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Effects of Linguistic Correlates of Stuttering on Emg Activity in Nonstuttering Speakers

Pascal H. H. M. van Lieshout
*Nijmegen Institute of Cognition
and Information
and University Hospital, Department
of Voice and Speech Disorders
The Netherlands*

C. Woodruff Starkweather
*Department of
Speech-Hearing-Language
Temple University
Philadelphia, PA*

Wouter Hulstijn
*Nijmegen Institute of Cognition
and Information
and University of Nijmegen
The Netherlands*

Herman F. M. Peters
*University Hospital, Department
of Voice and Speech Disorders
and University of Nijmegen
The Netherlands*

In this study changes in upper lip and lower lip integrated electromyographic (IEMG) amplitude and temporal measures related to linguistic factors known for their influence on stuttering were investigated. Nonstuttering subjects first read and then verbalized sentences of varying length (sentence length factor), in which meaningless but phonologically appropriate character strings were varied in their position within the sentence (word position factor) and their size (word size factor). It was hypothesized that the production of stressed, vowel-rounding gestures of words in initial position, longer words, and words in longer sentences would be characterized by specific changes in IEMG amplitude that would reflect an increase in speech motor demands, intuitively defined as articulatory effort. Basically, the findings corroborated our assumptions, showing that words in sentence initial position have shorter word and vowel durations in combination with an increase in IEMG activity. Similarly, we found shorter vowel durations for longer words, and in sentence final position an increase in IEMG activity. For longer sentences we found a clear increase in speech rate, but contrary to our expectations a decrease in IEMG activity. It was speculated that this might relate to the use of a movement reduction strategy to allow higher speech rates with increased coarticulation. These findings were discussed both for their implications in normal speech production, as well as for their possible implications for explaining stuttering behavior. To this end our data can illustrate both why stutterers might run a higher risk of stuttering at these linguistic loci of stuttering, and why they might come up with a strategic solution to decrease the motor demands in speech production. The basic outcome of this study shows that higher order (linguistic) specifications can have clear effects on speech motor production.

KEY WORDS: speech motor physiology, speech motor control, stuttering, linguistic effects

It is well known that the probability of a particular word's being stuttered is influenced by a number of "linguistic" factors—among others, the position of a word in the sentence (Soderberg, 1967), word size (Soderberg, 1966), and the length of the sentence containing the word (Jayaram, 1984; Tornick & Bloodstein, 1976). These probabilistic effects, known usually as the "distributional patterns of stuttering" or the "loci of stuttering" (see also Starkweather, 1987, for a more extensive review), have been attributed either to psychological processes such as anxiety about stuttering itself (Brutten & Shoemaker, 1967; Van Riper, 1982), perceived difficulty of speech production (Bloodstein, 1987), or more central language production processes (Duckworth, 1988; Wall, 1977; Wall, Starkweather, & Cairns, 1981; Wingate, 1988). The articulatory events that are observed in stuttered speech are thus explained in a rather indirect way, by either higher levels of emotional arousal or anxiety that interfere with neuromuscular control of speech (Bloodstein, 1987; Brutten & Shoemaker, 1967), or by assuming higher demands on cognitive/linguistic processing that interfere with parallel speech execution processes (Peters & Starkweather, 1990; Wail & Meyers, 1984).

Although word size, word position, and sentence length all represent different aspects of the linguistic variability of stuttering, it can also be argued that their effects are based on variations in contrastive stress or, more generally, in the prosodic pattern of speech production (Klouda & Cooper, 1988; Wingate, 1976, 1988). This argument can be made more specific by suggesting that linguistic variables (like word position, word size, and sentence length) are manifested in specific changes in speech motor activity, which in stutterers may "exacerbate pre-existing difficulties in organising motor behaviour" (Duckworth, 1988, p. 67). Or to put it differently, linguistic factors may influence stuttering behavior because they make direct demands on the speech motor system.

Little is known about the motoric effects that accompany word size, word position, and sentence length variations. A study by Slis (1971) showed that for specific phonetic/linguistic contrasts in the Dutch language higher IEMG peak values were found for those conditions that were assumed to require more "articulatory effort." According to Slis (1975), although this concept is

commonly used in the literature, it is not particularly well-defined, and seems to be largely based on intuition. Nevertheless, it may be shown that in a number of linguistic oppositions, allegedly differing in articulatory effort, there are consistent behavioural correlates, both in durational structure and in electromyographic activity. (p. 398)

Along this line of thinking, we assume that words in sentence initial position, longer words, and words in longer sentences require more articulatory effort, which would be shown by an increase in EMG activity for the selected articulatory gesture.

Speech acoustic effects have been described in more detail. Longer words have shorter stressed vowel durations (Klatt, 1973; Umeda, 1975), and words in sentence final position show prepausal lengthening reflected in longer durations of especially final syllables (Klatt, 1976; Umeda, 1975). Finally, longer utterances are characterized by faster speech rates (Malécot, Johnston, & Kizziar, 1972).

To summarize then, the purpose of the present study is to identify changes in speech motor activity that are expected to accompany acoustic changes determined by word position, word size, and sentence length. It is thereby hypothesized that words in sentence initial position, as well as longer words and longer sentences impose higher demands on the speech motor system. According to the findings of Slis (1971) this might be seen in higher levels of EMG activity.

Although our primary interest would be to relate such findings to stuttering, we used only nonstuttering subjects in this study, since several studies in the past have shown that stutterers, even in their perceptually fluent speech, differ from control speakers in amplitude and/or durational aspects of neuromotor input (e.g., Freeman & Ushijima, 1978; Shapiro, 1980; Van Lieshout, Peters, Starkweather, & Hulstijn, 1993). Using only normal speakers, the suspected EMG changes related to linguistic factors cannot be contaminated or masked by variations in the more general speech motor characteristics of stutterers. Of course, this also limits the possibility of extrapolating the significance of

our findings in explaining the linguistic effects on stuttering. Therefore, our discussion of the data will focus first on their relevance for normal speech production. Second, we will sketch a theoretical outline by which our findings in normal speakers and those in stutterers described in other studies could be brought together.

Method

Subjects

Subjects were 12 male, young adult native Dutch speakers (mean age 22.8 years, range 18–31) who responded to an advertisement in a publication at the University of Nijmegen, and screened for a negative history of stuttering or other speech/language disorders. The Dutch language has the advantage that vowel duration is constrained by phonological rules (Nootboom & Slis, 1972), which reduces permissible variability and thus enables the experimental effects on duration to be more visible against a background of variation. All subjects volunteered to participate in the experiment and were paid a standard amount of money per hour.

Design and Procedure

Design. The experiment was set up as a within-subjects design, with word position (sentence initial and sentence final), word size (1 syllable and 3 syllables) and sentence length (4 syllables and 10 syllables) as within-subject factors. For each subject there were 4 acoustic and 13 IEMG measures used as dependent variables.

Stimulus material. The stimuli (listed in Table 1) consisted of 10 target syllables of the form CVC, where C is either /t/ or /k/, and V is any of the three vowels (oo /o:/, eu /ø:/, oe /u:/) or the diphthong ui /oey:/, all defined by a central/back position and lip-rounding in Dutch (Nootboom & Cohen, 1984). Most syllables were meaningless but phonologically appropriate. However, because of the constraints placed upon the stimulus selection, some low frequency nouns had to be included.

The syllables were presented to the subject in a sentence frame, either as a one-syllable word (short word) or as the first syllable of a three-syllable word (long word), put together by adding the letter sequence "-eren" or "-elen" to the target syllable. These endings are standard suffixes in Dutch denoting verbalization and pluralization, respectively. The short and long words were embedded in two types of variable sentence frames, where the word containing the target syllable could be the first (initial position) or the last (final position) element in the sentence. To create a distinction between short and long sentences, the short sentence frames of 3 syllables were lengthened by the addition of one of two types of phrases, each containing 6 syllables (see Table 1). These phrases were placed after, so as to modify, the words "man" (man) or "kind" (child). The "zei/zegt" (says/said) and "man/kind" (man/child) variations, as well as the variation in the type of added sentence frame, were used as foils to keep the subjects from reading the frames in a stereotypical way. Each target syllable was used in the eight

TABLE 1. Experimental stimuli

Syllables	Suffixes	Frame sentences
toet [tu:t] ^a	-eren [-ə [°] rən]	<i>Sentence initial short</i>
teut [tø:t] ^a	-elen [-ələn]	... zegt/zei ^b het kind/de man
toek [tu:k]		... says/said the child/the man
took]to:k]		<i>Sentence initial long</i>
teuk [tø:k]		... zegt/zei het kind/de man met het geel en grijs hemd
kuik [koeyk]		... says/said the child/the man with the yellow and grey shirt
koek [ku:k] ^a		... zegt/zei het kind/de man die ik gisteren zag
køuk [kø:k]		... says/said the child/the man whom I saw yesterday
koet [ku:t]		<i>Sentence final short</i>
keut [kø:t]		De man/het kind zegt/zei ...
		The man/the child says/said ...
		<i>Sentence final long</i>
		De man/het kind met het geel en grijs hemd zegt/zei ...
		The man/the child with the yellow and grey shirt says/said ...
		De man/het kind die/dat ik gisteren zag zegt/zei ...
		The man/the child whom I saw yesterday says/said ...

^aLow frequent Dutch words (koek: 9; toet: 2; teut: 1; koet: 0). Values from Dutch text corpus of 720000 words (Uit den Boogaart, 1975).

^bA "/" denotes the two possible variations that were used.

[°]A "ə" denotes a schwa sound.

combinations that were formed by the word position, word size, and sentence length factors, leading to $10 \times 2 \times 2 \times 2 = 80$ (Syllables \times Word position \times Word size \times Sentence length) trials per subject.

Procedure. The 80 trials per subject were divided into two blocks of 40 trials each. Each block was preceded by one practice trial. The 40 trials per block were presented in a random order. Both blocks were repeated once, but the original blocks were used as primary data, whereas the trials in the repeated blocks were used to replace identical trials in the first section that were marked as errors (hesitations, speech errors, coughing, etc.).

Subjects were seated in front of a TV monitor on which the stimuli were presented in the middle of the screen. The chair in which they were seated was modified so as to allow the attachment of small parts of recording equipment. To the subject's left, at an angle of approximately 90 degrees so that he could not be seen by the subject, sat the experimenter. Stimulus presentation and real time experimental procedures were under the control of a computer. A series of 10 practice trials made it possible to check whether the subject understood the instructions, which were presented on a sheet of paper before the experiment. Emphasis was placed on the part of the instructions in which the subject was urged to speak in a natural way, and to start speaking as soon as the response signal was presented. Since this was not a reaction-time experiment, the latter part of the instructions was given only to prevent too much between- and within-subject onset variations. Before the experiment, the subjects were familiarized with the target syllables so as to avoid hesitations or other speech errors. When the

experimenter was satisfied that the subject understood what was expected of him, the experiment proper began.

Each stimulus was presented after a low frequency acoustic warning signal (100 Hz, 250 msec) for a variable period of time, depending on the length of the stimulus. Long sentences were presented for either 3 (short word) or 3.5 (long word) seconds, whereas short sentences were presented for either 2 (short word) or 2.5 (long word) seconds, to allow for differences in reading time caused by the variations in sentence length. A study by Peters, Hulstijn, and Starkweather (1989) showed that durations in this range provide sufficient time for subjects to read the stimulus on the screen. After this foreperiod, a short, high-frequency acoustic signal (1000 Hz) was presented to the subject. Simultaneously, a visual mark (asterisk) was placed in front of the stimulus on the TV screen. At this moment, the subject started to speak the sentence aloud, as previously instructed. As already mentioned, an emphasis was put on naturalness of speech and not on rapid speech or fast reaction times. Just before the "go" signal the computer program triggered the activation of the recording systems. After 4 seconds of recording, the systems were automatically shut down by the computer program and the subject was informed that the trial had ended by the presentation of a high frequency acoustic signal (500 msec), as well as by the disappearance of the sentence from the screen.

Instrumentation. For this study two signals were used—the speech acoustic signal and the electromyographic (EMG) activity of upper and lower lip. Speech was recorded at a constant mouth-to-microphone distance (25–30 cm) on a high quality tape recorder (Revox A77) using a condenser

microphone (AKG, type 451E). Surface EMG recordings were made of the Orbicularis Oris Inferior (OOI) and Orbicularis Oris Superior (OOS) using miniature silverball IEMG electrodes (San-ei Sokki, Inc.). The small size (diameter = .4 mm) of these spherical electrodes made it possible to attach them with paper-thin flexible surgical tape bilaterally to the upper and lower lip halfway between the median raphé and the corner of the mouth just beneath (upper lip) or above (lower lip) the vermilion border. The use of these electrodes has been shown not to interfere with normal lip movements (Peters et al., 1989). Both the OOI and OOS are considered to be prime movers for lip protrusion or rounding gestures (Boyce, 1990; Fromkin, 1966; McAllister, Lubker, & Carlson, 1974; McClean, 1984). The inter-electrode distance was about 20 mm center-to-center. The preamplified EMG signals were fed into an Elema Schönander amplifier ($g = .06$, LP = 700 Hz) and relayed to a Mingograph inkjet writer for visual inspection of the signals. The amplified signals were filtered and full-wave rectified by means of a low pass, third order Paynter filter, set at a bandwidth of 30 Hz and an averaging interval of 10 msec (Gottlieb & Agarwal, 1970). Subsequently, the signals were fed into a PDP 11/03 laboratory computer, which sampled at a rate of 110 Hz. The same computer was used for the presentation of the stimuli on the screen and the (de)activation of the recording equipment. The speech and integrated (I)EMG signals were also recorded on a 14 channel FM instrumentation recorder (TEAC), with a bandspeed of 2.4 cm/sec (frequency band of DC-625 Hz).

Leads for the four EMG electrodes were brought to a small board attached to the subject's chair at head level. To this board the EMG preamplifiers were attached. A cable was then brought to the Elema amplifiers. A marker, indicating the onset and offset of a trial, was recorded on a separate track of the tape recorder, and also digitized for subsequent temporal alignment of the signals.

Data Analysis

The acoustic signals were digitized (20 kHz) from the Revox tape recordings, together with the marker signal, using a special software package (ILS) for speech signal analysis. The speech signals were presented via a high resolution graphics system for acoustic (waveform) analysis. Using graphical displays of the waveform and interactive listening with earphones (Crystal & House, 1982), the following measures were taken: (a) onset and offset of the acoustic signal for the entire utterance (*sentence duration*), (b) onset and offset of the acoustic signal for the target word (*word duration*), and (c) onset and offset of the periodicity of the acoustic signal as related to the first vowel in the target word (*vowel duration*). An example of a representative trial illustrating the acoustic measures derived from a waveform for a long sentence with the target word in initial position is shown in Figure 1.

In order to account for variations among subjects in speech rate that might have influenced segment durations (Crystal & House, 1982), durations for each measure were adjusted for the subject's overall speech rate relative to the other subjects. This was accomplished by multiplying each

measurement by a rate adjustment factor (RAF), which was the ratio of the mean total duration of all sentences for all subjects and the mean total duration of all sentences for each individual subject. That is, $AD = MD * RAF$ (AD = adjusted duration and MD = measured duration in milliseconds), and $RAF = MTD_n / MTD_i$ (MTD_n = mean total duration of all sentences for all subjects, MTD_i = mean total duration of all sentences for each particular subject). In addition to these acoustic measures, a speech rate measure was calculated for each trial by taking the ratio of the (adjusted) sentence duration to the number of syllables in each sentence, resulting in the *mean syllable duration*.

Digitized rectified and filtered EMG signals for each single trial were displayed on a graphics terminal (Matrox) by computer software. The onset of the target vowel as determined in the acoustical analysis was used as a marker for an algorithm in which, from that point, the onset of IEMG activity for each lip was defined as the first (proceeding backwards) moment at which IEMG activity decreased to an a priori calculated noise level. The noise level was based on the mean IEMG activity of the first 100 msec of the IEMG signal after the "go" signal. If these first 100 msec showed more than just background IEMG activity, the noise level was adjusted by hand. Computer-derived estimates of the IEMG onset latency were always checked visually, and, if necessary, corrected. Thus, the interval between IEMG onset and vowel onset was defined. Using this interval, the following measures, the selection of which was motivated by the results of previous work (Van Lieshout et al., 1993), were automatically derived for upper lip and lower lip IEMG's: (a) duration of the interval (*IEMG duration*), (b) the highest IEMG value within the interval (*IEMG peak*), (c) the difference in time between the IEMG peak and IEMG onset (*IEMG peak latency*), (d) the average IEMG amplitude of the interval, calculated by taking the ratio of the sum of the IEMG activity for the whole interval to the interval duration (*IEMG mean amplitude*), and (e) the IEMG amplitude at the onset of the vowel (*IEMG at vowel onset*). A representative trial showing IEMG signals for upper lip and lower lip, as well as the onset of IEMG activity for a word in sentence initial (A) and sentence final (B) positions, relative to the onset of the target vowel, is shown in Figure 2. In addition to the measures just described, the onset of the upper lip IEMG activity was subtracted from the onset value of the lower lip IEMG, and this *inter-lip interval* was used as a measure for lip coordination (see Hulstijn, Van Lieshout, & Peters, 1991).

Digitized IEMG amplitude values are expressed in 12-bit integer values, denoted here as arbitrary units. Given the within-subject design of this study, no attempt was made to recalculate the integer values into the original raw EMG microvolts, in particular because before the experiment started, gains were set to optimize signal amplitude using a standard gesture (extreme lip rounding) as a reference for each subject. Once determined, the gains for a given subject were not changed during the experiment.

All data were analyzed using a MANOVA method for analyzing repeated measures designs as described in O'Brien and Kaiser (1985). Univariate results for each dependent variable will be presented. Only the data from the two original blocks were used. In case of missing data in

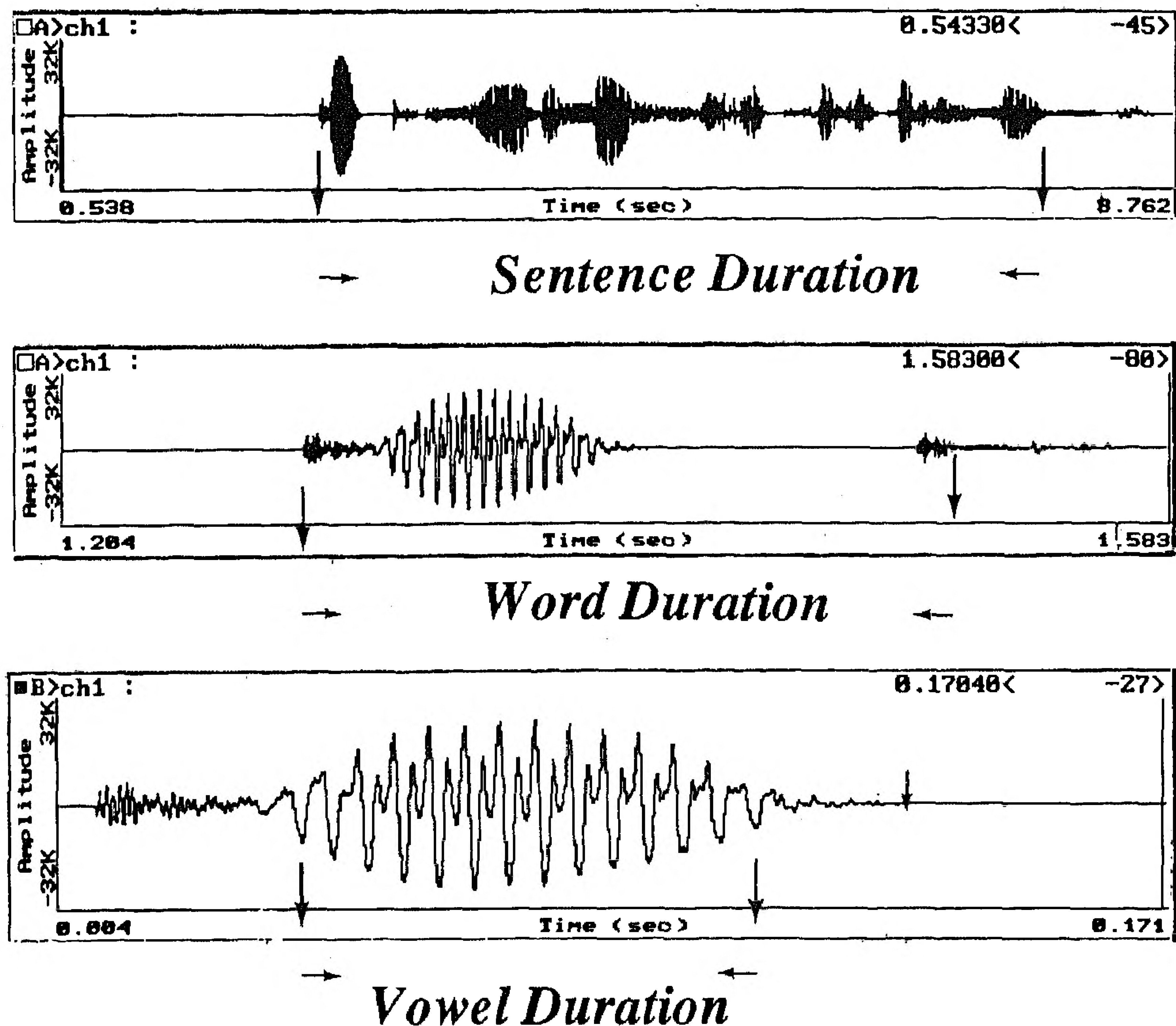


FIGURE 1. Representative example of a trial, showing acoustic waveforms illustrating the measures of utterance duration, word duration, and vowel duration.

these two blocks, the corresponding data from the repetition blocks were used. Before statistical analysis, data were averaged over the 10 target syllables for each level of the within subject factors (word position, word size, and sentence length). A statistical test for significant outliers on these averaged data (Grubbs, 1969) revealed that 7 out of $12 \times 8 \times 17$ (Subjects \times Data points \times Dependent variables) = 1632 data (.4%) had to be replaced by their respective cell means. Analysis of variance revealed no differences between effects for the uncorrected and corrected data set. A significance level of .05 was set for all tests. All tests were performed with $df(1,11)$.

Measurement Reliability

Replicate measurements were made of the entire data set (80 trials) of one randomly chosen subject for both audio and IEMG signals. The audio measurements were made by the second author, who also did the original audio measurements, and the IEMG measurements were made by the first author, who also did the original IEMG measurements. The measurement procedures were identical to the original ones. For the audio signals measurements were made on sentence duration, word duration, and vowel duration. For the IEMG signals measurements were made on the onset of upper lip and lower lip IEMG, since only these two IEMG measures could be influenced by rater judgment, for exam-

ple, in cases where the automatic noise algorithm could not be used. The audio and IEMG replicate measurements were compared to the original measurements. For sentence duration, the mean absolute difference was 19.5 msec (Pearson correlation [r] between original and replicate measurements = .99). For word duration the absolute mean difference was 17.3 msec ($r = .93$). For vowel duration the mean absolute difference was 18.3 msec ($r = .94$). The mean absolute difference for upper lip, lower lip IEMG onset was 3.3 msec ($r = .99$) and 19.1 msec ($r = .99$), respectively. Although there were some absolute differences, most likely related to the time delay between both measurements, the intra-judge agreement scores are well above .90 for all selected measures.

Results

Table 2 shows the means and standard deviations (in parentheses) for the acoustic measures, as well as the difference between the two levels of each factor (in msec) and its significance.

The corresponding data for the IEMG measures are shown in Table 3 for the upper lip and in Table 4 for the lower lip. The data on the inter-lip interval can be found in the text on IEMG effects for word position, word size, and sentence length.

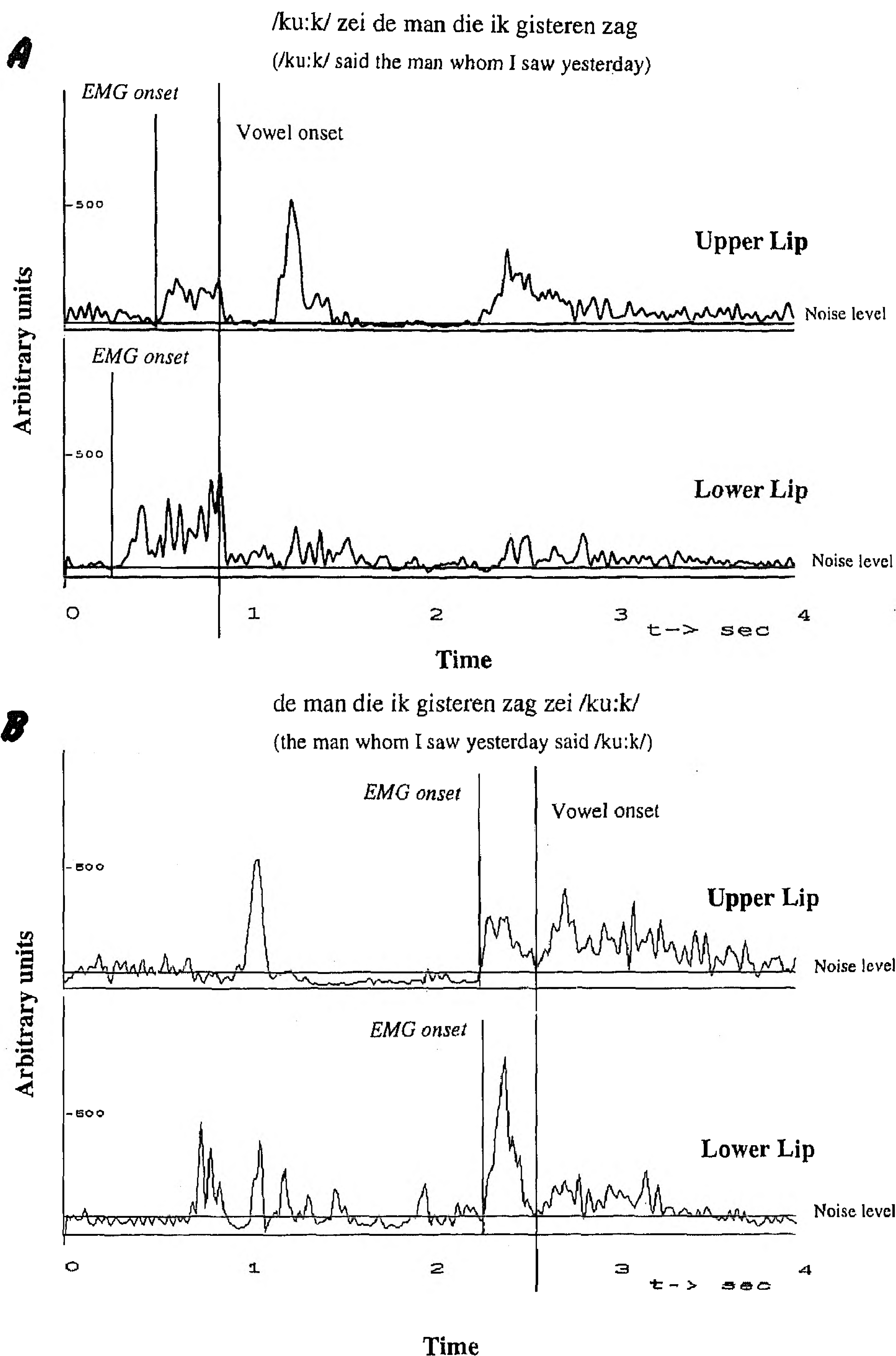


FIGURE 2. Representative example of a trial showing IEMG signals for upper lip and lower lip, as well as the onset of IEMG activity for a lip-rounding gesture for a target word in sentence initial position (A) and sentence final position (B), relative to the time of the acoustic onset of the target vowel.

Main Effects of Word Position

Acoustic effects. As shown in Table 2, words in sentence final position had a significantly longer word and stressed vowel duration, which illustrates most likely the expected prepausal or phrase final lengthening effect (Klatt, 1976). In

addition, sentence durations were found to be longer when the target word was in final position. Subtracting the word durations from the sentence durations, it can be seen that the frame sentences for the target words in sentence initial position have a shorter duration (1196 msec) than the same

TABLE 2. Means (standard deviations) in msec for both levels of the word position, the word size, and the sentence length factor, as well as their difference (Diff) and its significance for the acoustic measures ($N = 12$).

	Sentence initial position	Sentence final position	Word size short	Word size long	Sentence length short	Sentence length long
Utterance duration	1555 (143)	1666 (213)	1491 (157)	1729 (195)	1086 (131)	2134 (216)
Diff		111**		239***		1049***
Word duration	359 (37)	414 (51)	280 (27)	493 (54)	387 (43)	386 (33)
Diff		56**		213***		-1.3
Vowel duration	124 (15)	131 (17)	137 (16)	118 (15)	127 (16)	127 (14)
Diff		7*		-19***		0
Mean syllable duration	201 (19)	218 (22)	223 (22)	196 (19)	222 (23)	197 (18)
Diff		17***		-27***		-25***

$p \leq .10$; * $p \leq .05$; ** $p \leq .01$; *** $p \leq .001$

frame sentences combined with words in sentence final position (1252 msec). It seems then, that the subjects spoke the remainder of the sentence (the frame part) at a faster rate when it followed instead of preceded the target word.

IEMG effects. As shown in Table 3 and 4 the position of a word in a sentence had some clear effects on the IEMG measures. Words in sentence initial position in contrast to words in sentence final position showed higher IEMG peak amplitudes and higher IEMG amplitudes at vowel onset, in combination with longer IEMG durations and longer IEMG peak latencies. Although both lips showed these effects, they were much clearer and (except for IEMG duration) only

significant for the lower lip data. With respect to the interval between the onset of upper and lower lip it was found that in sentence initial position the lower lip preceded the upper lip by 12.8 msec ($SD = 17.5$), whereas in sentence final position both lips were closely synchronized (difference of 1.1 msec [$SD = 15.0$], the upper lip is leading). This position effect was significant [$F(1,11) = 6.11, p < .05$].

Main effects of Word Size

Acoustic effects. Longer words obviously took more speaking time than shorter words, as is shown in the

TABLE 3. Means (standard deviations) in msec or arbitrary units (a.u.) for both levels of the word position, the word size, and the sentence length factor, as well as their difference (Diff) and its significance for the upper lip IEMG measures ($N = 12$).

UPPER LIP	Sentence initial position	Sentence final position	Word size short	Word size long	Sentence length short	Sentence length long
IEMG duration (in msec)	337 (76)	287 (42)	308 (54)	316 (51)	307 (51)	317 (53)
Diff		-50*		8		10
IEMG peak latency (in msec)	186 (56)	163 (31)	174 (45)	176 (36)	176 (42)	174 (39)
Diff		-23#		2		-2
IEMG peak (in a.u.)	308 (167)	290 (151)	297 (157)	301 (139)	296 (146)	302 (152)
Diff		-18		4		6
IEMG mean amplitude (in a.u.)	130 (65)	128 (53)	129 (58)	130 (52)	131 (56)	128 (55)
Diff		-2		1		-3
IEMG at speech onset (in a.u.)	139 (68)	128 (68)	137 (73)	130 (60)	137 (63)	130 (70)
Diff		-11		-7		-7#

$p \leq .10$; * $p \leq .05$; ** $p \leq .01$; *** $p \leq .001$

TABLE 4. Means (and standard deviations) in msec or arbitrary units (a.u.) for both levels of the word position, the word size, and the sentence length factor, as well as their difference (Diff) and its significance for the lower lip IEMG measures ($N = 12$).

LOWER LIP	Sentence initial position	Sentence final position	Word size short	Word size long	Sentence length short	Sentence length long
IEMG duration (in msec)	360 (88)	286 (46)	323 (62)	323 (62)	317 (60)	329 (64)
Diff		-74**		0		12#
IEMG peak latency (in msec)	204 (59)	164 (28)	183 (45)	186 (36)	185 (46)	183 (36)
Diff		-40*		3		-2
IEMG peak (in a.u.)	535 (173)	442 (191)	474 (146)	504 (198)	494 (179)	484 (166)
Diff		-93*		30		-10
IEMG mean amplitude (in a.u.)	226 (89)	214 (98)	212 (81)	229 (103)	228 (96)	212 (88)
Diff		-12		17*		-16*
IEMG at speech onset (in a.u.)	264 (145)	214 (127)	237 (133)	241 (138)	247 (142)	231 (129)
Diff		-50**		4		-16

$p \leq .10$; * $p \leq .05$; ** $p \leq .01$; *** $p \leq .001$

significant increase in word duration (Table 2). The increase in duration is not located just in the target word itself, but also in the duration of the frame sentence (sentence duration minus word duration), which is 1211 msec for the short word sentences and 1236 msec for the long word sentences. The decrease in mean syllable duration that was found is therefore not signaling an overall increase in speech rate, but relates to the local effect of adding two unstressed syllables to the target word, including the expected significant decrease (19 msec) in stressed vowel duration (Klatt, 1973; Umeda, 1975).

IEMG effects. Word size effects, regardless of sentence length and word position, are shown in Table 3 and Table 4. Again, as with the position factor, the lower lip effects were stronger than the upper lip effects, but only the increase in the lower lip IEMG mean amplitude for the longer words was found to be significant. Differences in the duration of IEMG activity were not found. With respect to the inter-lip interval it was found that for longer words both lips were closely synchronized (mean interval duration of 2.4 msec [SD = 11.3]), showing a significant difference of 6.9 msec [$F(1,11) = 6.60$, $p < .05$] as compared to the shorter words (mean interval duration 9.3 msec [SD = 16.0]).

Main Effects of Sentence Length

Acoustic effects. The most apparent effect for the sentence length factor, as shown in Table 2, was the faster speech rate for longer sentences, indicated by a significant decrease in mean syllable duration. When expressed in syllables per second (1000/mean syllable duration), the short sentences (on average 4.9 syllables long) were spoken at a rate of 4.5 syl/sec, and the long sentences (on average 10.8

syllables long) were spoken at a rate of 5.1 syl/sec. This can be compared to the differences found by Malécot et al. (1972) for their French data, showing for short utterances (2–5 syllables) an average rate of 5.4 syl/sec, and for long utterances (10–50 syllables) an average rate of 5.9 syl/sec. It seems that, in general, the French-speaking subjects spoke at a somewhat faster rate, but since both experiments are so different, this comparison is of limited value. More significantly, the differences in speaking rate between short and long sentences are strikingly similar for both studies (.6 syl/sec in our study and .5 in the study by Malécot et al.).

Although the effect on speaking rate seems comparable to the effect found with the word size manipulation, it is clear that both effects are based on different sources. As mentioned above while discussing the word size effects, the speech rate effect found for word size had a local source, based on adding two unstressed syllables to a word, for which the most significant influence was seen in the decreased vowel duration. In the sentence length manipulation, however, there was no localized effect on either word or vowel duration. This makes sense, since the target word itself was not changed in size, but within the (frame) sentence we added syllables (all real words). Therefore, only the decrease in mean syllable duration for longer sentences can be interpreted as an overall increase in speech rate.

IEMG effects. The manipulation in sentence length produced only small and insignificant changes in the IEMG measures, except for the lower lip mean IEMG amplitude. Here a significant decrease was seen for the long sentences (Table 4). This general decrease in IEMG amplitude was seen in combination with a trend for a longer lower lip IEMG duration in the long sentence condition.

Interactions

Figure 3 shows word size effects for the lower lip IEMG data, separated for word position. On the X-axis time is plotted backwards from the vowel onset of the target word (time 0), and on the Y-axis IEMG amplitude is indicated in arbitrary units. Illustrated are the lower lip IEMG measures of duration, peak amplitude, and peak latency, as well as the IEMG amplitude at vowel onset. Upper lip data were similar but less clear, as already indicated, and are therefore left out of the figure. Connecting the datapoints produces an impression of an averaged IEMG signal.

The main effect of word position—longer IEMG duration and higher (peak) IEMG amplitude for sentence initial position—is clearly illustrated. It is also shown that word size effects differed for word position. Figure 3 indicates that longer words in sentence final position were initiated with more IEMG activity than short words, but in sentence initial position this was not the case. This observation was supported by significant word position by word size interactions for lower lip IEMG peak [$F(1,11) = 8.79, p < .05$], lower lip mean IEMG amplitude [$F(1,11) = 6.73, p < .05$], and finally for the lower lip IEMG amplitude at vowel onset [$F(1,11) = 5.03, p < .05$]. The means and standard deviations for these measures are shown in Table 5. For the upper lip IEMG data this interaction was found only for IEMG peak amplitude [$F(1,11) = 7.28, p < .05$], the means and standard deviations of which can also be found in Table 5.

In the acoustic data a word position by word size interac-

EMG amplitude (arbitrary units)

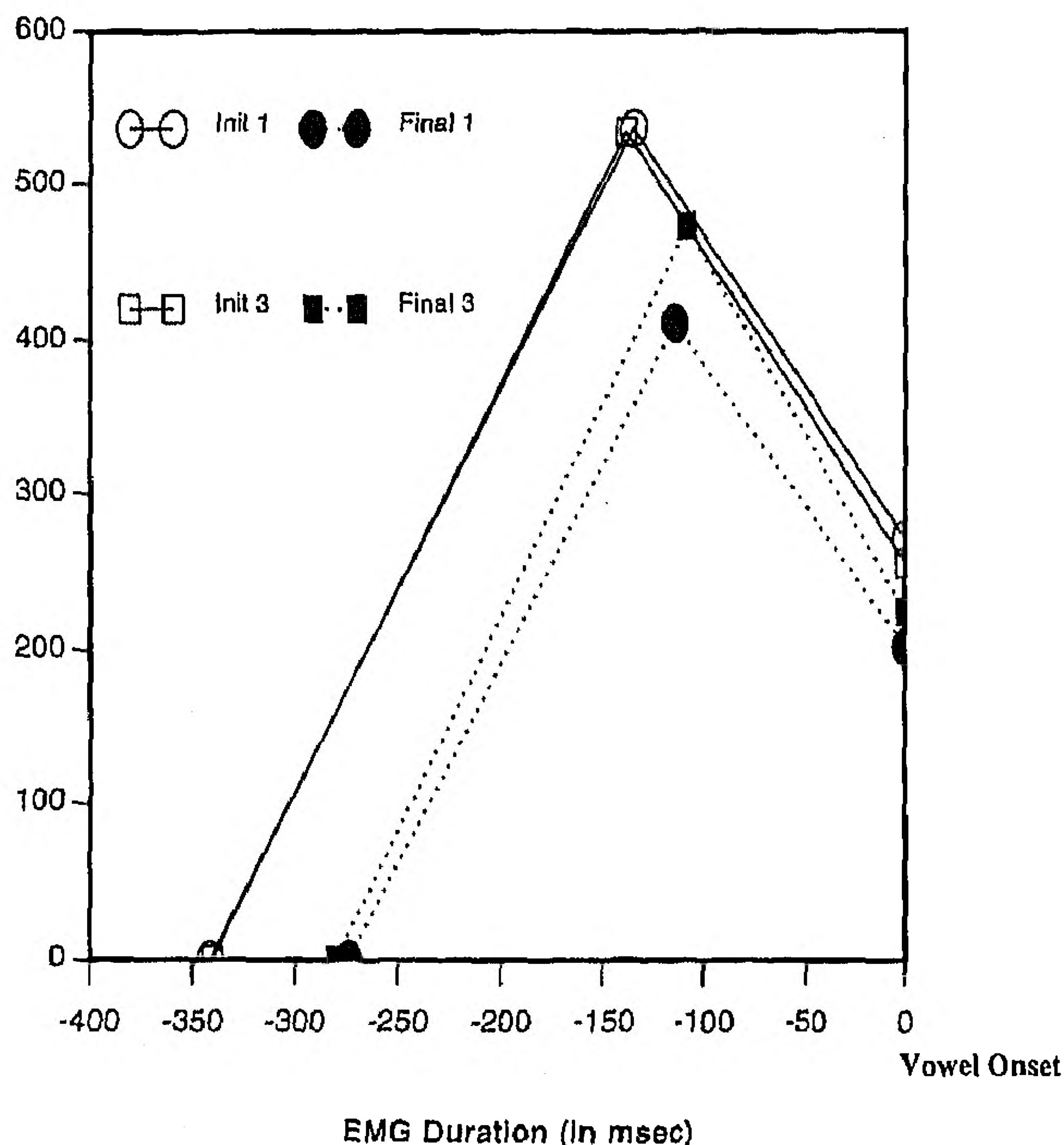


FIGURE 3. Schematic representation of IEMG patterns, showing word size (1 vs. 3 syllable nonwords) effects for lower lip IEMG duration, IEMG peak amplitude, and IEMG peak latency in sentence initial (Init) and sentence final (Final) word position (see text for more details).

tion was found for vowel duration [$F(1,11) = 35.17, p < .001$] and word duration [$F(1,11) = 5.55, p < .05$]. For vowel duration (Table 5) this interaction is based upon a larger difference in vowel duration between short and long words in sentence final position. Apparently, word position only affected the stressed vowel durations in short words and not in long words. Word duration (Table 5) showed a similar discrepancy between short and long words in the magnitude of the word position effect, although in contrast to vowel duration, there was an effect of word position on both short and long word durations. When the vowel and word duration data are combined, it is clear that for longer words phrase final lengthening occurred only in the final parts of the word.

A significant interaction between word position and sentence length was found only for the interlip interval [$F(1,11) = 5.15, p < .05$]. Both short and long sentences showed smaller intervals in sentence final position (i.e., both lips are more closely synchronized in time), but the effect was a bit stronger for the longer words (means [SD]: 10.2 msec [20.0] for short sentences and 15.5 [17.1] for long sentences with the target word in sentence initial position; 1.6 [16.3] for short sentences and 3.8 [15.1] for long sentences with the target word in sentence final position). No other interactions were found to be significant.

Discussion

This discussion will be split in two parts. In the first part we will discuss the implications of our findings for normal speech production. In the second part, the findings will be brought together with data from studies on stuttering to develop a preliminary theoretical outline by which the effects of word position, word size, and sentence length on stuttering behavior could be explained from a speech motor perspective.

Implications for Normal Speech Production

The main goal of the present study was to identify changes in a number of IEMG measures in the amplitude and time domain as related to linguistic factors (word position, word size, and sentence length) that are known for their influence on stuttering behavior. Other studies (see introduction) have shown earlier that these factors have clear acoustic effects. Our results for the acoustic data in general replicated these findings, in that longer sentences were produced with higher speech rates, longer words had shorter stressed vowel durations, and words in sentence final position showed phrase-final lengthening effects in word and vowel durations. However, with respect to this latter finding we also found that for longer words in sentence final position, the lengthening effect was found only for the final parts (unstressed syllables) of the word.

We hypothesized that the above-mentioned acoustic variations would correlate with specific changes in our IEMG measures. More specifically, we expected that words in sentence initial position, longer words, and longer sentences would require more articulatory effort, evidenced by an increase in IEMG activity (Slis, 1971, 1975). Basically, our

TABLE 5. Means (standard deviations) for selected interaction contrasts (see text for more details).

	Short word in sentence initial position	Long word in sentence initial position	Short word in sentence final position	Long word in sentence final position
<i>Lower lip</i>				
IEMG peak	536 (161)	535 (191)	411 (164)	474 (223)
IEMG mean amplitude	223 (81)	230 (98)	200 (86)	227 (112)
IEMG at speech onset	271 (152)	257 (143)	202 (120)	225 (136)
<i>Upper lip</i>				
IEMG peak	318 (178)	299 (156)	277 (152)	302 (153)
<i>Acoustic measures</i>				
Vowel duration	129 (17)	119 (14)	145 (19)	117 (18)
Word duration	244 (31)	474 (48)	316 (45)	513 (71)

findings supported this hypothesis. For words in sentence initial position, regardless of word size and sentence length, we found higher IEMG amplitudes (and longer IEMG durations) for the initiation of lip-rounding gestures. This was especially apparent for the lower lip data. Longer words also showed more lower lip IEMG activity during the initiation of lip-rounding gestures, however only in sentence final position. Only for sentence length the effects contradicted our assumption by showing smaller IEMG amplitudes together with a trend for longer IEMG durations.

For the interlip interval data, it was shown that words in sentence initial position showed a larger interval between the onset of upper and lower lip IEMG activity than words in sentence final position, particularly in the final position of long sentences. Longer words were found to show a smaller lip interval than short words.

The rest of this part of the discussion will consider in more detail the acoustic and IEMG findings for each linguistic factor.

Word position. To start with word position, it has been a kind of common intuition that the "beginning of a speech unit of almost any size is 'harder' than the rest" (p. 340, Jayaram, 1984). Our IEMG findings for lip rounding gestures now seem to provide a rationale for this intuition, suggesting that movements at the onset of an utterance are made with more articulatory effort. Since there was also a small but significant shorter vowel duration in sentence initial position, it may be that the increase in EMG activity reflects the use of higher movement velocities (see Lindblom, 1983, for a discussion on this topic).

Why are movements at this sentence position made with more articulatory effort? A few suggestions that have been brought forward in earlier studies might form a useful basis for further research. For example, McAllister et al. (1974) found longer IEMG durations for rounded vowel production

in initial word position, in contrast to noninitial positions (preceded by unstressed VC-). Because the standard deviations of IEMG durations in initial position were also larger, they suggested that the difference might result from a more variable lip position prior to speech onset than during speech production. It seems reasonable to assume that more variable lip positions would require more articulatory effort to synchronize both lips, including faster or more forceful movements to bring both lips in a rounded position in time. In our IEMG data we find some support for the assumptions of McAllister et al. (1974). On average the IEMG durations for initial word position showed larger standard deviations (absolute and relative) as compared to word final positions. Besides, we found a larger interlip interval at the onset of an utterance, which might suggest problems in coordinating both lips closely in time. Of course, with more variable lip positions that would make sense. On the other hand, in our study subjects had enough time to prepare themselves before speaking, and in such a situation we would expect less instead of more variable lip positions. Clearly, without movement data this issue cannot be solved. Perhaps we could look for still another explanation that might account for the increase in articulatory effort at sentence initial position.

Nooteboom (1972) suggested that sentence initial positions are linguistically marked, for which he used the concept of *communicative dominance*. Words in early sentence positions are most likely to be content words (see also Wingate, 1988), and because they often convey new information, they are likely to receive more contrastive stress. More stress is characterized by higher peak amplitudes of the stressed vowels, for example, by making more extended or forceful movements, and thus might entail more articulatory effort (Nooteboom, 1972; see also Klouda & Cooper, 1988, and Wingate, 1976, 1988). This theory, however, as

valid as it may be for normal speech production, seems less plausible when used to explain the word position data of our experiment. We used frame sentences that most likely will have focused the attention of our subjects on the target items, irrespective of their sentence position. In that case, it can be expected that all target words became communicatively dominant and received equal intentional contrastive stress. This was our intention. From our own observations during the experiments and afterwards by listening carefully to the subjects' speech, we did not notice any clear differences in contrastive stress as a function of word position.

In short, then, the IEMG data suggest that vowel rounding gestures for words in sentence initial position are made with more articulatory effort. However, whether this increase in effort is related to more variable lip positions, or to a linguistic strategy to communicate salient information by means of intentional contrastive stress, or even to a totally different factor, is a matter of speculation and open to further inquiry.

Word size. In our study we found an expected decrease in vowel duration, together with higher IEMG amplitudes and a smaller interlip interval in the longer words. As mentioned before, shorter vowel durations could entail faster lip-rounding movements with an increase in EMG activity. The latter was found in our IEMG data for longer words in final sentence position (see Figure 3). However, the effect did not appear in sentence initial position. We can only speculate about the origin of this difference for word position. Perhaps, if movement velocity is already increased at the onset of an utterance, a kind of ceiling effect could occur and an additional increase for longer words would not show in the IEMG signals.

The smaller interlip intervals we found for longer words, irrespective of sentence position, might also indicate the use of higher movement velocities. De Nil and Abbs (1991) found less variability in articulator sequence patterns for lip closing gestures at short movement durations, as compared to long movement durations. Less variability also means better predictability and the possibility of reducing the interval between the lip EMG onsets. Unfortunately, there are no kinematic data available, to our knowledge at least, that could support the assumption that for vowel-rounding gestures in longer words there is really an increase in movement velocity.

Sentence length. For sentence length we found the expected increase in speech rate, which, as already mentioned in the Results section, was strikingly similar to the increase found by Malécot et al. (1972) for a comparable contrast in sentence length. This overall increase in speech rate was found in combination with an unexpected decrease in (lower lip) IEMG activity and a trend for longer IEMG durations. Sentence length did not have a clear effect on either word or vowel durations, so the increase in speech rate was most effective for the frame part of the utterance. The increase in speech rate can be achieved in two ways: either by decreasing the number and length of pauses within (and between) sentences (Crystal & House, 1982), or, as pointed out by Lindblom (1983), by using a movement-reduction strategy to encourage coarticulation. If our subjects would have reduced the movement amplitude while

speaking at faster rates, it could be expected that the IEMG pattern would more or less spread out in time (see also Lindblom, 1983), showing a more or less general decrease in IEMG activity and an increase in IEMG duration. This was found in our data, and we therefore are inclined to think that our subjects indeed reduced the movement amplitudes, and not just decreased the number of pauses. A reduction in movement amplitudes would have made our subjects' speech less clearly articulated. Since the speech rate effect was found primarily for the frame part of the utterance, there was no obvious need for our subjects to be more precise in their articulation.

In conclusion, the data from this study suggest that lip-rounding gestures for vowels in words in initial position and longer words are characterized by an increase in articulatory effort, presumably reflecting either faster and/or more forceful movements. The effect of sentence length was more general and might have induced a strategy by which higher speech rates are realized by reduced movement amplitudes, indicating more coarticulation for the frame part of the longer sentences.

Implications of the Findings for Stuttering

Although people who stutter were not included in this study, we would like to give a very brief and preliminary account of how our findings might relate to some of their speech behaviors. Several studies in the past have shown that people who stutter, as compared to matched controls, show higher IEMG amplitudes (Freeman & Ushijima, 1978; Shapiro, 1980; Van Lieshout et al., 1993), and especially longer IEMG durations (Almé & McAllister, 1987; Guitar, Guitar, Neilson, O'Dwyer, & Andrews, 1988; Hulstijn, Summers, Van Lieshout, & Peters, 1992; Peters et al., 1989; Van Lieshout et al., 1993). Zimmermann (1980) proposed a model in which he claims that whenever "normal ranges are exceeded the afferent nerve impulses generated are presumed to increase the gains of associated brainstem reflex pathways. If excitation reaches a 'threshold' level, oscillation and/or tonic behaviors occur" (p. 130). According to Zimmermann's theory, people who stutter are either at the low end of the threshold continuum or have more variability in their speech motor system. From this perspective we could argue that faced with conditions in which more articulatory effort is required, people who stutter might run the risk of exceeding the critical threshold, at which point the speech motor system could become unstable. So, if people who stutter put more articulatory effort in producing movements in sentence initial position or in longer words, like our normal speakers seem to do, they might run a higher risk of becoming disfluent. This way, linguistic factors could be effective in influencing stuttering behavior because they make direct demands on the speech motor system.

Zimmermann (1980) also suggested that people who stutter could remain below these critical threshold values, by reducing movement velocities and increasing movement durations. These control strategies, however, seem to be typical not just for those who stutter, as our data with normal speakers for sentence length seem to illustrate. To achieve faster speech rates, we suggested that our subjects might

have reduced movement amplitudes, which allows for more coarticulation. As an apparent side effect, the target positions of sounds are no longer achieved (Lindblom, 1983) and speech may become less clear. A study by Peters et al. (1989) showed that when stutterers and nonstutterers were urged to respond as quickly as possible, they "appeared to adopt an unusual way of talking, characterized by less pitch variation and less clear articulation" (p. 674). This impression was supported by an evaluation of speech quality made by perceptual judgments. Clearly, their finding not only seems to illustrate the use of a movement reduction strategy in a situation where speech rate was expected to increase, but also illustrates that people who stutter were just as efficient as controls in using this strategy. The effectiveness of this strategy was also clear, since those who stutter showed a clear decrease, instead of the expected increase in disfluency for the time pressure condition in the experiment of Peters et al. (1989).

A further indication that people who stutter may take advantage of using the movement reduction or "undershoot" strategy, as Lindblom (1983) called it, is provided by a study of Klich and May (1982). They found more centralized formant frequencies for people who stutter as compared to controls, which they thought suggested that "stutterers' fluent vowel production is more restricted temporally and spatially" (p. 369). Also, the results reported by McClean, Goldsmith, & Cerf (1984), Smith (1989), and Smith, Denny, & Wood (1991), which showed that stutterers were not different from nonstutterers in IEMG levels, or even showed lower levels, might relate to the possibility that stutterers have used such a strategy in these experiments. Clearly, people who stutter (like normal speakers) can choose not to use this type of motor control strategy, for example, whenever less clear articulation might interfere with communication purposes. We would predict that whenever in such situations more articulatory effort is required, as in sentence initial position and with longer words or sentences, disfluency will increase. It is the combination of speech rate and accuracy that would bring stutterers to their limits in motor control. As the study by Peters et al. (1989) showed, just asking subjects to increase speech rate will probably not prevent them from using control strategies that are effective in reducing the demands put on the motor system.

General Conclusions

The results of the study described here indicate that linguistic factors that are well known for their influence on stuttering behavior are characterized by specific changes in acoustic and IEMG measures. For word position and word size the nature of these variations suggested an increase in demands on the speech motor system. For sentence length, however, our data suggest that the higher demands can stimulate the use of specific speech motor control strategies that will make it possible to compensate, although not without costs in terms of clarity of articulation. However, for less relevant parts of a sentence this seems hardly a problem. In discussing the implications of these findings for people who stutter, we speculate that the increase in articulatory effort for initial word positions and longer words will bring their speech motor system to some critical point of instability. To avoid that situation, people who stutter might be much more in need of using compensatory motor control strategies, such as movement reduction, to remain fluent. If so, it is in our view important to keep in mind that differences between people who stutter and normal speakers in speech motor characteristics might not reflect a disorder of movement, but rather the effective use of a motor control strategy to prevent stuttering to surface, even to the extent that group differences in the selected measure(s) of interest could disappear. In general, we think that the results of this study imply that higher order (cognitive/linguistic) constraints may have a direct impact on the management of the speech motor control system.

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Contact author: Pascal H.H.M. van Lieshout NICI/KUN, P.O. Box 9104, 6500 HE Nijmegen, The Netherlands.