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# Variations in Articulatory Movement With Changes in Speech Task

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Stephen M. Tasko  
Michael D. McClean  
Western Michigan University,  
Kalamazoo

Studies of normal and disordered articulatory movement often rely on the use of short, simple speech tasks. However, the severity of speech disorders can be observed to vary markedly with task. Understanding task-related variations in articulatory kinematic behavior may allow for an improved understanding of normal and disordered speech motor behavior in varying communication contexts. This study evaluated how orofacial kinematic behavior varies as a function of speaking task in a group of 15 healthy male speakers. The speech tasks included a nonsense phrase with a high frequency of stop consonants, a sentence, an oral reading passage, and a spontaneous monologue. In addition, rate and intensity conditions were varied for the nonsense phrase and sentence. The articulatory positions of the upper lip, lower lip, tongue blade, and mandible were recorded, and measures reflecting (a) average features of individual movements or *strokes* (i.e., peak speed, distance, and duration) and (b) overall spatial variability of the articulators for each task were extracted, derived, and analyzed. Results showed a number of task- and condition-related differences in speech kinematic behavior. The most prominent result from the task comparison was that the nonsense speech task exhibited larger, faster, and longer movement strokes than the other speech tasks. For some articulators (lower lip and tongue), there were task-related differences in spatial variability. Changes in loudness and rate revealed variation in kinematic measures that were often complicated by articulator identity and task type. The results suggest that an expanded range of speech tasks and conditions may aid in the study of normal and disordered speech motor behavior.

**KEY WORDS:** speech movement, kinematics, speaking task, speech motor assessment

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Speech production is a complex process that may be viewed from a number of physical levels, including the acoustic, aerodynamic, neuromuscular, and kinematic domains. The last on this list, the kinematic domain, has received a significant degree of research interest. Presumably, this interest is in part grounded in the fact that the nervous system uses movement to make the vocal tract shape modifications necessary for many critical aerodynamic and acoustic processes to take place. As a result, studies of articulatory movement have addressed a wide range of topics, including the influence of phonetic identity/context on speech movement (Kent & Moll 1972a, 1972b), temporal coordination of multiple articulators (Caruso, Abbs, & Gracco, 1988; Gracco & Abbs, 1986; Westbury, Severson, & Lindstrom, 2000), movement scaling with prosodic changes (Ostry & Munhall, 1985), motor equivalence

(Hughes & Abbs, 1976), and spatiotemporal variability of speech movement sequences (Smith, Goffman, Zelaznik, Ying, & McGillem, 1995). Although this is not an exhaustive list, it does reflect the empirical efforts aimed at resolving some of the major theoretical issues relevant to speech production.

The vast majority of these articulator movement studies have involved the systematic variation of parameters such as speech rate, intensity, or phonetic context while a speaker produces short simple test utterances. More often than not, these test utterances are narrow, in terms of phonetic diversity, and designed to produce alternate opening and closing of the vocal tract (e.g., vowels alternated with stop consonants). The phrases *sapapple* and *Buy Bobby a poppy* are familiar examples (Caruso et al., 1988; Gracco & Abbs, 1986; Smith et al., 1995). The use of restricted speech samples provides a level of experimental control necessary to address many research questions, and it implicitly assumes that these restricted speech tasks represent, to some degree, speech-related movements in general. However, during a typical day, an individual can be involved in a wide variety of speaking tasks that can include conversational exchanges with one or more partners, spontaneous or prepared monologues, and reading aloud written materials. This contrast prompts a simple question: How well do the articulatory kinematics underlying simple speech tasks (that emphasize open/close movements) generalize to other speech tasks that may be considered more representative of day-to-day communication?

At the acoustic level of analysis, Crystal and House (1982, 1988a, 1988b, 1988c) found that segmental durations measured during extended oral reading failed to exhibit many of the well-known speech timing rules that were largely established using citation-style speech tasks. The authors reported that durational measures from their corpus were inconsistent or required qualification for 26 of 39 previously published assertions about the timing features of speech segments (Crystal & House, 1988a). For example, the Crystal and House oral reading corpus did not support many of the rules defining the role of consonantal context on vowel lengthening. On the other hand, one third of the timing regularities in the oral reading corpus agreed with previous claims. For example, vowel categories tend to maintain their relative duration across context and stress. Thus, some rules are robust and resistant to such task-level variation. The acoustic timing studies of Crystal and House clearly demonstrate how cross-task comparisons can serve to enhance the adequacy of speech production descriptors. Studies that have evaluated normal articulatory kinematic behavior beyond the recitation of simple speech tasks are few (Nelson, 1983; Tasko & Westbury,

2002), and we are unaware of any reports that have explicitly compared aspects of speech kinematics across speech tasks with different cognitive, linguistic, and motor demands.

Kinematic variables extracted from a variety of speech tasks may be used to characterize a kinematic performance space for a given speaker or group of speakers. Such a performance space may be used to describe task-based motor transformations. Tasks may be defined broadly, such as reading or monologue, or the task may be defined more narrowly in terms of specific linguistic or phonetic properties. Further, altering production conditions (e.g., changing rate and loudness) across different task types may be useful for evaluating the generalizability of assertions of how transformations are achieved. It has been suggested that speech intensity variation may be viewed as system-wide scaling adjustment (Dromey & Ramig, 1998). Alternatively, the articulatory basis of speech rate change appears to involve a more complex transformation (Adams, Weismer, & Kent, 1993; Dromey & Ramig, 1998; Gay, 1981). Evaluating multiple articulatory systems over multiple speech tasks across different speech conditions would provide a more global view of such speech motor transformations and perhaps contribute to developing more comprehensive models of speech motor behavior. Such a view is supported by Adams et al. (1993), who remarked "that kinematic descriptions that are limited to only one gesture type or one single articulator may be inadequate for characterizing general organizational principles in speech production" (p. 50).

Some theoretical perspectives suggest that speakers invoke global system-level objectives based on principles such as *ease* or *economy of effort* (Nelson, 1983; Lindblom, 1990; Perkell, Zandipour, Matthies, & Lane, 2002). Theories of this type predict that speakers will use a task-dependent strategy with an optimal trade-off between meeting communicative objectives and global performance objectives such as economy of effort. We hold the view that broad, system-level goals due to differing task demands may be revealed by broad measures of speech motor behavior.

The potentially important role that speech task may play in speech motor behavior is further highlighted by evidence from the clinical literature that speech disorders can exhibit task-dependent severity. This sensitivity to speaking task has long been known in persons who stutter, where level of speech fluency can be quite variable for different speaking situations (Van Riper, 1982, p. 204). Some persons who stutter can exhibit high degrees of fluency during a speaking task such as oral reading but show great difficulty engaging in a spontaneous conversational exchange. More recently, there is evidence that communication breakdown can be task

dependent in the dysarthrias associated with cerebellar disease (Kent & Kent, 2000; Kent, Kent, Rosenbek, Vorperian, & Weismer, 1997) and Parkinson's disease (Kempler & Van Lancker, 2002). This has prompted Kent and Kent (2000) to suggest that task-based profiling may be useful for distinguishing forms of dysarthria. These clinical observations suggest that different speaking tasks can serve to stress speakers in different ways. The source of these stressors is likely to involve a complex interplay between cognitive, emotional, linguistic, and motor demands. It has been suggested that internally mediated (i.e., from memory) movement sequences engage neural pathways that are distinct from externally (i.e., visually) mediated movement sequences (Rothwell, 1994). It may be that different speech tasks engage distinct neural pathways, which may serve to highlight or minimize deficits. For example, oral reading most certainly engages vision-related neural pathways as well as structures involved in literacy-based cognitive/linguistic activities. Developing methodologies that exploit different speech tasks may be used to reveal task-related differences in speech motor behavior, thereby assisting in classifying and treating speech disorders.

This study was designed to evaluate normal variation in articulatory kinematic behavior underlying a range of broadly defined speech tasks and conditions. Multiple articulators were included to evaluate for articulator-based interactions with task and condition variation. Speech tasks included the recitation of a nonsense phrase composed of a vowel–stop consonant sequence, recitation of an English sentence, extended oral reading, and spontaneous monologue. The nonsense phrase is phonetically narrow and not unlike tasks often included in speech movement studies. It was included to address the question we originally posed: How well do the articulatory kinematics underlying simple speech tasks (that emphasize open/close movements) generalize to other speech tasks that may be considered more representative of day-to-day communication? This general question was addressed using statistical tests to evaluate the possibility that speakers scale kinematic measures in different ways for the four tasks and to determine whether kinematic measures on one task are associated with the same measures on other tasks. In addition, the phrase- and sentence-level tasks were evaluated under altered rate and loudness conditions to evaluate the hypothesis that task type and articulator might interact with rate- and loudness-based kinematic transformations.

The behavioral and phonetic diversity of the speech tasks used in this study necessitated a methodology that could be applied to any speaking context and reveal what might best be termed “broad” kinematic descriptors of speech. These kinematic descriptors take two

general forms. One set of measures includes well-known kinematic descriptors of individual movement events (i.e., peak speed, distance, and duration). For this study, the movement events from which these measures were extracted were determined using a recently described method for parsing continuous multidimensional movement streams into a sequence of movement strokes (Tasko & Westbury, 2002). This approach reflects the articulatory kinematic behavior of relatively short-lived movement events within the speech task. A second pair of measures was selected that provided an estimate of the size and general shape of the distribution of midsagittal, two-dimensional articulator position over the entire length of the task. Size was quantified using a standard distance measure (magnitude of the variation across the two spatial dimensions). Shape was estimated by determining the percentage of variance accounted for by the principal component of the spatial distribution. This measure, which would range from 50% to 100%, would reflect the “dimensionality” of the data. These two sets of measures provide different views of the same behavior and were included because we expected that they may be differentially sensitive to task and condition variation.

## Method

### Participants

Fifteen adult male speakers ( $M = 24.7$  years,  $SD = 12.5$  years) participated in the study. None of the participants reported or exhibited speech and hearing difficulties.

### Speech Tasks

Four speech tasks were included in this study. (a) The nonsense phrase, /ə bæd dæbə/ (hereafter, BAD), was produced under a variety of rate and loudness conditions (described below). Speakers were instructed to apply equal stress to /bæd/ and the first syllable of /dæbə/. This simple speech task was included because it elicits from the speaker alternate opening and closing of the vocal tract (e.g., vowels alternated with stop consonants), not unlike phrases so often used in speech kinematic studies (e.g., *Buy bobby a poppy* and *sapapple*). (b) The sentence *Combine all the ingredients in a large bowl* (hereafter, SENT) was produced under a variety of rate and loudness conditions. This sentence, which is part of the Texas Instruments–Massachusetts Institute of Technology (TIMIT) database (Lamel, Kassel, & Seneff, 1986), was selected without particular reference to its phonetic content. (c) A shortened version (176 syllables) of the *Hunter* script (hereafter, OR; Crystal & House, 1982) was read aloud at a comfortable rate and loudness. (d) A

spontaneous monologue (hereafter, MON) was given about the participant's job or favorite hobby.

Tasks BAD and SENT were recited under habitual, fast, slow, loud, and soft conditions. The fast and slow rates were produced at self-selected rates that the speaker considered to be twice and half their habitual speaking rate, respectively. The loud and soft conditions were produced at sound pressure levels (SPLs) approximately 6 dB above and 6 dB below habitual SPL, respectively. The experimenter monitored SPL using a VU meter and provided verbal feedback to the speaker. Speakers were allowed time to practice each of the rate and loudness conditions.

Each of the phrase-level stimuli (BAD and SENT, each over the five conditions) was recorded in a single 30-s sweep. However, for some participants the slow production of SENT was often recorded over two sweeps in order to acquire a reasonable number of tokens. The number of tokens acquired per speaker in each condition ranged from 7 to 30 for BAD and from 7 to 18 for SENT. OR and MON were each recorded over two 30-s sweeps. Recording order was the same for all speakers: BAD-habitual, SENT-habitual, BAD-loud, SENT-loud, BAD-soft, SENT-soft, BAD-fast, SENT-fast, BAD-slow, SENT-slow, OR, and MON.

## Data Acquisition and Signal Processing

During the experimental session, the participant was seated in a sound-attenuated room. The participant produced a wide range of speaking activities as acoustic, orofacial kinematic (Carstens AG100 Articulograph; Carstens Medizinelektronik, Lenglern, Germany), and chest wall motion (Respirtrace™; Ambulatory Monitoring, Inc., Ardsley, NY) signals were synchronously acquired. This study only considered the acoustic and orofacial articulator position data. Each of the 30-s recording sweeps was separated by a 1–2-min rest period in which the participant was instructed on the next speech task. The entire experimental session lasted approximately 75 min.

Orofacial articulator motion was recorded using a Carstens AG100 Articulograph. Sensor coils were placed along the midline of the vermilion border of the upper (UL) and lower lips (LL), at the gum line between the mandibular incisors (MAN), and on the midline surface of the tongue, approximately 1 cm from the tip (TB). A sensor was placed on the bridge of the nose (NO) to monitor possible head movement, independent of the helmet, during the experimental session. The UL, LL, and nose sensors were attached to the skin surface using double-sided biomedical tape. The MAN and TB sensors were glued to the oral mucosa using a commercially available surgical adhesive (Isodent). Prior

to recording, each speaker was encouraged to talk to adjust to the presence of the sensors. The motion of all sensors was tracked at a rate of 250 samples/s. The UL, LL, MAN, and TB sensors were digitally low-pass filtered at 8 Hz and the NO sensor was filtered at 3 Hz. To minimize the possible contribution of head movement to the other sensors' positions, head-related motion reflected in the NO sensor was subtracted from motion of the other four sensors.

Following acquisition of the speech records, speakers were recorded performing a jaw occlusion task for about 5 s. The mean NO and MAN position of the jaw occlusion record was used to re-express the UL, LL, MAN, and TB sensors in a Cartesian coordinate system where the ordinate passes through the mean NO and MAN sensor position and the axis origin is mean MAN position obtained during a jaw occlusion task. A method outlined by Westbury, Lindstrom, and McClean (2002) was used to estimate jaw rotation and decouple LL and TB motion from jaw motion.

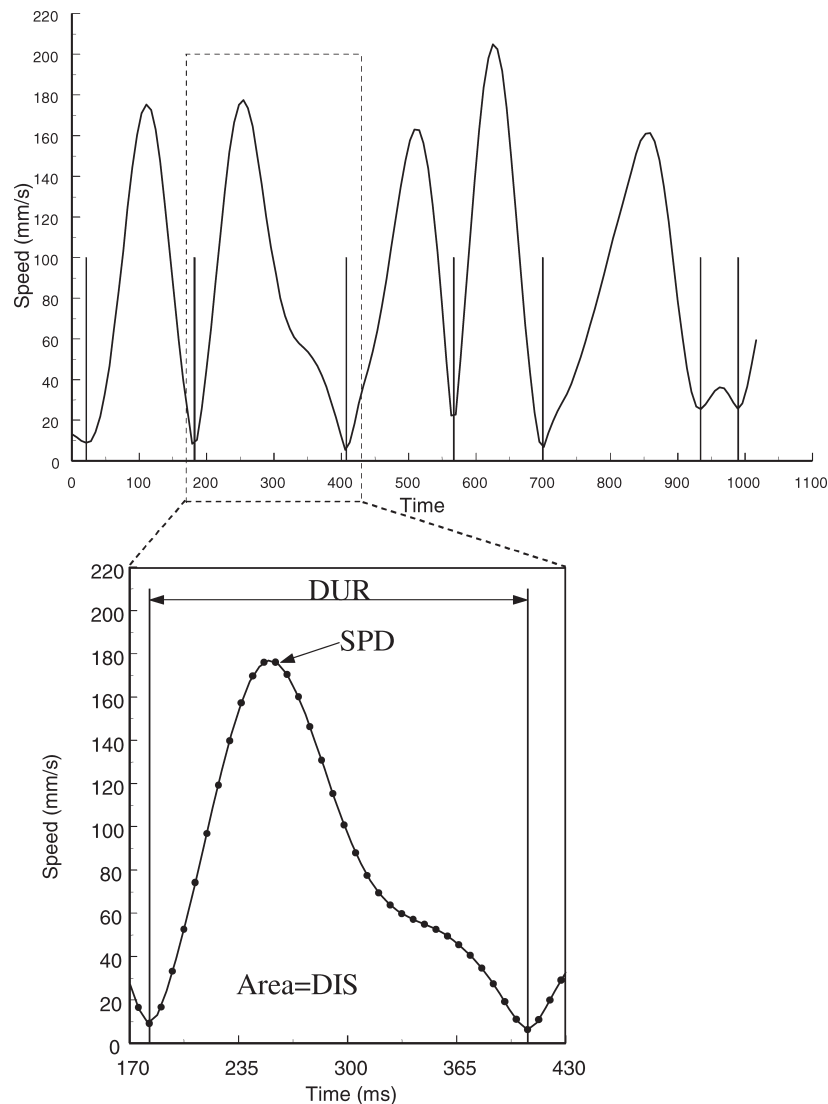
The acoustic waveform was recorded using a Shure M93 microphone positioned 7.5 cm from the participant's mouth and sampled at a rate of 16 KHz. The microphone-amplifier setup was calibrated to an 80-dB, 1-KHz reference tone.

## Data Analysis

### Kinematic Features of Discrete Movement Events

For each sensor, the first order time derivatives of the position history  $[x(t), y(t)]$  were approximated using a three-point central difference method, and movement speed (i.e., the magnitude of the change of position with respect to time, or simply  $[(dx/dt)^2 + (dy/dt)^2]^{1/2}$ ) was calculated. All kinematic analysis was based on the speed history of each sensor. Basing kinematic analysis on the speed history is advantageous because speed is a measure that is invariant to differences in the chosen reference axis (Tasko & Westbury, 2002). The upper panel of Figure 1 shows a 1-s sample of a tongue blade speed history. This plot is typical of speech movements in general. For a given speech task, each articulator exhibits a speed history with an alternating pattern of peaks and troughs. We used a method described by Tasko and Westbury for parsing each articulator's speed history into a series of discrete movements or *strokes*. This simple method identifies a stroke as the period bounded by two successive minima in the speed history. Minima correspond to the moment of sign change in the first time derivative of the speed history. Thus, a stroke is operationally defined as a single period of acceleration and deceleration. In the upper panel of Figure 1, vertical lines identify the onset/offset of successive strokes.

**Figure 1.** The upper panel plots the TB speed history for approximately 1 s of connected speech. The signal has been parsed at local magnitude minima in the speed history in order to define individual movement strokes. The lower panel is an expansion of the speed history of an individual movement stroke. The following kinematic measures have been labeled: peak stroke speed (SPD), stroke distance (DIS), and stroke duration (DUR).



Once identified, each stroke may be characterized using any number of kinematic descriptors. Three kinematic descriptors were derived. Stroke duration (DUR) is the period between stroke onset and offset. Peak stroke speed (SPD) is the maximum speed value between stroke onset and offset. Stroke distance (DIS) is the distance traveled between stroke onset and offset and was calculated by deriving the speed history's time integral over the duration of the stroke. The lower panel of Figure 1 shows a labeled speed history for an individual stroke.

For the nonsense phrase BAD, only those vocal tract opening and closing movement strokes associated with /b/ and /d/ were included in the analysis. Open/close

movements were identified as strokes that (a) were temporally adjacent to the acoustically defined /b/ and /d/ and (b) exhibited a spatial trajectory consistent with opening or closing. For the initial /b/ production, both closing- and opening-related movements of the UL, LL, and MAN were extracted. For the second /b/, only the closing-related movements of UL, LL, and MAN were used because it was often difficult to reliably identify opening movements, presumably due to its location within the utterance. For the /d/ production, closing- and opening-related movements of TB and MAN were identified. For the SENT, OR, and MON tasks, no attempt was made to label the strokes, phonetically or

otherwise. Instead, the analysis for these tasks included all speech-related strokes. To avoid including kinematic events that are not primary to speech production, we excluded from analysis strokes that occurred during speech pauses longer than 250 ms.

It is known that the distribution of the kinematic features of these strokes is not normal (Tasko & Westbury, 2002). As a result, the median served as the central tendency measure for statistical analysis. For each Task × Speaker × Articulator combination (12 tasks × 15 speakers × 4 articulators), a unique number of strokes was identified. The actual number of strokes for a given combination was a function of the number of tokens recorded per task and the number of strokes identified within a token and/or across the task. Table 1 summarizes the range of observation numbers for each task and articulator. Therefore, the median for each Task × Speaker × articulator combination was based on an unequal number of observations. The observation numbers, which are summarized in Table 1, served as weights for subsequent statistical analysis (described below).

### Spatial Variation of Speech Tasks and Conditions

During each speech task, each of the four sensors produces a two-dimensional distribution of its spatial position. Spatial variability was quantified in two ways. First, the absolute variation from the mean ( $x, y$ ) position was quantified using standard distance. Standard distance, or  $[\sum S_x^2 + \sum S_y^2]^{1/2}$  is the magnitude of the standard

deviation ( $S_x, S_y$ ) in each of the two spatial dimensions. This measure simply reflects the amount of deviation (in millimeters) from the mean position without regard for the shape of the scatter. As with speed, standard distance (SDIS) is an attractive measure because it is independent of the chosen coordinate system. Second, the spatial distribution of positions was realigned so that the coordinate axes reflect the first and second principal components of the data variance (calculated using the data's covariance matrix). Figure 2 plots the tongue blade trajectory associated with the speed history in Figure 1. The heavy black lines in the plot represent the new coordinate axes based on the principal components analysis. The proportion of variance (VAR) accounted by the first principal component provides an estimate of the dimensionality of the position cluster. VAR will have a value ranging from 50% (reflecting equal variance accounted by the first and second principal components) to 100% (reflecting all variance accounted by the first principal component). For example, a round spatial distribution will have a smaller VAR than an elliptical spatial distribution. For each task–speaker–articulator combination, SDIS and VAR were calculated.

### Evaluation of Rate and Loudness Changes

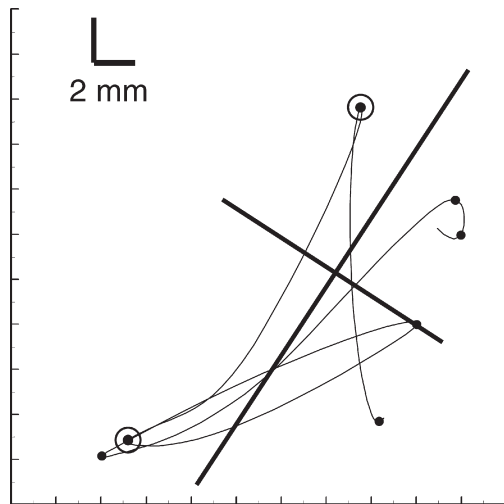
In order to evaluate the effect of the rate and loudness conditions on the speakers' productions of BAD and SENT, change in syllable rate and SPL was determined for the rate and loudness conditions respectively. For

**Table 1.** Mean and range of strokes observed for each of the speech task conditions and articulators. These values were used to assign weights within the analysis of variance (ANOVA) models to account for differences in measurement precision.

Speech task	Articulator							
	UL		LL		MAN		TB	
	M	Range	M	Range	M	Range	M	Range
MON	425	301–592	437	365–598	412	323–564	431	359–562
OR	373	288–457	361	311–429	335	281–385	358	304–443
SENT-habitual	185	144–236	175	141–223	163	139–196	172	133–204
SENT-loud	196	157–266	185	139–244	174	133–205	184	150–236
SENT-soft	191	144–238	178	142–209	167	127–192	173	141–203
SENT-fast	190	135–243	189	139–241	178	123–225	180	120–226
SENT-slow	345	184–519	322	190–459	278	155–383	302	173–394
BAD-habitual	52	39–66	52	39–66	85	63–107	36	26–54
BAD-loud	56	36–78	56	36–78	91	55–130	38	24–54
BAD-soft	51	21–69	51	21–69	83	31–113	35	14–54
BAD-fast	66	42–87	66	42–87	106	62–145	45	28–63
BAD-slow	39	30–54	39	30–54	63	49–90	27	20–36

Note. UL = upper lip; LL = lower lip; MAN = the gum line between the mandibular incisors; TB = the midline surface of the tongue, approximately 1 cm from the tip. See text for explanation of the speech tasks.

**Figure 2.** A plot of the two-dimensional TB trajectory corresponding to the speed history in Figure 1. The heavy lines represent a coordinate system based on the first two principal components. This was used to determine VAR, which is the percentage of variance accounted for by the first principal component.



the habitual, slow, and fast rate conditions, the syllable rate was derived from the acoustically determined utterance duration of each replicate using TF32 (Milenkovic, 2002) software. Change in speaking rate was expressed as a percentage increase/decrease in syllable rate (syllables/second) relative to the habitual rate. The SPL for the (acoustic) duration of each token was derived using a custom written MATLAB (The Mathworks, Inc., 1999) routine that rectified and digitally low-pass filtered the acoustic signal at 10 Hz. Mean SPL was extracted for each token and then an average was taken across all tokens in each condition. These averages were used to determine the decibel change in mean SPL for loud and soft conditions relative to habitual loudness.

### Statistical Analyses

A total of 15 repeated-measures analyses of variance (ANOVAs) were used to evaluate the effects of the speech tasks and conditions on the five dependent variables. The speech task data (BAD, SENT, OR, and MON) were analyzed separately from the rate and loudness condition data (BAD and SENT only). The degrees of freedom were adjusted to avoid violations of the sphericity assumption of repeated-measures ANOVA. A conservative approach was applied that involved dividing the degrees of freedom in the numerator and denominator of the  $F$  test by the number of levels within the factor minus one (Howell, 2002).  $P$  values were adjusted (for ANOVAs and post hoc paired  $t$  tests) to maintain an experimentwise Type I error rate of less than 5%.

For SPD, DIS, and DUR, weights were used in the ANOVA models to account for difference in the number of observations on which median values were derived. Simple correlation was used to evaluate the association of measures across different tasks and conditions.

## Results

### Group Comparisons: Habitual Rate and Loudness Speech Tasks

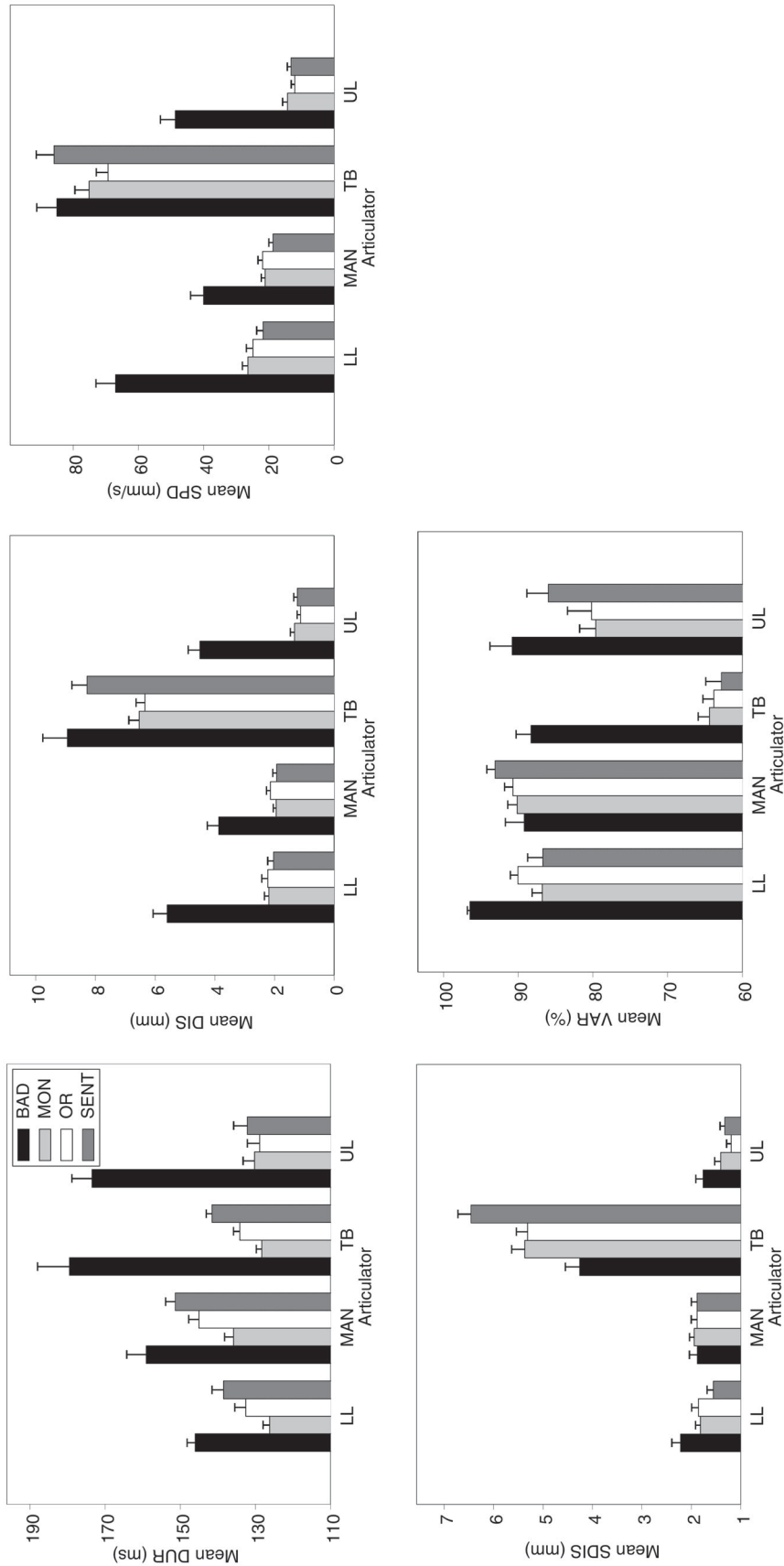
Figure 3 plots bar charts for each of the five dependent variables, broken out by task and articulator identity. There are two prominent features in the data presented in Figure 3. First, for many of the measures and articulators, the BAD task is clearly distinguished from the other tasks. Second, for many of the articulators and measures, the SENT, OR, and MON tasks appear quite similar.

The five dependent measures were submitted to separate repeated-measures ANOVAs where speech task (MN, OR, SENT, and BAD) and articulator type (UL, LL, MAN, and TB) were treated as factors. The top of Table 2 includes the  $F$  ratios and degrees of freedom (original and adjusted) associated with each of the five ANOVAs performed. First, note the large, significant  $F$  ratios for the articulator main effect in this analysis and in the rate and loudness variation analyses (described in the next section). These effects reflect the articulators' different kinematic operating ranges and are not discussed in this article. Our main reason for including articulator as a factor is to explore potential interactions between tasks and articulator.

The speech task main effect was significant for all kinematic measures except SDIS. Post hoc comparisons of individual tasks were made using paired  $t$  tests with a  $p$  value adjusted for multiple comparisons ( $p < .0005$ ). For SPD, DIS, DUR, and VAR, BAD was found to have significantly larger mean values than MON, OR, and SENT. For SPD, DIS, and VAR, no other post hoc comparisons were significant. For DUR, SENT had significantly larger mean values than MON.

Task  $\times$  Articulator interactions were significant for only SDIS and VAR. Figure 3 reveals these interactions clearly. For VAR, it is clear that the results of the main effect comparisons (i.e., that BAD differed from the other tasks) were largely driven by TB variation. TB exhibited much higher VAR values for BAD relative to the other tasks. Post hoc comparisons ( $p < .00014$ ) of individual tasks, broken out by articulator, revealed that for TB, VAR for BAD was significantly larger than SENT, OR, and MON. For LL, VAR for BAD was significantly larger than OR and MON, but not SENT. These results indicate that the phonetic context of BAD

**Figure 3.** Bar plots showing the group mean and standard error for each of the four articulators across the four habitual rate and loudness speech tasks. Each panel corresponds to each of the five dependent measures.



**Table 2.** ANOVA results for habitual rate and loudness tasks and the rate and loudness variation tasks.

	df	df (adjusted)	F ratio				
			SPD	DIS	DUR	SDIS	VAR
Habitual rate & loudness							
Task	3	1	43.42*	25.94*	32.17*	4.77	33.10*
Error (task)	42	14					
Art.	3	1	159.15*	113.63*	6.01	185.86*	48.99*
Error (art.)	42	14					
Task × Art.	9	1	12.31	4.83	2.80	44.48*	14.59*
Error (Task × Art.)	126	14					
Rate variation							
Task	1	1	144.72*	128.52*	177.80*	24.62*	64.14*
Error (task)	14	14					
Rate	2	1	121.12*	76.56*	54.74*	6.05	0.25
Error (rate)	28	14					
Art.	3	1	105.88*	115.01*	11.49	135.26*	28.72*
Error (art.)	42	14					
Task × Rate	2	1	4.01	14.91*	63.18*	1.67	1.67
Error (Task × Rate)	28	14					
Task × Art.	3	1	22.35*	11.43	13.77*	169.15*	59.53*
Error (Task × Art.)	42	14					
Rate × Art.	6	1	32.20*	29.34*	19.78*	5.99	1.26
Error (Rate × Art.)	84	14					
Task × Rate × Art.	6	1	7.88	1.98	11.03	1.82	1.60
Error (Task × Rate × Art.)	84	14					
Loudness variation							
Task	1	1	162.76*	158.00*	84.21*	14.83*	77.69*
Error (task)	14	14					
Loudness	2	1	60.31*	50.24*	0.68	58.46*	1.34
Error (loudness)	28	14					
Art.	3	1	107.30*	115.32*	4.09	138.29*	21.45*
Error (art.)	42	14					
Task × Loud	2	1	23.61*	16.99*	1.47	1.77	2.91
Error (Task × Rate)	28	14					
Task × Art.	3	1	20.68*	10.08	12.67*	139.37*	47.58*
Error (Task × Art.)	42	14					
Loud × Art.	6	1	13.26*	9.77	1.89	12.35	1.92
Error (Loud × Art.)	84	14					
Task × Loud × Art.	6	1	9.11	7.16	0.64	3.65	0.60
Error (Task × Loud × Art.)	84	14					

Note. SPD = the peak speed within each stroke; DIS = the distance moved within a stroke; DUR = the duration of each stroke; SDIS = standard distance; VAR = the proportion of variance; art. = articulator.

\* $p < .0033$ .

results in TB and LL have a more unidimensional movement trajectory than the other tasks.

For the variable SDIS, post hoc comparisons revealed that TB exhibited significantly larger SDIS values for SENT when compared to the other three tasks. Additionally, TB demonstrated significantly smaller SDIS values for BAD relative to OR. Post hoc comparisons also revealed that for UL, BAD was significantly larger than OR and that for LL, BAD was significantly larger than SENT.

It could be argued that the task-related DUR variations observed in Figure 3 simply reflect speech rate differences across the tasks. This prompted a simple comparison between acoustically derived syllable rates for BAD, SENT, and OR. If speech rate is the underlying cause of the DUR patterns, a substantially slowed speech rate for BAD relative to the other tasks would be predicted. Mean syllable rates for BAD, SENT, and OR were found to be 4.7, 5.1, and 4.0 syllables/s, respectively. This syllable rate pattern is not consistent with

the kinematic patterns. A set of paired *t* tests ( $p < .017$ ) revealed that OR was significantly slower than both BAD and SENT and that SENT and BAD did not differ with regard to syllable rate. Thus, the DUR variations did not appear to be simply due to altered speech rate.

To summarize the primary findings of this analysis, (a) there was a general trend for movement strokes associated with the BAD task to be faster, longer, and of greater magnitude than the movement strokes associated with sentence repetition, oral reading, and monologue; (b) TB and LL exhibited more unidimensional spatial variation for the BAD task when compared to the other three tasks; and (c) TB spatial variation (SDIS) was larger for SENT than for other tasks.

### Group Comparisons: Rate and Loudness Variations

The habitual rate and loudness data used in this analysis are the same as those used in the previous analysis. The effect of the instructions to vary rate and loudness are demonstrated in Table 3. For the rate manipulation task, the speaker group slowed syllable rate to 62% and 66% and increased syllable rate to 135% and 137% of their habitual syllable rate for the BAD and SENT tasks, respectively. For the loudness manipulation task, soft speech had mean SPLs of 4.93 dB (BAD) and 4.95 dB (SENT) lower and loud speech had mean SPLs of 6.37 dB (BAD) and 6.71 dB (SENT) higher than the habitual loudness productions. The shaded region of Table 3 includes data evaluating syllable rate variation for the loudness manipulation task and SPL changes for the rate manipulation task. It can be observed that the instruction to vary loudness had minimal effects on syllable rate. However, during the rate manipulation, there was a trend for SPL to systematically vary with speech rate. Slow and fast speech conditions are characterized by a 1–2-dB decrease and increase in SPL, respectively.

### Rate Variation Condition

The kinematic measures were submitted to a series of repeated-measures ANOVAs where articulator type, speech task (SENT and BAD), and rate (fast, habitual, and slow) were treated as factors. The middle of Table 2 includes the degrees of freedom (original and adjusted) and *F* ratios associated with each of the five ANOVAs performed.

The upper three bar charts in Figure 4 plot the results for those kinematic measures (DUR, DIS, and SPD) that exhibited a significant main effect for rate. The upper left plot suggests a trend for DUR to increase as speakers move from fast to habitual rate and from habitual to slow rate. These trends are supported by post hoc paired *t* tests ( $p < .0017$ ) comparing the fast to habitual rate change and the habitual to slow rate change. The effect of rate variation on SPD and DIS appears less systematic than for DUR. Moving from habitual to slow rate, there is a significant decrease in SPD and DIS. However, there is no statistically supported trend in SPD and DIS when speakers moved from habitual to fast rate conditions.

DUR, DIS, and SPD exhibited significant Rate  $\times$  Articulator interactions indicating that the main effects observed for rate were not equivalent across the four articulators. This prompted further exploration using a set of paired *t* tests ( $p < .00041$ ) comparing the effects of rate manipulation for the three measures across the four articulators. For DUR, LL and MAN demonstrated significant differences for both the slow-habitual and fast-habitual comparisons. UL demonstrated a significant difference in DUR for only the slow-habitual comparison. Neither comparison was statistically supported for TB. For DIS, a significant slow-habitual comparison was demonstrated for UL and TB but not for LL and MAN. For SPD, a significant slow-habitual comparison was observed for all articulators except MAN.

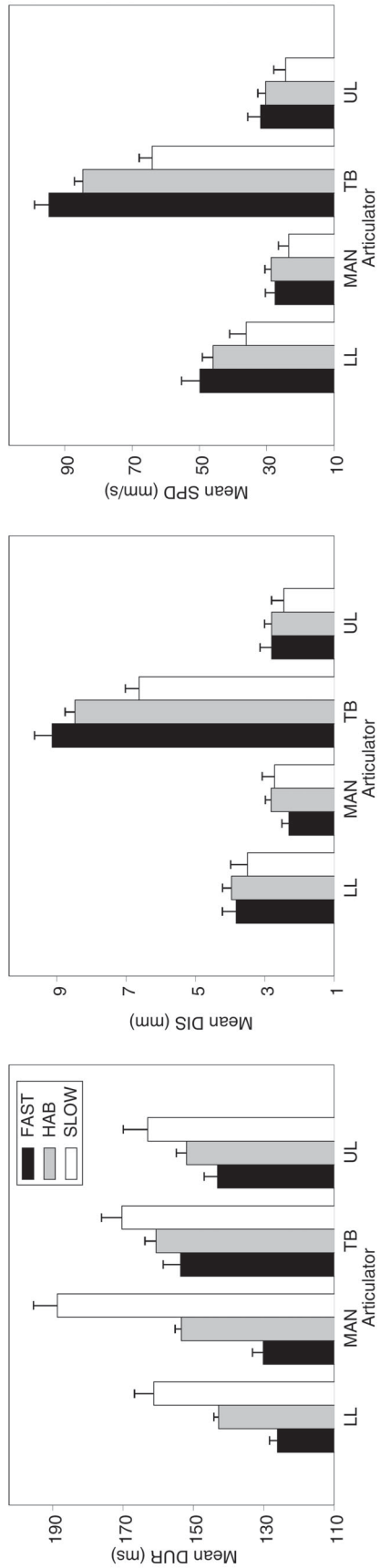
**Table 3.** Effect of rate and intensity manipulation on syllable rate and sound pressure level (SPL).

Task	% habitual rate				dB relative to habitual SPL			
	Slow	Fast	Soft	Loud	Soft	Loud	Slow	Fast
BAD								
M	62	135	104	97	-4.93	6.37	-1.25	1.30
SD	14.9	18.5	7.5	6.0	1.85	1.69	2.39	2.04
SENT								
M	66	137	105	102	-4.95	6.71	-2.05	1.6
SD	17.2	15.2	9.2	6.2	1.72	1.72	1.99	1.20

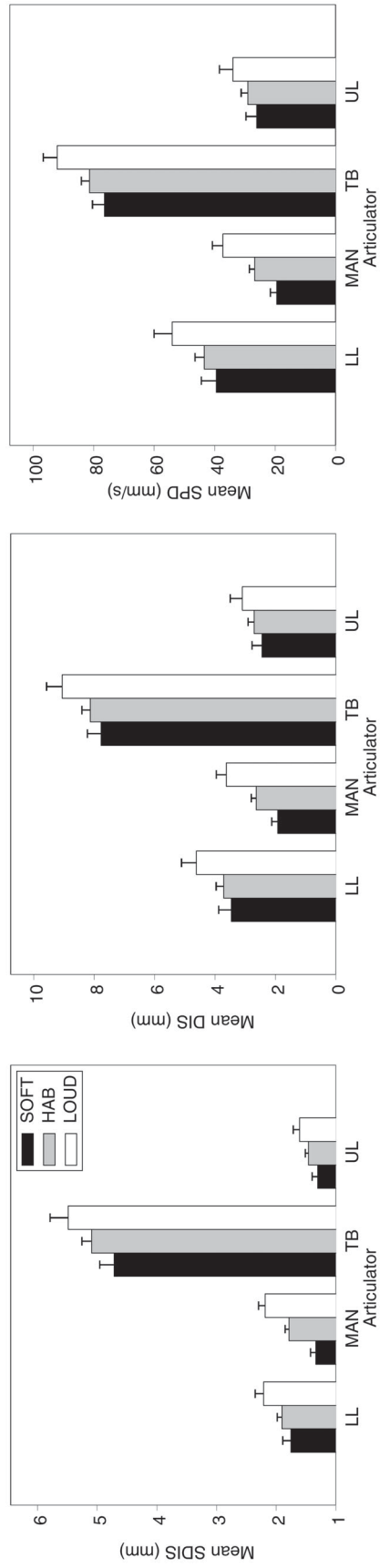
*Note.* Group means and standard deviations are reported. Rate change is represented as a percentage of habitual syllable rate. Intensity change is represented as a decibel change relative to habitual SPL. The shaded cells include data on rate variation for the intensity condition and intensity variation for the rate condition.

**Figure 4.** Bar plots showing the group mean and standard error for each of the four articulators across the speech rate and loudness variations. Only those variables exhibiting statistically significant main effects are shown.

### SPEECH RATE VARIATION



### LOUDNESS VARIATION



Finally, there was a significant Rate  $\times$  Task interaction for DUR and DIS, indicating that rate-related variation in DUR and DIS was influenced by the speech task. Figure 5 plots DUR for each of the two tasks (SENT and BAD). It appears that the rate effect on DUR is more pronounced for BAD than for SENT. For DIS, paired  $t$  tests ( $p < .00055$ ) revealed that BAD demonstrated no significant variation in DIS across the rate conditions, whereas SENT demonstrated significantly smaller strokes for the slow condition as compared to the fast and habitual conditions.

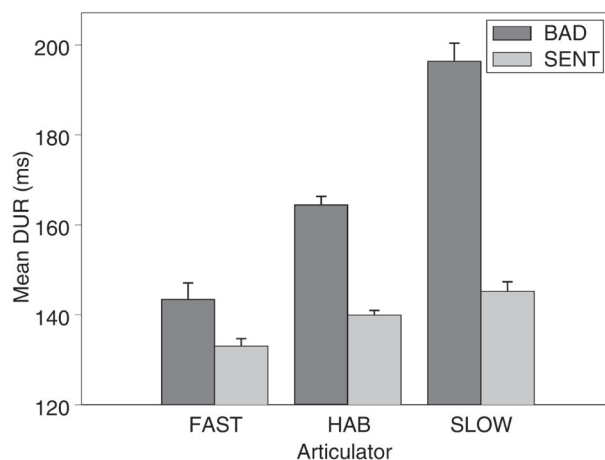
### Loudness Variation Condition

Similar to the rate analysis, the kinematic measures were submitted to a series of repeated-measures ANOVAs where articulator type, speech task (SENT and BAD), and loudness (soft, habitual, and loud) were treated as factors. The bottom of Table 2 includes the results and the lower three bar charts of Figure 4 plot the measures (SPD, DIS, and SDIS) that exhibited statistically significant main effects for loudness. Figure 4 illustrates a trend for a reduction and increase in SPL to be associated with respective reductions and increases in SDIS, DIS, and SPD. These trends were supported by post hoc paired  $t$  tests ( $p < .0017$ ) comparing the soft and habitual condition and the habitual and loud condition. A significant Loudness  $\times$  Articulator interaction was observed only for SPD. Post hoc paired  $t$  tests ( $p < .00041$ ) revealed that the soft-habitual comparison was significant only for MAN and that the habitual-loud comparison was significant for MAN and LL.

Task  $\times$  Loudness interactions were observed for SPD and DIS. Post hoc paired  $t$  tests ( $p < .0017$ ) revealed that for both SPD and DIS, there were larger differences between the loud and soft conditions for BAD as compared to SENT.

To summarize, both rate and loudness changes were accompanied by changes in a range of kinematic parameters. Variation in loudness resulted in commensurate variation in the distance (DIS) and speed (SPD) of speech-related movement strokes and in the size of the spatial variation of the trajectory (SDIS). For SDIS, these observations were consistent across articulator and task. For DIS and SPD, task interacted with loudness such that BAD exhibited larger differences than SENT when shifting from soft to loud speaking conditions. For SPD, articulator identity interacted with loudness such that MAN was the articulator that varied most as speakers shifted from soft to habitual to loud speech. Rate-related transformations tended toward greater complexity, as evidenced by more numerous interactions. Although stroke DUR varied for the different rate conditions, it was not consistent across articulator and task. Rate-related DUR changes appeared to be more pronounced for

**Figure 5.** Bar plot demonstrating the Task  $\times$  Rate interaction for movement stroke duration.



BAD than for SENT. SPD was reduced for slow rates, but did not exhibit increases for fast rates. DIS demonstrated a similar pattern, but only for the SENT task. As with DUR, rate related changes in SPD and DIS varied as a function of articulator, and significant variations were generally observed for all articulators except MAN.

### Correlation Between Kinematic Variables for Habitual Rate and Loudness Speech Tasks

Pearson correlations between the various habitual speech tasks were performed to evaluate for associations between speech tasks. These are summarized in Table 4. Asterisks mark correlations that met a .01 level of significance. This arbitrary criterion was established so that trends across measures, articulators, and conditions could be made. When the correlations are organized by measure, SDIS had the most correlations meeting criteria (21/24), followed by SPD (18/24), DIS (16/24), VAR (4/24), and DUR (3/24). When organized by articulator, LL and MAN had the largest number of correlations that met the criteria (19/30 and 17/30, respectively), followed by UL (15/30) and TB (11/30). When the correlations are organized by task comparisons, the comparisons with the most correlations meeting criteria were BAD-SENT (13/20), SENT-OR (13/20), and MON-OR (13/20), followed by SENT-MON (10/20), BAD-OR (8/20), and BAD-MON (5/20).

### Discussion

This study sought to describe some articulatory kinematic features of healthy participants producing a number of behaviorally and phonetically diverse speaking

**Table 4.** Pearson correlations between the habitual rate and loudness speech tasks.

Measure	Task pair	UL	LL	MAN	TB
		<i>r</i>	<i>r</i>	<i>r</i>	<i>r</i>
SPD	BAD-MON	.60	.66*	.53	.41
	BAD-OR	.63	.76*	.81*	.41
	BAD-SENT	.79*	.77*	.77*	.67*
	SENT-MON	.80*	.77*	.55	.65*
	SENT-OR	.93*	.75*	.83*	.74*
	MON-OR	.75*	.80*	.77*	.85*
DIS	BAD-MON	.52	.66*	.48	.38
	BAD-OR	.59	.76*	.78*	.31
	BAD-SENT	.73*	.78*	.76*	.58
	SENT-MON	.77*	.78*	.53	.63
	SENT-OR	.92*	.76*	.82*	.67*
	MON-OR	.69*	.81*	.69*	.84*
DUR	BAD-MON	.17	.36	.50	.23
	BAD-OR	.45	.30	.17	.30
	BAD-SENT	.38	.20	.23	.44
	SENT-MON	.35	.55	.47	.52
	SENT-OR	.69*	.55	.42	.34
	MON-OR	.40	.88*	.74*	.35
SDIS	BAD-MON	.70*	.77*	.54	.54
	BAD-OR	.72*	.79*	.80*	.73*
	BAD-SENT	.72*	.82*	.64*	.84*
	SENT-MON	.66*	.75*	.70*	.70*
	SENT-OR	.77*	.80*	.87*	.85*
	MON-OR	.62	.86*	.71*	.91*
VAR	BAD-MON	.61	.24	.68*	-.15
	BAD-OR	.51	.40	.29	-.07
	BAD-SENT	.65*	.37	.66*	-.09
	SENT-MON	.39	.12	.66*	.02
	SENT-OR	.52	.30	-.13	.25
	MON-OR	.50	.36	.33	.62

Note. *N* = 15 in all cases.

\**p* < .01.

tasks. The tasks included nonsense phrase recitation in which analysis was focused on stop-related open/close movements (BAD), sentence recitation (SENT), extended oral reading (OR), and spontaneous monologue (MON). In addition, the rate and loudness of the two phrase length tasks (BAD and SENT) were experimentally varied to evaluate for potential interactions between task type and rate/loudness changes. Two broad sets of measures were used. One set of measures (i.e., SPD, DIS, and DUR) was based on the median of a distribution of individual movement events within the task. The second set of measures (SDIS and VAR) was based on the size and shape of the positional distribution for the entire speech task.

## Task-Related Variation

A prominent set of results in this study arose from the comparison between the BAD task and the other three tasks. On average, the movement strokes for the BAD task were larger, faster, and longer than the strokes in the other speech tasks. In addition, some articulators (namely the LL and TB) exhibited BAD-related differences in the size and shape of their spatial variation. These results suggest that the BAD task has articulatory kinematic characteristics quite distinct from the other speech tasks. The primary motivation for including the BAD task is that this task uses a highly constrained vowel–stop consonant–vowel phonetic environment commonly used in speech movement studies (Caruso et al., 1986; Dromey & Ramig, 1998; McClean, 2000) and allows us to address the question of how well movements that occur in this restricted task reflect the broader spectrum of speech-related movement. In absolute terms, at least for the lips and mandible, the BAD task clearly overestimates the size of the movement strokes one might expect to see for the less-contrived speech tasks. That such differences occur is not an entirely surprising finding. The BAD task differs from the other tasks in many ways. Thus, numerous plausible explanations for the kinematic differences exist. Given that BAD is restricted to alternating stops and vowels, it could be reasonably argued that the source of task-related differences is due to a lack of phonetic equivalence across tasks. This account could be tested in future studies that limit movement analysis of the recitation, reading, and monologue tasks to the phonetic contexts that are equivalent to BAD. Because BAD is a somewhat novel nonsense utterance that contains no linguistic meaning, speakers may adopt a speaking style that differs from the other tasks. This could take the form of increased clarity/precision or decreased coarticulatory influences (Lindblom, 1990). Such an account introduces the possibility that speakers invoke distinct speech production modes that rely on factors such as task naturalness. Another alternative is that the cognitive demand required for BAD may distinguish itself from other tasks and that this is reflected in speech motor behavior. It is plausible to suggest that the BAD task requires fewer cognitive resources or resources that are directed more toward the actual production of the utterance than on factors such as linguistic/communicative intent or, in the case of oral reading, written language decoding. Any or all of these accounts may reasonably contribute to the observed differences. The key finding of this study is that in strictly kinematic terms, task differences do exist. A comprehensive theory of speech production must explain more than the kinematic facts about simple tasks such as BAD. Theories must also explain kinematic facts about the complexities of speech movement

as it is produced in more natural ways. Unless an effort is begun to tackle these more challenging communication contexts, our empirical and explanatory accounts of normal and disordered speech will be lacking.

We do not mean to suggest that restricted speech samples are of no value in speech production research. The importance of these differences will depend on the kinds of research questions posed. For example, a task like BAD might be appropriate if the goal is to motorically challenge an articulator or assess its dynamic range over a relatively narrow trajectory. This could be quite useful with clinical populations where articulatory subsystems exhibit differential impairment (i.e., flaccid dysarthria). In contrast, studies of speech motor equivalence involve analysis of multiple articulators contributing to a common phonetic goal and would probably be enhanced by the use of more natural forms of speech task. These observations may also be relevant to studies that compare articulatory kinematic measures in normal and disordered speaker groups. Although differences may be observed between speaker groups, it would be difficult to make generalizations to more natural speaking activities.

In contrast to the generally consistent differences between BAD and the other tasks for the measures based on individual movement strokes, the measures that reflect features of the overall spatial distribution (SDIS and VAR) did not show the same consistent task-related findings across the articulators. The upper lip and mandible exhibited a trend toward minimal differences in SDIS and VAR between BAD and the other tasks (although for UL, the BAD-OR comparison for SDIS was significant). The lower lip and tongue blade demonstrate consistently less “dimensionality” in the spatial distribution of its movement trajectories (i.e. a smaller VAR) for the BAD task relative to the other tasks. This is most evident for TB. In the BAD task almost 90% of the variability in the TB spatial distribution is along a single dimension, whereas in the other tasks this accounted variance drops to about 65%. Further, TB showed systematic increases in the size of the spatial distribution for the SENT task relative to the other tasks. These results highlight the different kind of information these indices of spatial variability provide relative to the movement stroke kinematics. There is recent evidence that the kinematic variability of the jaw during speech and nonspeech tasks tends to mirror some of the jaw’s biomechanical characteristics (i.e., stiffness; Shiller, Laboissiere, & Ostry, 2002). The results of Shiller et al. emphasize that the use of carefully constructed speech tasks with biomechanically detailed articulatory models may help reveal how kinematics may be constrained by biomechanical factors. The general results in this study suggest that, relative to other articulators, the

tongue may require larger and more diverse speech samples to “map” its spatial variability.

Even though the BAD task exhibits many kinematic features that distinguish it from the other tasks, the speaker group demonstrated modest correlations between certain kinematic measures (principally SPD, DIS, and SDIS) across the various tasks, including BAD. These associations suggest that speakers exhibit a tendency for similarities in the task-related scaling of speech movement. For example, those speakers who exhibit the largest, fastest movements for BAD often exhibit the largest fastest movements for the other tasks. Although the source of these associations is not clear, it may be due to anatomical factors such as vocal tract and articulator size (Kuehn & Moll, 1976), and/or speaker strategies that are general to speech production.

It should be noted that the SENT, MON, and OR tasks exhibited many similarities across the measures. The only consistently significant pattern of variations was that tongue blade SDIS was larger for SENT compared to the other tasks. Otherwise, these three tasks were quite similar. These results speak to a practical matter related to studying speech-related movement. Measures drawn from relatively small but phonetically diverse samples of connected speech may provide a reasonable estimate of speech kinematic behavior typically observed in spontaneous speech.

## ***Rate and Loudness Variation***

We studied the effect of rate and loudness variation on the production of BAD and SENT to evaluate the general hypothesis that task and articulator identity might interact with rate and loudness variation. Moving from soft to habitual to loud speech resulted in a systematic increase in DIS and SDIS. A similar pattern was also observed for SPD, but it was statistically significant for MAN (for all comparisons) and LL (for only the soft-habitual comparison) only. Although this loudness-related scaling of kinematic events occurred for both tasks, there is evidence that it was more pronounced for BAD as compared to SENT. This interaction between task and loudness is not that surprising given the phonetic structure of BAD. During this phrase, the vocal tract closes and opens three times in four syllables. Rapidly shifting from a closed vocal tract with minimal acoustic radiation to an open vocal tract with specific SPL requirements is likely to place greater kinematic demands on oral articulators than SENT, a phrase which contains a broader repertoire of speech sounds, including nasals and sonorants. The point to be made by the presence of Loudness  $\times$  Articulator and Loudness  $\times$  Task interactions is that the loudness variation may involve a more complex strategy than the fairly simple,

system-wide scaling of speech movements that previously have been suggested (Dromey & Ramig, 1998; McClean & Tasko, 2003). Such complexities may only be revealed by studies that sample multiple articulators and tasks.

The results of the speech rate manipulation were, in general, even more complex than for the loudness condition. Although significant rate main effects were observed for rate SPD, DIS, and DUR, there were several significant interactions. MAN and LL consistently demonstrated respective increases and decreases in DUR for the slow and fast rate conditions. UL and TB did not demonstrate this pattern. Further, rate-related variation in DUR and DIS varied as a function of speech task (see Figure 5), suggesting that limiting observations of rate-related kinematic changes to open/close movements might not generalize in straightforward ways to other phonetic and behavioral environments.

There was a trend (not shared by MAN) for SPD and DIS to decrease for the slow rate condition, but no systematic pattern was observed for the fast rate condition. The lack of systematic variation for the fast rate condition could be explained by previous claims that speakers use different strategies that trade between speed and distance to simultaneously meet temporal and phonetic demands (Kuehn & Moll, 1976).

One potential source of the complexity of the rate variation task may be related to the manner in which the task was produced. As can be observed on the right side of Table 3, speakers tended to vary SPL with speech rate. Although the degree of SPL variation is much less than that observed for the loudness condition, it is on the order of 1–2 dB. Increasing rate and loudness might interact in complex ways and account for some of the results. Such a hypothesis could be evaluated by systematically varying rate across a range of SPLs. Regardless of cause, the speech rate results support the view that rate change generally involves complex motor transformations (Adams et al., 1993; Dromey & Ramig, 1998; Gay, 1981; McClean & Tasko, 2003).

As a whole, the rate and loudness data reveal an interesting pattern for MAN that was not consistently observed for the other articulators. MAN exhibited significant rate-related DUR variation, but no significant rate-related SPD and DIS variation. For the loudness condition, MAN was the only articulator to consistently exhibit significant increases/decreases in the three measures of interest (SPD, DIS, and SDIS) with increases/decreases in loudness. One interpretation is that the duration of MAN movements is largely driven by syllabic timing variation, whereas the magnitude of MAN movements is principally driven by loudness variation, and that the duration and magnitude of MAN movements are only indirectly influenced by the phonetic demands

that enslave the tongue and lips. Such an interpretation suggests a role for the mandible in speech production that is distinct from other articulators, a view that is consistent with recent speech production theory (MacNeilage, 1998). Future studies could explore this possibility more directly.

Our long-term goal is to develop a system for task-based profiling that may be applied to clinical populations. Studying speech kinematic behavior using tasks that sample different regions of the overall distribution of behavior (i.e., BAD vs. the other tasks) and using measures that may be differentially sensitive to features of speech motor behavior (i.e., SPD, DIS, and DUR vs. SDIS and VAR) may have clinical utility. For example, speech motor profiles that include a range of kinematic information may be helpful for correlating motor and clinical behavioral findings, distinguishing different subtypes of disorder, quantifying degree of impairment, and enhancing theories of normal and disordered speech production.

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Contact author: Stephen M. Tasko, PhD, Department of Speech Pathology and Audiology, Western Michigan University, Kalamazoo, MI 49008.  
E-mail: Stephen.tasko@wmich.edu