origin of this group difference is yet unclear and may relate either to deficits in neuromuscular timing or to strategic choices in the control of neuromuscular output, for example, to compensate for a lack of speech motor skill.

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Appendix

Experimental stimuli (including English translation):

WORDS:

1 syl	*2 syl*	*3 syl*	*4 syl*
BIES (piping)	BIETSER (cadger)	BIEFBURGER (beef burger)	BIERCONSUMPTIE (beer consume)
MEET (starting/end point)	MEELDAUW (mildew)	MEESTERKOK (Chief cook)	MEERTRAPSRAKET (multi-stage rocket)
DOOP (baptism)	DOOFPOT (extinguisher)	DOOPLEERLING (catechumen)	DOORKIESSYSTEEM (direct dialing system)
NAAD (seam)	NAARLING (odious person)	NAAICURSUS (sewing-class)	NAAMVALSUITGANG (case ending)

SYMBOLS: