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Working Memory and Motor Speech Interactions In Young Adults

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WORKING MEMORY AND MOTOR SPEECH INTERACTIONS IN YOUNG ADULTS

By

KATHERINE CAVALIERE

B.A., New Mexico State University, 2014

A thesis submitted to the
Faculty of the Graduate School of the
University of Colorado in partial fulfillment
of the requirement for the degree of Master’s of Arts
in Speech-Language Pathology
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and Hearing Sciences

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This thesis entitled:
Working Memory and Motor Speech Interactions in Young Adults
written by Katherine Cavaliere
has been approved for the Department of Speech, Language, and Hearing Sciences

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Kathryn Hardin, M.A., CCC-SLP, CBIST

Date

The final copy of this thesis has been examined by the signatories and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

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WORKING MEMORY AND MOTOR SPEECH INTERACTIONS

Cavaliere, Katherine (M.A., Speech Language Hearing Sciences)

Working Memory and Motor Speech Interactions in Young Adults

Thesis directed by

Neeraja Sadagopan, Ph.D., CCC-SLP

ABSTRACT

Cognition, language, and the speech motor system have robust interactions. The purpose of this study was to examine the specific interactions between working memory and speech motor performance in a dual-task activity. Nineteen healthy young adults read sentences of increasing length and complexity in two counterbalanced conditions: control (no concomitant task) and experimental (while performing a dual working memory task). Lip aperture values, production durations, and accuracy of speech were measured. Results indicated that the working memory has a significant effect on speech motor coordinative patterns and the percentage of syllable errors. Additionally, sentence length and complexity significantly affects speech motor coordinative patterns, percentage of syllable errors, and production duration. These findings suggest that the speech motor system is affected by increased cognitive demands, likely due to limitations of cognitive resource allocation. Clinical implications for the assessment and treatment of motor speech disorders in aging populations are discussed.
ACKNOWLEDGEMENTS

I would like to express gratitude to my thesis advisor, Neeraja Sadagopan, Ph.D., CCC-SLP, for her guidance and engagement throughout this study. Furthermore, I would like to thank my thesis committee members, Gail Ramsberger, Sc.D., CCC-SLP and Kathryn Hardin, M.A., CCC-SLP, for their insightful comments and questions.
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Introduction

While research in the past several decades has given light to the fact that movement, cognition, and language have robust and dynamic interactions (Dromey & Benson, 2003; Maner, Smith, & Grayson, 2000), research on the specific nature of interactions between cognition and movement control has been sparse. Recent evidence has supported links between language, cognition and movement control in the area of speech in young (Nip & Green, 2012) and elderly populations (Sadagopan & Smith, 2013), as well in other demographics (Kleinow & Smith, 2000; Maner, Smith, & Grayson, 2000; Sadagopan & Smith, 2008; Walsh & Smith, 2011). Such research is important when considering the motor systems of aging populations, particularly those with motor speech disorders. The tendency for cognitive skills such as working memory and processing speed to decrease in elderly individuals (e.g., Finkel, Reynolds, McArdle, & Pedersen, 2007; Luo & Craik, 2008), as well as in certain populations with communication disorders (Bottcher, 2010; Howard, Blinks, Moore, & Playfer, 2000; Janvin, Psych, Larsen, Aarsland, & Hugdahl, 2006; Ravizza, McCormick, Schlerf, Justus, Ivry, & Fiez, 2005; Williams-Gray, Foltynie, Brayne, Robbins, & Barker, 2007) has been widely documented, making the interaction between cognition and movement control particularly relevant. Although cognitive-motor interactions have been alluded to in previous studies, this research has been limited in scope and warrants more in-depth study. “Cognition” is a broad term that encompasses several constructs (e.g. attention, memory), and the nature of the interaction between specific cognitive constructs and the speech motor system has not yet been explored in detail. Since verbal output is the combined result of interactions between language, cognition, and motor systems, it is important to consider all three aspects of communication in understanding motor speech behavior. The present study is aimed at exploring the interactions between cognition (specifically
working memory), language and speech motor performance in an effort to add to existing literature in this area.

**Literature Review**

**Language- Motor Interactions in Speech Production**

Many studies have been conducted to examine interactions between language and speech motor control. Maner, Smith, & Grayson (2000) assessed the effects of increasing utterance length and syntax complexity on 5-year-old children and young adults. Kinematic data was collected while presenting children and adults with sentence stimuli containing predominantly bilabial phonemes, increasing in length and complexity. It was found that compared to adults, childrens’ repeated speech movements had greater variability as the linguistic demands increased, suggesting that children’s speech motor systems were more greatly impacted by the increased processing requirements. Although this study could not determine whether the impact was primarily due to the increased length or complexity, it nonetheless demonstrated the influence that linguistic processing has on speech motor control. These results were subsequently replicated and expanded upon by Sadagopan & Smith (2008), who examined the speech kinematics of seven age groups of participants ranging from 5-year-olds to young adults. Results found that children showed greater motor speech variability than young adults in the presence of linguistic demands. Children (particularly before 9-years-old but through adolescence) were more susceptible to the impact of greater linguistic processing demands when compared to young adults.

Kleinow and Smith (2000) investigated linguistic-motor interactions in the speech of individuals who stutter. The authors measured speech kinematics in both adults who stuttered and adults who did not stutter during conditions of increasing linguistic complexity and length.
WORKING MEMORY AND MOTOR SPEECH INTERACTIONS

The authors found that for both groups, speech kinematics were significantly impacted by longer and more complex sentences. There was greater articulatory variability in adults who stuttered across all conditions, and increasing linguistic complexity was highly correlated with articulatory variability in this group. This suggested that the motor speech systems of individuals who stuttered were more impacted by the increased linguistic processing demands. Furthermore, when sentences were lengthened by embedding a phrase into meaningless words, thus increasing the length without increasing the linguistic complexity, speech kinematics were not impacted for either group. This supported the notion that linguistic processing for complex productions, and not just increased length of utterance, impacted the motor speech system.

Interestingly, varying results about syntactic complexity were found by Walsh and Smith (2011) when examining the linguistic-motor speech interactions in older adults with Parkinson’s Disease (PD). This population frequently is diagnosed with dysarthria, a motor speech impairment due to abnormalities in strength, speed, range, tone, or accuracy of the speech muscles (Duffy, 2013). Walsh and Smith (2011) presented sentences of varying length and syntactic complexity for oral reading to both people with PD and healthy age-matched adults. Kinematic findings indicated that both groups displayed greater articulatory variability when linguistic load increased, and those with PD were not significantly more impacted than healthy age-matched peers. Adults with PD, however, showed several general differences from healthy adults during all sentence productions, including higher variability of oral motor coordination, longer time before initiating speech, and more speaking task errors. These reflected the general motor speech impairment, and possible speech planning and processing deficits associated with PD. A lack of difference between adults with PD and age-matched healthy adults introduced more questions about the motor system in people with Parkinson’s Disease. The results,
however, demonstrated that all older adults in the study (ranging from 62-82 years) were susceptible to the effects of linguistic variables on speech motor performance. All of the above studies support the need to examine the potential influence of linguistic processing demands across the lifespan and how these impact the motor speech system.

**Cognitive-Motor Interactions in Speech Production**

Other studies have been conducted to examine cognition as an impacting factor on motor speech. Dromey & Benson (2003) constructed dual-task studies to look at speech motor output during the performance of cognitive, as well motor and linguistic tasks. Young adult participants were asked to orally repeat a sentence in several conditions, including speech-only, motor task (manipulating nuts and bolts), linguistic task (generating verbs), and cognitive task (counting backwards by 7’s). The authors found that the linguistic task and cognitive task conditions had the greatest impact on lip movement consistency such that lip movement was more variable than during the speech-only or motor task conditions. Furthermore, the rate of speech greatly increased during the cognitive task. Dromey & Benson (2003) offered the functional distance hypothesis as a possible explanation for the impact of the linguistic and cognitive tasks on speech characteristics. That is, they suggested that the linguistic and cognitive processing took place close to brain areas devoted to speech movement sequencing that impact lip movement variability, causing interference by way of competition of resources, whereas the motor task did not cause similar interference due to its greater functional distance in the brain.

This line of research was continued in Dromey and Bates’ (2005) study on the mutual impacts of speech, linguistic processing, visuomotor activity, and cognitive processing on performance. Rather than consider only the impact of other processing tasks on motor speech, they considered the impact of speech motor control on the accuracy of other tasks as well. Young
adult participants were given a speech-only task (repeating a sentence), a linguistic-only task (constructing a grammatical sentence), a cognitive task (two-digit subtraction), and a visuomotor task (clicking a moving shape on a screen). After completing the tasks in isolation, each was then paired with the speaking task. Their results found that dual linguistic and speech processing resulted in greater lip movement variability, supporting the results found by Dromey & Benson (2003). Furthermore, accuracy in the linguistic task was reduced when combined with a speech task. Results of this study varied from Dromey & Benson’s (2003) previous research, indicating that the greatest effect of the dual cognitive-speech task was increased vocal intensity, and that motor speech variability did not change in the presence of the dual cognitive and speech task. The authors hypothesized that these results were confounded by a lack of simultaneity during the cognitive-speech dual task. Based on variable response latencies after the stimuli were presented, the authors speculated that some participants may have paused to process the math problem and then quickly spoke the carrier phrase in isolation after the math processing had already occurred (Dromey & Bates, 2005). This indicates that in order to isolate the impact of cognitive processing on motor speech, care must be taken in methodology to ensure that processing during the cognitive task and speaking are co-occurring. One of the authors’ recommendations for possible methodologies included mixed-modality testing, in which the participants simultaneously speak a sentence and respond to multiple-choice math problems by pushing a button. Although their methods had limitations, Dromey & Bates’ (2005) study demonstrated that dividing cognitive resources in normally-speaking young adults led to changed performance on speech and linguistic tasks.

In addition to motor speech variability, cognitive processing has been found to also impact rate of speech (e.g., Dromey & Benson, 2003), as mentioned previously. Nip & Green
(2012) designed stimuli that varied in processing type (i.e. motor, linguistic, or cognitive processing): a diadochokinetic rate task, a syllable repetition task, a sentence repetition task, and a narrative story retell task, in an attempt to examine possible causes for rate differences in children and adolescents relative to young adults. The authors found that speaking rate slowed for all age groups during cognitively and linguistically complex tasks such as sentence repetition and story retell, as compared to diadochokinetic and syllable repetition tasks. The authors proposed that if biologic factors, such as slower movement capabilities, were the cause of differences in speaking rate between children and adults, childrens’ speech rate would be stable across all tasks, regardless of complexity. Instead, childrens’ speech rate was impacted by processing complexity as well, suggesting that cognitive and linguistic processing, rather than the biologic differences, accounted for participants’ reduced speaking rate.

In summary, several studies have isolated the effects of linguistic factors (Kleinow & Smith, 2000; Maner, Smith, & Grayson, 2000; Walsh & Smith, 2011) as well as cognitive variables (Dromey & Bates, 2005; Dromey & Benson, 2003) on speech motor performance. These authors agree that language, cognition, and motor speech factors interact in complex ways and have dynamic effects on kinematic variables of speech production. Although cognition has been included as a variable in some of the above studies of speech motor control (Dromey & Bates, 2005; Dromey & Benson, 2003), methodological considerations in these studies led to cautious interpretations of results. For example, in Dromey and Benson’s (2003) study, the cognitive task involved counting backwards by sevens; however, the authors suggested that a more challenging mental arithmetic task that involves mental rehearsal, activating the phonological loop, may show more significant speech interactions. Furthermore, as mentioned
above, Dromey and Bates (2005) suggested that future studies should carefully design methodology such that cognitive processes and verbal execution take place simultaneously. Given that cognitive interactions with motor speech performance have possible implications for the success of research, assessment, and treatment of aging adults with motor speech impairments, continued research in this area is important. As a preliminary step, the current study seeks to measure the speech kinematics of young adults as they are given working memory tasks while speaking sentences of varying length and complexity. This study builds upon the work of Dromey and Benson (2003) and Dromey and Bates (2005) by attempting to examine the effects on speech kinematics as cognitive processing is simultaneously occurring. In consideration of the methodological recommendations of Dromey and Bates (2005), a goal of the present study is to engage the phonological working memory loop in order to assess cognitive-linguistic demand effects of speech motor variables. The task design utilized in the present experiment was aimed at activating and engaging the working memory component of cognition, which involves continuous rehearsal, manipulation, and retrieval (Baddeley, 2007) of targets. As a first step, this study was conducted on young adult participants with intact cognitive and speech motor systems. We hypothesized that young adults would demonstrate greater motor speech variability when given a dual task that activates their working memory while speaking. If, in fact, the expected interactions between cognitive and motor systems are noted in this age group, a compelling argument can be made for the need of continued research in elderly individuals with vulnerable cognitive mechanisms.

Methods

Participants

Nineteen young adult participants, ages 18-22, (\(M = 20;6\) (years; months), range = 18;2-
22;11) were included in the analysis of this study. While an attempt was made to recruit an even number of males and females, eighteen females and three males were recruited from the University of Colorado-Boulder campus and surrounding communities. Although all twenty-one participants completed the study, two female participants’ data was excluded from analysis due to technical complications during data collection, leaving data from sixteen females and three males. All participants were monolingual native speakers of General American English. Participants had normal histories of speech, language, and hearing development and were not past recipients of speech-language therapy. Additionally, participants were excluded given a positive history of neurological insult, such as concussions, seizures, or loss of consciousness, or if they took medication that could impact cognitive and/or motor performance (e.g., muscle relaxants). Participants passed a basic health questionnaire through self-report of the above medical questions, a digit span screening (minimum of 5 digits forward repeated orally), oral mechanism screening (no disordered structure or function of the oral mechanism), audiological screening of 20 dB HL presented at 500, 1000, 2000, and 4000 Hz, and a basic vision screening using a Snellen eye chart (reading at a distance and font size equal to experimental stimuli on the computer screen). Participants were instructed to wear glasses or contacts if required on the day of the experiment, and during vision testing. Participants were excluded if they failed any part of the screening process.

**Stimuli**

Stimuli (listed in Table 1) were chosen from a study by Walsh & Smith (2011), and were developed by those authors based on previous analysis of behavior and brain imaging. Stimuli included six sentences utilizing primarily bilabial phonemes, including /p/, /b/, and /m/. The production of bilabial phonemes allowed ease and consistency in the selection of articolatory
movements to be measured. Additionally, the sentences represented natural speech and communication by including combinations of the following linguistic variables: simple/complex, long/short, subject or object relative. Sentences were made longer by including adjectives in front of nouns, and they were made more complex by embedding phrases into them (e.g. “who saw”). Subject vs. object relative sentences differed in whether the noun is followed by a verb or a noun, with object-relative sentences considered linguistically more complex. Including sentences with varying length and complexity allowed for the examination of the differential influence of working memory factors on short vs. long and simple vs. complex sentences. The sentences are displayed in Table 1. Stimuli were presented visually in a large, easy-to-read black font on a computer screen placed approximately 8 feet in front of participants, just above a motion-tracking device.

**Equipment**

Participants were seated in front of an Optotrak Certus motion tracking system (Northern Digital Inc., Waterloo, Canada). Articulatory movement was tracked through small infrared light emitting diode (IRED) markers. Participants wore plexiglas goggles, which had splints extending downward from each side. Five IRED markers were attached to participants’ skin and goggles using double-sided tape, including in the center of the forehead, the right and left corners of the goggles at eye level, and the right and left splints near the corners of the mouth. These markers formed the ‘rigid body’ (Smith, Sadagopan, Walsh, & Weber-Fox, 2010) and were used to track overall head motion. Additionally, markers were placed on the midline at the vermilion border of the upper and lower lips, as well as on the midline under the jaw. These markers recorded upper lip, lower lip, and jaw displacements respectively, relative to the rigid body. Throughout the experiment, the displacement of the markers was tracked by the Optotrack Certus, with each
### Table 1: Verbal Stimuli

<table>
<thead>
<tr>
<th>SENTENCE DESCRIPTION</th>
<th>SENTENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple, short</td>
<td>The boys and the pipers baked moist pumpkin pies.</td>
</tr>
<tr>
<td>Simple, long</td>
<td>The messy boys and the merry pipers baked many moist pumpkin pies.</td>
</tr>
<tr>
<td>Complex, subject-relative, short</td>
<td>The boys who saw pipers baked moist pumpkin pies.</td>
</tr>
<tr>
<td>Complex, subject-relative, long</td>
<td>The messy boys who saw merry pipers baked many moist pumpkin pies.</td>
</tr>
<tr>
<td>Complex, object-relative, short</td>
<td>The boys whom the pipers saw baked moist pumpkin pies.</td>
</tr>
<tr>
<td>Complex, object-relative, long</td>
<td>The messy boys whom the merry pipers saw baked many moist pumpkin pies.</td>
</tr>
</tbody>
</table>
marker’s position sampled at 250 samples/s. Furthermore, a microphone was mounted roughly 8 inches from the participant to collect an audio signal, which was gathered by the Optotrak Data Acquisition Unit and in synchrony with movement trajectories. A simultaneous audio recording was also made on a digital recorder, Marantz PMD670, at 16-bit and 48,000 Hz sampling rates. The audio recordings were used to analyze the participant’s accuracy of verbal utterance.

**Experimental Protocol**

Experimental data was collected over one 1.5-hour-long session. After administering screening procedures and signing a consent form, participants were then given the following assessments: digit span test from the *Woodcock Johnson IV Test of Cognitive Abilities* (Schrank, McGrew, & Mather, 2014), sentence repetition test from the *Woodcock Johnson IV Test of Oral Language* (Schrank, Mather, & McGrew, 2014), a custom-created timed math worksheet (50 addition problems; see Appendix 1), and an oral reading fluency screening based on 9th grade reading passages (Rasinski, 2003). The results of these assessments are listed in Table 2.

<table>
<thead>
<tr>
<th>ASSESSMENT</th>
<th>UNIT OF MEASUREMENT</th>
<th>MEAN AND STANDARD DEVIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digit Span Forward</td>
<td>Number of digits</td>
<td>6.68(1.2)</td>
</tr>
<tr>
<td>Digit Span Backward</td>
<td>Number of digits</td>
<td>4.63(1.3)</td>
</tr>
<tr>
<td>Sentence Repetition</td>
<td>Percent sentences correct</td>
<td>95.26(6.12)</td>
</tr>
<tr>
<td>Math Worksheet</td>
<td>Seconds to complete</td>
<td>60.05(13.69)</td>
</tr>
</tbody>
</table>
After initial testing was completed, participants were seated in front of the Optotrak Certus camera system and infrared markers were placed on the participant as previously described. The examiner read instructions to the participants, and then two practice blocks were completed to familiarize participants with the tasks. The practice blocks were identical to the subsequent experimental blocks, both in task and in instructions. Participants were provided feedback if they asked questions about the task, but otherwise were not corrected for errors. Once practice blocks were completed, participants began the experiment. Because this study utilized a within-subjects design, participants began either with the control or the experimental condition (which were counterbalanced across subjects in order to account for any potential practice effects in sentence production). Two practice blocks were administered before both the control and the experimental conditions, regardless of order of the conditions. During the control condition, stimuli were presented in blocks of six sentences, with each sentence visually presented in pseudo-random order within a block. Each sentence was displayed on the screen for 8 seconds. Participants were instructed to read each sentence out loud at their habitual pitch and loudness, “as fast and as accurately as they can.” Audio and kinematic data were collected while the sentences were read. A 30-second pause was inserted between blocks, after which the next stimulus block was presented. A total of 10 blocks of stimuli were presented in the control condition; i.e., participant read each sentence 10 times for a total of 60 productions. Participants were given a 5-minute break after the first ten blocks of stimuli. During the break, participants were offered a drink of water and were allowed to rest, but remained in their seat connected to the Optotrak infrared markers.

During the experimental condition, the six sentences were again visually presented in pseudo-random order similar to the control condition; however, prior to the presentation of each
sentence, a memory item (single letter and single-digit addition problem, e.g. ‘L 4+3’) was presented visually on a separate slide for three seconds. After three seconds, the slide with the letter and arithmetic problem was replaced with the slide containing the target sentence. Participants were instructed, ahead of time, to mentally complete the addition problem, and retain the letter and numeric answer in order while reading the sentence immediately after the memory item. They were also told that they would be required to recall the letters and numbers at frequent intervals. Placing the memory task items before the sentence (rather than simultaneously with or right after the sentence) was more likely to cause active phonological rehearsal of the participant while producing the oral sentence, and thus avoiding the methodological problem of sequential performance noted by Dromey and Bates (2005). At the end of a single six-sentence block, participants were prompted to recall the letters and number sums in order of presentation (e.g., L 7, R 4, A 9). All participants were presented with a total of 20 blocks of stimuli, 10 in the control condition and 10 in the experimental condition.

**Behavioral Data Analysis**

Production accuracy was measured by the author through offline analysis of audio recording. Two accuracy measures were taken: the percentage of syllable errors and the percentage of syllables correct. Syllable errors included syllable additions, omissions, and substitutions. The percentage of syllables correct was impacted by omissions and substitutions only. Additions did not impact the total percentage of syllables correct if the participant self-corrected and included the target syllable. These values were averaged for each sentence over the 10 productions in each condition.

Memory task responses were also recorded in a spreadsheet both online and offline (based on audio recording). Six accuracy measurements were taken: letters recalled in order,
numbers recalled in order, correct letters recalled, correct numbers recalled, total letters recalled, and total numbers recalled. The letters and the numbers recalled in the order was measured by counting the number of letters and numbers that the participant recalled in an accurate order placement in the string of letters and numbers. Correct letters and numbers recalled was measured by counting the letters and numbers that the participant recalled that had appeared at any point in the block. Total letters and numbers recalled was measured by counting the total letters and numbers that the participant recalled, regardless of whether they had appeared in the block. These values were taken at the end of each six-sentence block and averaged over the 20 total blocks of stimuli.

**Kinematic Data Analysis**

Upper lip, lower lip, and jaw movement trajectories were imported into MATLAB (Mathworks, 2009) for data analysis. Continuous lower lip movement trajectories for each sentence were displayed on a computer screen, along with corresponding velocity signals. Movement signals for each sentence were extracted by identifying initial and final opening movements. Extraction started at the peak velocity for the opening movement of the first word (i.e. /b/ to /ɔ/ in “boy” or /m/ to /ɛ/ in “messy”) and ended at the peak velocity for the opening movement in the final word (i.e. /p/ to /æ/ in “pies”) similar to procedures described in Walsh & Smith (2011). Only accurate sentences were included in subsequent kinematic analyses.

For the current study, we focused on the ‘lip aperture’ movement variable (Smith & Zelaznik, 2004). The lip aperture difference signal was computed by a custom-designed MATLAB software program by point-by-point subtraction of the lower lip movement from the upper lip movement. Though articulatory variability can be measured using different lip and jaw variables, lip aperture is found to be more consistent from trial-to-trial productions of a target
WORKING MEMORY AND MOTOR SPEECH INTERACTIONS

(Smith & Zelaznik, 2004). Based on all the accurate productions of a sentence, a lip aperture variability (LAVAR) index was computed. In order to obtain this index, all the accurate productions for that sentence were time- and amplitude-normalized. Amplitude normalization were achieved by subtracting the mean of the productions and dividing by the standard deviation. Time normalization was achieved as signals were superimposed on one another and projected onto a 1000 point time base using interpolation. The standard deviations of the trajectories were computed as a function of relative time at 2% intervals. These were then summed to produce the lip aperture variability index. A lower LAVAR index represents high signal consistency (Smith & Zelaznik, 2004) and vice versa. LAVAR values were computed for each of the six sentences per condition, per participant. 10 possible productions of each sentence were analyzed for use in the LAVAR computation. Only accurate productions free of significant errors were included in the LAVAR computation. LAVAR indexes were computed using a range of 6-10 lip aperture waveforms (only those with no errors; See Table 4.)

Movement duration for each sentence was also obtained (through automatic computation by the MATLAB software program). Duration was analyzed using only the same accurate productions free of significant syllable errors that were used in the LAVAR analysis.

Statistical Analysis

A repeated measures analysis of variance (ANOVA) was completed for each of the dependent variables: behavioral accuracy (percent syllables correct and percent syllable errors), and kinematic variables (movement variability and duration) with CONDITION (experimental vs. control) and SENTENCE (6 complexity levels) as the within subject variables. Significant interactions were examined through post-hoc testing using Tukey-Kramer simultaneous confidence intervals. Alpha was set to .05 for all statistical tests.
Results

Behavioral Data

Percent syllables correct. No significant CONDITION or SENTENCE effect on the percent of syllables spoken correctly was obtained. The percent of syllables spoken correctly remained consistent and highly accurate in the presence of the working memory task, as well as when sentences became longer and/or more complex. These accuracy measures indicated that even if participants made a syllabic error, they self-corrected and included the target syllable, which contributed to a consistent percentage of syllables correct. The average percent syllables correct for the control condition was 99.95%, and the average percent syllables correct for the experimental condition was 98.98%, suggesting that participants may have ceilinged out on syllable accuracy. Percent syllables corrected are shown in Figure 1. Although self-corrected productions were included in the measure of speech accuracy, they were not included in kinematic analysis.

Percent syllable errors. A significant main effect of CONDITION, $F(1,18) = 8.39, p < .01$, on number of errors was noted. The percentage of total syllabic errors, including additions, omissions, and substitutions of syllables, was significantly higher in the experimental condition than in the control condition. These errors were included in the total error count, even if they were subsequently self-corrected. Anecdotally, the most common types of errors included syllable additions, particularly on words that were included in some sentences but not in other sentences, such as “messy” and “many.” (e.g. “The meh…boys whom the pipers saw baked mi…moist pumpkin pies.”) The percentage of syllable errors in each sentence by condition, averaged across 10 productions for each participant, is demonstrated in Figure 2. Additionally, there was a significant SENTENCE effect, $F(5,90) = 4.47, p = .001$, on the percent syllable errors, indicating that the length and complexity of the sentence impacted the number of
Figure 1. Percent syllables correct per sentence for control and experimental conditions
errors that the participants made. The SENTENCE x CONDITION effect failed to reach significance. Post hoc analysis using Tukey-Kramer’s Multiple-Comparison’s test revealed that there were significant differences between percent syllable errors for the following sentences: Sentence 2 from 3, Sentence 3 from 6, 2, and 4, Sentence 4 from 3, and Sentence 6 from 3.

Memory performance. Performance on the memory task (i.e., recall of the letter-number string at the end of each block of sentences) during the experimental condition is presented in Table 3. Letters recalled in order, numbers recalled in order, correct letters recalled, correct numbers recalled, total letters recalled, and total numbers recalled are all indicated in Table 3. These were averaged for each participant across 10 trials in the experimental condition. Mean and standard deviation of these variables are reported in Table 3.

Table 3. Means and standard deviations of behavioral memory performance

<table>
<thead>
<tr>
<th>MEMORY VARIABLE</th>
<th>MEAN AND STANDARD DEVIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Letters recalled in order</td>
<td>2.82(1.4)</td>
</tr>
<tr>
<td>Numbers recalled in order</td>
<td>2.86(1.31)</td>
</tr>
<tr>
<td>Correct letters recalled</td>
<td>3.22(1.38)</td>
</tr>
<tr>
<td>Correct numbers recalled</td>
<td>3.18(1.29)</td>
</tr>
<tr>
<td>Total letters recalled</td>
<td>3.59(1.39)</td>
</tr>
<tr>
<td>Total numbers recalled</td>
<td>3.67(1.33)</td>
</tr>
</tbody>
</table>

A mean of only 2.82 and 2.86 letters and numbers respectively recalled in order out of six potential figures showed that participants were challenged to recall the specific order that they had seen. Mean accuracy increased when counting the total letters and numbers recalled that had appeared at any point in the block, although even this measure was only around 50% accurate.
Figure 2. Percent syllable errors per sentence in control and experimental conditions.
Kinematic Analysis

Productions that included errors such as additions, deletions, and transpositions were excluded from kinematic analysis. Therefore, depending on the number of accurate productions available per participant, kinematic analyses (LAVAR and movement duration) were computed using either 100% of data or a variable number of sentences. Table 4 reports the number of participants per category of available accurate sentences and per sentence: 10 productions (100% of the data), 7-9 productions, or <7 productions out of the possible 10 productions.

From the table, it is clear that most kinematic measures were based on a complete set of accurate data, especially for the shorter, simpler sentences. As sentences became longer and more complex, it became more likely that the kinematic measure would be based on a slightly reduced number of productions, due to the greater likelihood of syllable errors. Although data sets for longer, more complex sentences were reduced, very few data sets were made up of less than 7 productions. In the few instances when less than 7 productions were used, measures were based on no fewer than 5 productions. This follows methodologies established in several previous studies in which LAVAR indexes were computed using 5 or fewer productions (Sadagopan & Smith, 2013; Smith, Sadagopan, Walsh, & Weber-Fox, 2010; Walsh, Smith, & Weber-Fox, 2006.)

LAVAR index. A significant effect of CONDITION, F(1,18) = 23.27, p = .0001, on LAVAR was obtained. LAVAR increased in the experimental condition, reflecting greater interarticular variability when participants were concurrently engaged in a memory task. Recall that since only accurate sentence productions were included in both control and experimental conditions, any change in LAVAR values reflects underlying coordinative changes, such that LAVAR increased in sentences that were both longer and more complex. No
Table 4. Number of analyses utilizing 10, 7-9, or <7 productions

<table>
<thead>
<tr>
<th>SENTENCE</th>
<th>NUMBER OF PARTICIPANTS WITH 10 ACCURATE PRODUCTIONS</th>
<th>NUMBER OF PARTICIPANTS WITH 7-9 ACCURATE PRODUCTIONS</th>
<th>NUMBER OF PARTICIPANTS WITH &lt;7 ACCURATE PRODUCTIONS</th>
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<tbody>
<tr>
<td></td>
<td>Control Condition</td>
<td>Experimental Condition</td>
<td>Control Condition</td>
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<tr>
<td>Sentence 1</td>
<td>15</td>
<td>10</td>
<td>4</td>
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<tr>
<td>Sentence 2</td>
<td>13</td>
<td>13</td>
<td>6</td>
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<tr>
<td>Sentence 3</td>
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<td>7</td>
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<td>Sentence 4</td>
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<tr>
<td>Sentence 5</td>
<td>14</td>
<td>8</td>
<td>5</td>
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<tr>
<td>Sentence 6</td>
<td>10</td>
<td>12</td>
<td>9</td>
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</table>
significant CONDITION x SENTENCE interaction was found. The lowest LAVAR value, reflecting highly consistent interarticulatory coordination, was noted for Sentence 1, which was both short and simple. The highest LAVAR values were noted for Sentences 4 and 6, which were both long and complex.

Post hoc analysis using Tukey-Kramer’s Multiple-Comparison’s test revealed that there were significant differences between LAVAR values for the following sentences: Sentence 1 from 6 and 4; Sentence 2 from 4; Sentence 6 from 1; and Sentence 4 from 1 and 2. LAVAR indexes are displayed in Figure 3.

Production durations. A repeated measures ANOVA revealed no significant CONDITION effect on mean duration. This demonstrated that participants took similar amounts of time to read sentences during both the control and the experimental conditions. The expected significant effect of SENTENCE on duration, $F(5,90) = 376.33, p < .0001$, was found. Mean durations significantly increased as sentence length and complexity increased. No significant interaction was found between CONDITION x SENTENCE factors. Post hoc analysis using Tukey-Kramer’s Multiple-Comparison’s test revealed significant differences of mean duration between all sentences except Sentence 4 and 6. All sentences differed in length and/or complexity; however, Sentences 4 and 6 were both long and complex, differing only in subject-relative versus object-relative structure. These results suggest that both length and complexity, but not subject/object relative structure, contributed significantly to differing mean durations. Durations are shown in Figure 4.

Behavioral and kinematic data was analyzed excluding male participants ($n=3$), leaving a sample of 16 females, in order to assess a more homogenous group. All significance of behavioral or kinematic variables remained; however, the significance value of the
Figure 3. LAVAR index per sentence in control and experimental condition
Figure 4: Movement duration per sentence in control and experimental condition
SENTENCE effect on LAVAR changed from $F(5,90) = 6.01$, $p < .0001$ to $F(5,75) = 4.00$, $p < .01$.

Discussion

Memory Condition Effects on Speech Performance

The present study attempted to characterize the effects of a verbal working memory task on speech motor performance during a sentence reading activity. The goal was to examine the effects of the cognitive task on articulatory variability, movement duration, and accuracy of speech targets. LAVAR, which measures lip aperture variability, was significantly higher when participants read sentences while rehearsing numbers and letters than when they read the sentences without the added task. That is, the coordinative articulatory movements of the speech system were significantly more variable when a verbal working memory task was simultaneously completed along with speech production. This change in LAVAR occurred in sentences with similar (and high) levels of accuracy, and in the absence of a significant lengthening of sentence durations in the experimental group. Behavioral accuracy of sentence reading, as measured by the percent syllables correct, was not significantly altered by the performance of a concurrent cognitive task, although the total percent of syllabic errors increased during the dual task. This indicated that participants were less accurate in their speech during the experimental condition, but self-monitored well enough to correct their errors and ultimately produce their target syllables.

The above findings might be explained, in part, by cognitive resource allocation. Before speech is executed when reading sentences aloud, a series of processes must occur. These
include the linguistic process of decoding or recognizing words, speech motor planning, and the issuing of motor signals that will appropriately coordinate muscle activity. The theory of cognitive resource allocation (Kahneman, 1973) suggests that attention is a finite cognitive resource that can either be allocated to one task or shared between two tasks, with resulting reduced focus on any one of the tasks. Studies have extended this theory to apply to varying types of tasks, such as cognitive and motor tasks. These studies have found that when participants engaged in cognitive and motor activities simultaneously, both types of activities were impacted (Dromey & Benson, 2003; Dromey & Bates, 2005). According to the theory of resource allocation, these dual-tasks placed a load on the cognitive system that required attention to be split for both the motor and the cognitive tasks, reducing the precision of both tasks. Increased LAVAR, a measurement of articulatory variability, during the added verbal working memory task demonstrated that the participants in the present study indeed were less precise in their motor task when their cognitive load included both a verbal working memory and a motor task. Additionally, their recall accuracy on the cognitive task was not high, suggesting a bidirectional influence when the cognitive resources were divided.

The Baddeley model of working memory divides verbal working memory into three components: the phonological loop and the visuospatial sketchpad, which serve as storage systems, and the central executive, which serves as the attentional control system (Baddeley, 2007). The phonological loop is the focus of the current study. The phonological loop utilizes rehearsal and storage of phonological information for temporary manipulation and recall (Baddeley, 2007). The phonological loop was targeted in the current study through the choice of memory stimuli. That is, recall of a string of letters and numbers requires rehearsal in the phonological loop. The current study and methodology built upon past literature that
demonstrated interactions between the phonological loop and concurrent performance of other tasks. One study examined a dual-task in which participants with Alzheimer’s Disease (AD), as well as healthy age-matched peers, recited strings of digits while engaged in a concurrent fine motor task (i.e. marking X’s in a trail of boxes.) Performance during the dual task condition significantly declined, and the effect was greatest for participants with AD (Della Salla, Baddeley, Papagno, & Spinnler, 1995). These findings were later supported in a study that demonstrated interactive deficits between phonological loop and a visuospatial task (Logie, Cocchini, Delia Sala, & Baddeley, 2004.)

Results of the verbal working memory performance demonstrated that the working memory task was challenging and activated the participants’ phonological working memory as intended. This demonstrated, however, that participants were actively engaged in the memory task while reading the sentences. If the mean performance on correct letters and numbers had been close to zero, it could be surmised that the task was too difficult, the participants were not engaged, or that participants had given up, thus reducing the likelihood that memory interference had been achieved. Similarly, if the mean performance on correct letters and numbers had been close to six, it could be surmised that the task had been too easy and participants may not have needed active phonological rehearsal, thus reducing the likelihood that memory interference had been achieved. The results of the participants’ memory performance demonstrated that dual-task memory and speech interference had likely been achieved.

There was no significant impact of the verbal working memory condition on sentence duration. Participants did not significantly change the length of time they took to read sentences when a memory task was added. These results differed from the Dromey & Benson (2003) study, in which a cognitive dual-task significantly impacted the duration of speech such that
participants spoke faster in the dual task condition. In their study, Dromey and Bension (2003) utilized beeps (spaced every 3 seconds) to artificially pace participants as they completed the dual-task. Therefore, participants were aware of their time limits and likely anticipated the next upcoming beep. The authors hypothesized that as participants became distracted with the cognitive task, they paused to process the cognitive task and then spoke faster in order to keep up with the pacing beeps (Dromey & Benson, 2003). The pacing beeps were designed to ensure that participants completed the speaking and cognitive tasks simultaneously, but also placed an artificial time limit on each utterance. In a later study by Dromey & Bates (2005), the duration of utterances was not significantly impacted by the presence of cognitive tasks, which is commensurate with the present study’s findings. This might be because the authors took care to create methodology that did not create a perceived time pressure on participants as they spoke. They selected a relatively long interstimulus interval (i.e. 10 seconds) in which participants spoke sentences between the presentations of math problems. This was similar to the present study, in which 8 seconds were given to read sentences between memory items.

This finding is also supported by literature in the limb motor domain. One study examined the interaction between walking speed and cognitive tasks. Walking speed, which relates to duration of movement, was measured while participants calculated a digit subtraction task. Although walking speed was significantly impacted by the dual-task condition for participants with idiopathic PD, the speed was not affected for healthy peers. This study found that for people without disorders, a dual cognitive task did not affect limb movement duration (Bond & Morris, 2000). This finding was built upon in a later study that measured walking speed during increasingly more complex dual cognitive tasks. Most of the cognitive tasks did not impact walking speed significantly; only the most complex cognitive task (i.e. generating
spontaneous speech) began to impact walking speed (Plummer-D’Amata & Altmann, 2012). This leads to questions about the complexity of cognitive tasks and the speech motor system. Future research should examine whether increasing the complexity of the cognitive task would begin to impact speech movement duration.

In the present study, LAVAR values, which indicate articulatory variability, increased in the experimental condition in spite of maintained sentence duration and sentence accuracy similar to the control condition. This suggests that coordinative movement changes are not the result of durational or accuracy shifts, but rather the result of an underlying difference that is the result of the cognitive-motor interaction.

One concern of the previously-mentioned cognitive-motor dual-task study by Dromey & Bates (2005) was that their design did not promote true simultaneity of the tasks. Dromey & Bates (2005) reported a significant decrease in speech latency between the spoken carrier phrase and the cognitive task response. Authors reported that participants were pausing to process the cognitive task, quickly saying the sentence and then immediately giving the cognitive task response. The decreased latency suggested that participants were in fact not completing the cognitive and speaking tasks simultaneously, but had already processed the cognitive task before the speaking task began. In the present study, attempts were made to create an authentic dual-task design. The consistent durations between the control and the memory conditions suggested that the tasks were simultaneous. Sentences remained on the screen for an equal time, regardless of whether a memory condition had been presented or not. Participants did not pause after receiving the memory item in order to process it separately and then read the sentences before it was removed; this would have resulted in reduced utterance duration. The constant utterance duration suggested that the tasks were likely completed simultaneously.
Accuracy of speech was measured both in the percentage of syllable errors and in the percentage of syllables correctly spoken. Errors included additions, omissions, and substitutions of syllables. Speech errors significantly increased when the verbal working memory task was included in the speaking task, meaning that participants were less precise in their speech when the cognitive load was added. This cognitive-motor interaction can again be explained by the theory of cognitive resource allocation; as the attention was divided between speaking and processing the verbal working memory task, the precision was reduced.

This finding is supported by past studies that examined motor accuracy in other types of cognitive-motor dual tasks (Jou & Harris, 1992; Kleinow & Smith, 2005). One study examined the interactions of a verbal working memory task and swallowing functions (Troche, Okun, Rosenbek, Altmann, & Sapienza, 2014). Participants with PD were assessed for swallowing safety using videofluoroscopic imaging. They were then assessed again for swallowing safety while given a working memory task. In the dual-task condition, participants were given a string of digits while swallowing, and were then asked to recall the digits immediately after the swallow. For one subgroup of participants, those mildly impaired in attention, swallowing safety decreased when given the added verbal working memory task. Reduced swallowing safety is equated with imprecise and inaccurate motor execution of the pharyngeal and laryngeal systems. The authors suggested two conclusions related to cognitive resource allocations: 1) swallowing and the working memory task shared attentional resources, and 2) accuracy of the motor task reduced when the attentional resources were divided (Troche, Okun, Rosenbek, Altmann, & Sapienza, 2014). Although the speech motor system and the swallowing motor system are relatively close in proximity, they are separate systems. Therefore, extrapolations to the current study should be considered cautiously; however, imprecision and inaccuracy of motor
functioning when the cognitive load increased was found in both of these studies. In the current study, similar applications of the cognitive resource allocation theory can explain why more syllable errors were made when participants had the added verbal working memory task.

An additional measure of accuracy of speech was in the percentage of syllables correct. Errors that impacted the percentage of syllables correct included omissions and substitutions. There was no significant change in the number of syllables correct in the memory condition. Anecdotally, participants often made a syllable omission or substitution, but then self corrected their error and included the correct syllable in their revision. This suggested that although speech precision was reduced when considering all speech errors, participants maintained self-monitoring awareness during the cognitive speech task, ultimately achieving their targets and syllable accuracy.

**Sentence Condition Effects on Speech Performance**

A second goal of this study was to examine the impact of sentence length and complexity on articulatory variability, movement duration, and accuracy of speech targets. Additionally, the examination of interactions between experimental condition and sentence length/complexity was of interest. Sentences of varying length and complexity were including in the speaking tasks. The stimuli were taken from Walsh & Smith (2011), who designed the sentences to disambiguate sentence length and sentence complexity. In this set of stimuli, both short and long simple sentences were included, as well as short and long complex sentences.

It has historically been difficult to separate sentence length and complexity, as complex sentences tend to be longer (Maner, Smith, & Grayson, 2000; Kleinow & Smith, 2000, Sadagopan & Smith, 2008). In one pair of studies, no significant length effect was found for speech variability when the sentences were artificially lengthened with filler words (i.e. “One
two three Buy Bobby a puppy four five six”; Kleinow & Smith, 2000). In a subsequent study by the authors, stimuli were created to include complete, meaningful sentences that isolated length and complexity by adding clauses. Sentences were included that were both simple and complex while length was held constant, as well as both long and short sentences while complexity was held constant. In this study, significant effects for both length and complexity were found on speech variability (Kleinow & Smith, 2005).

The results of the present study replicated previous findings (Maner, Smith, & Grayson, 2000; Kleinow and Smith, 2005). Sentence length and complexity individually impacted speech variability. Sentence 1, which is both short and simple, demonstrated the lowest LAVAR and thus, the most consistent articulatory movements. Conversely, Sentences 4 and 6, which are both long and complex, demonstrated the highest LAVAR and thus, the greatest variability in articulatory movements. In this set of stimuli, complex sentences were differentiated by subject-relative syntax (e.g. The boys who saw pipers baked moist pumpkin pies,) and object-relative syntax (e.g. The boys whom the piper saw baked moist pumpkin pies.) Post-hoc analysis revealed that there was no significant difference in LAVAR between complex subject-relative and object-relative sentences. This differed from a study that utilized the same sentence stimuli in which there was a significant difference between short complex subject-relative and object-relative sentences (Walsh & Smith, 2011). It is hypothesized that the sample demographic differences, including age and the presence of PD, contributed to this difference. The participants in Walsh & Smith’s (2011) study had a mean age of 73, and half were diagnosed with PD, while participants in the present study had a mean age of 20.5 years. There is literature that demonstrates changes in the accuracy and precision of speech as people age, although specific LAVAR differences were not found (Sadagopan & Smith, 2013). It is possible that either aging
or the presence of PD, or a combination of both, made participants in Walsh and Smith’s (2011) study more sensitive to subtle changes in sentence complexity, and their speech motor systems were impacted. The difference between subject-relative and object-relative may not have provided enough of a change in linguistic load to impact the speech motor systems of the young adults in the present study.

Duration, or the length of time taken to read each sentence, was significantly impacted by the sentence itself. Expectedly, sentences that were greater in length had longer durations. This included sentences that were simple and long, such as Sentences 2. Additionally, the complexity of the sentences impacted their durations. As stated above, stimuli were chosen such that length could be differentiated from complexity as a factor. The sentence with the longest duration was Sentence 6, which is both long and complex. More interestingly, post-hoc analysis showed that Sentences 1 and 5 were significantly different from each other. These sentences have roughly the same length, but differ only in complexity. This demonstrated the role that complexity plays in the duration of utterances. A linguistic stimulus that is more complex necessarily requires greater processing time, which increases the duration of the speech output. This replicated past findings that linguistic complexity significantly impacted speech duration (Sadagopan & Smith, 2013).

This present findings are also supported by studies that utilized other types of cognitive-linguistic processing, such as the Stroop test. In this test, participants name a color of text that is incongruent from the word that they are seeing. In this condition, speech durations significantly increased (Kleinow & Smith, 2005). As in the present study, increased complexity of the task impacted speech duration. Some studies have reported conflicting findings about duration when sentences are embedded in longer phrases (Kleinow & Smith, 2000; Kleinow & Smith, 2005;
Sadagopan & Smith, 2008). In these studies, however, length was not differentiated from complexity in the sentence stimuli. It was proposed by the authors that when given a longer sentence, participants spoke faster, thus decreasing their duration.

When examining accuracy, the percentage of total syllable errors in the participants’ speech was significantly impacted by the sentence type. Specifically, sentences that were more complex (i.e. Sentences 3 and 5), had higher numbers of total errors, including additions, omissions, and substitutions. The percentage of correct syllables, a measure of the participants’ accuracy in reaching the syllable targets, was not affected by the sentence type. This demonstrated that although participants made more errors during the verbal working memory condition and during longer and more complex sentences, a level of self-monitoring was maintained and participants corrected most of their errors. They ultimately reached their syllable targets and maintained a high percentage of correct syllables. The finding that the percentage of syllabic errors increased with linguistic complexity replicated previous findings that percentage of phoneme errors on nonwords increased as nonword complexity increased (Sadagopan & Smith, 2013). Linguistic complexity likely increased the overall cognitive load, taxing the overall attentional resources and decreasing the precision of speech.

Although this study included only young adults, implications extend to other groups as well. Changes in cognition, particularly working memory, have been documented in aging populations (Finkel et. al., 2007; Luo & Craik, 2008). This study provides preliminary research into the impact of cognition on speech motor performance. When considering aging people with reduced working memory capacities, the speech motor system might be even more sensitive to the impact of resource allocation. A recent study used electroencephalogram (EEG) technology to measure brain activity while participants walked on a treadmill versus sitting in a chair.
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(Malcolm, Foxe, Butler, & DeSanctis, 2015). The results indicated that aging adults had much later onset of event-related potential brain activity than young adult counterparts while walking, and also had significantly less accurate gait than young adult counterparts. The authors proposed that this was evidence of loss of flexible resource allocation across multiple tasks as people age (Malcolm, Foxe, Butler, & DeSanctis, 2015). This demonstrates the role that reduced cognitive resource allocation likely plays in many aging adults. Given the present findings, the impact of cognitive interactions with the speech motor system must be considered during research, assessment, and treatment.

Limitations of the Present Study

A possible limitation to the present study is variation in the stimuli between the control and experimental conditions. Specifically, the experimental condition contained the visual memory stimuli of the letter and addition problem on slides between the sentences. The control condition did not contain any slides between sentences. It is unclear if there would be an impact on the findings if the memory stimuli had been included in the control condition, with the instructions for participants to ignore it. In addition to engaging the verbal working memory, the memory slides provided a visual distraction during sentence reading. Questions arise about whether the presence of a visual distraction, even in the absence of phonological rehearsal, would affect the speech motor system. Dromey & Bates (2005) examined the effect of a visuomotor-speech dual task on the speech motor system. The visuomotor task, using a mouse to click on a moving object on a computer screen, significantly affected speech movements. Interestingly, the visuomotor condition impacted the speech system in different ways than other dual tasks, reducing utterance duration and lip displacement. The authors proposed that the visuomotor task recruited different aspects of attention that the other cognitive tasks. Although
our visual memory stimuli did not contain a motor component, this finding leads to questions about the impact of visual distraction on the speech motor system. This supports the question about whether equalizing the visual distraction in both conditions would affect attention differently than in the present study, thus impacting the speech motor system differently.

Future studies in this line of research should consider ways to target the verbal working memory and better control for other cognitive confounds. Care should be taken to create low variability in the stimuli between each condition, and baseline information about verbal working memory performance should be collected to ensure that the verbal working memory is being taxed.

Conclusion

The present data provide evidence for the fact that cognitive functions, specifically the verbal working memory, significantly increased the articulatory variability of the speech motor system. In addition to articulatory variability, the verbal working memory dual-task influenced the accuracy of the speech output, measured in number of errors. Additionally, sentence length and complexity had significant effects on articulatory variability and mean duration of utterance. This study built upon the findings of Dromey and Benson (2003) and Dromey and Bates (2005). These effects can be explained by cognitive resource allocation; that is, when participants are given an added cognitive task or the complexity of their cognitive processing is increased, they must split their attention and the precision of both activities decreases. Indeed, decrements in LAVAR values as well as the occurrence of an increased number of syllable errors in the experimental condition support the hypothesis. The findings from the present study have potential implications for the assessment, treatment, and research of motor speech behavior.
References


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