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Dissociation between phonological working memory structures and motor programming units during speech motor-sequence learning

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Abstract

Purpose: This study investigated the nature of phonological working memory (PWM) structures and speech motor programming units by examining how performance gains from practicing non-native phoneme sequences generalize to novel sequences that overlap to varying degrees with the practiced sequences.

Method: CCVCC words were constructed using consonant clusters that violated English phonological constraints, thus making them difficult to produce initially. After practicing a subset of the words over two consecutive days, participants were tested on the production of several types of word pairs, including *novel* words containing unpracticed clusters, *practiced cluster* words containing consonant clusters that were practiced but in different words from the test words, and *fully learned* words that were practiced in their entirety.

Results: Utterance duration improvements from practicing clusters in one syllabic context fully transferred to *novel* words that included these clusters, while error rate improvements from practicing clusters in one syllabic context only partially generalized to new syllables utilizing these practiced clusters. Additionally, error rates for the first word in the pair (which depend primarily on motor program structure) showed partial improvements for *learned clusters* regardless of whether the cluster was practiced in the same part of the syllabic frame (onset or coda), whereas error rates for the second word (which reflect both PWM and motor programming mechanisms) were higher than even *novel* words if the cluster was practiced in the wrong syllable frame location, presumably due to interference effects in PWM.

Conclusions: These results provide support for an onset-nucleus-coda syllabic frame structure in PWM and a syllable-frame-independent representation of common phoneme sub-sequences for motor programs.

44 *Keywords:* speech motor control; phonetic encoding; serial ordering; motor-sequence learning;
45 working memory; motor programming
46

**Dissociation between phonological working memory structures and
motor programming units in speech motor-sequence learning**

1. Introduction

One of the fundamental issues in the field of speech production is how speakers map discrete phonological units (e.g., phonemes, syllables, words) onto properly timed vocal tract articulations which lead to an audible, intelligible speech signal. Over the years, considerable progress has been made in describing the nature of the complex mapping between cognitive planning units and motor programs that activate the muscles of the vocal tract (for discussion, see Guenther, 2016). Current understanding is mediated by psycholinguistic and neurobiological models designed to explicate the interaction of motor, sensory, linguistic, and cognitive skills in shaping articulatory behavior (e.g., Dell, 1986; Shattuck-Hufnagel, 1979, 1983, 1986, 1992, 2015; Levelt, 1989; MacNeilage, 1998; Levelt, Roelofs, & Meyer, 1999; Cholin, Levelt, & Schiller, 2006; Goldrick & Blumstein, 2006; Guenther, Ghosh, & Tourville, 2006; Bohland, Bullock & Guenther, 2010; Christiansen & Chater, 2016; Hickok, 2017). However, as with most issues concerning speech, there is still much more work to be done.

The issue we address in the current research concerns how speakers learn to rapidly coordinate and implement multiple serial vocal tract movements (or gestures) associated with the consonants and vowels within a planned utterance. To date, the majority of research on speech production has focused on elucidating the mechanisms and processes involved in executing individual phonemes and simple syllables. Relatively little is known about the cognitive structures and processes involved in planning and producing complex or extended *sequences* of speech movements (see, e.g., Bohland & Guenther, 2006; Bohland *et al.*, 2010; Rong, Isenberg, Sun & Hickok, 2018). However, a viable theory of language and speech production must provide a

70 detailed mechanistic account of this complex serial behavior, which is characteristic of natural
71 communicative speech.

72 Investigating how speakers learn and execute speech sequences is a critical activity in
73 developing models of speech production for multiple reasons. First, production planning of
74 phoneme sequences has inherent cognitive demands: the to-be-articulated segments must be
75 phonetically encoded, concatenated and temporarily stored in a verbal working memory repository
76 in such a way that preserves their serial order (see, e.g., Acheson & MacDonald, 2009; Bohland *et*
77 *al.*, 2010; Shattuck-Hufnagel, 2015; Guenther, 2016). Second, speech motor sequencing
78 necessitates fine-grained articulatory control. Kinematic analyses indicate that the implementation
79 of clusters of consonants places multiple, concurrent demands on the speech articulators, primary
80 the tongue, because the vocal tract gestures for neighboring segments are rapidly produced in
81 partially overlapping time frames (e.g., Browman & Goldstein, 1988; Byrd, 1996; Tiede, Shattuck-
82 Hufnagel, Johnson, Ghosh, Matthies, Zandipour, & Perkell, 2007). Third, the production of
83 consonant sequences, and, in particular, those with high articulatory complexity, present a
84 challenge for first and second language learners (e.g., Song, Demuth, Shattuck-Hufnagel &
85 Ménard, 2013; Wilson, Davidson, & Martin, 2014) as well as clinical populations with motor
86 speech disorders (e.g., Buchwald & Miozzo, 2012; Buchwald, Gagnon, & Miozzo, 2017), with
87 clusters often omitted or reduced. Taken together, these factors suggest the existence of rich
88 cognitive systems and processes for learning how to plan and execute sequences of phonological
89 units.

90 Throughout the years, numerous models and theories, such as those advanced by Lashley
91 (1951), Shattuck-Hufnagel (1979, 1983, 1992), Levelt *et al.* (1999), Bohland *et al.* (2010), and
92 Christiansen and Chater (2016), have commonly proposed that speakers produce frequently

occurring sequences of phonological units by parsing them into larger units, or “chunks,” at various stages of the speech production planning process. At the phonological encoding stage, where the planned utterance is mapped from morphemes onto syllables and phonemes, some have proposed that such a chunking process would allow groups of individual phonemes to be selected, concatenated, and stored as a cohesive cognitive planning unit in verbal working memory, which would facilitate the preparation of a speech sequence at a lower processing cost (e.g., Shattuck-Hufnagel, 1979, 1983, 1992; Bohland *et al.*, 2010; Christiansen & Chater, 2016). At the articulation stage, where those planning units are then “released” to the motor system for articulation, it has also been posited that the motor elements for frequently occurring subsequences become temporally integrated into cohesive sensorimotor programs for producing such subsequences with rapid, highly coordinated movements that have been learned through repeated vocal production practice (e.g., Levelt & Wheeldon, 1994; Guenther, Ghosh & Tourville, 2006; Bohland *et al.*, 2010; Segawa, Tourville, Beal & Guenther, 2015; Guenther, 2016).

While researchers generally share the assumption that chunk segmentation and concatenation underlie serial speech planning and production, no consensus has yet been reached regarding the mechanisms that support these processes, or the structure and format of the chunks that these processes operate on (see Bohland *et al.*, 2010; Guenther, 2016, chapter 8, for discussion). Because the type of information represented at each stage of the production planning process likely differs, it is perhaps unsurprising that theories differ in their accounts of the content and size of chunks. Phonological segment error patterns in spontaneous speech, such as the swapping of phonemes in the same phonological position in different planned syllables or words have led to the proposal that frequently produced consonant clusters are, at some level, treated as single units in working memory (e.g., Fromkin, 1971; Shattuck-Hufnagel, 1983, 1992); this is

based largely on the observation that swapping errors often involve entire clusters moving between words (e.g., “dretter swying” for “swearer drying”).

Results from psycholinguistic experiments using the “word game” paradigm have been interpreted instead as evidence that the fundamental units of phonological working memory and speech sequencing are onset-rhyme units (see, Fowler, Treiman, & Gross, 1993; cf. Pierrehumbert & Nair, 1995). For example, in one experiment (Fowler *et al.*, 1993), participants were auditorily presented with trisyllabic pseudowords, and then instructed to repeat, but replace either one (or two) phoneme(s) in the middle-stressed syllable with a fixed sequence. The results were clear in demonstrating that participants responded significantly faster and more accurately when instructed to replace the rhyme of a given syllable, compared to when they were asked to replace the onset and nucleus of a given syllable.

Still others have theorized, based on considerations such as coarticulation patterns and syllable frequency effects, that, at the subsequent articulation stage, syllables are the ideal chunk size for speech motor programming units (e.g., Levelt & Wheeldon, 1994; Cholin *et al.*, 2006; Bohland *et al.*, 2010; Guenther *et al.*, 2006; Guenther, 2016). The fundamental idea here is that, when frequently uttered together, sensorimotor programs for temporally adjacent articulatory gestures fuse together over time to form cohesive action units, which facilitates the production of rapid, highly coordinated movements. On this view, a highly optimized sequence of movements is learned for each frequently produced syllable in the native language.

Our recent work on this issue used a motor-sequence learning paradigm in which the generalization of performance gains from practicing novel phoneme sequences was used to infer the nature of speech chunks (Segawa, Masapollo, Tong, Smith, & Guenther, 2019). In these experiments, native English-speaking participants were trained over several days to produce a set

of CCVCC non-words involving non-native (i.e., phonotactically-illegal) consonants clusters (e.g., *shkizg*, *bdepf*, *dgamj*), where C stands for consonant and V stands for vowel. The experimental design consisted of two phases: a training phase, during which participants repeatedly produced a set of words, and a subsequent testing phase, during which participants were tested on their ability to produce the previously trained words and a novel set of transfer words. During the training phase of the experiment, we observed that participants progressively executed the target words faster and with increased accuracy, indicative of motor-sequence learning. After learning, we tested for generalization by having participants produce four types of transfer words that systematically varied in their amount of overlap with the trained words: (1) words that were included in their entirety in the training phase (*practiced CCVCC*), (2) novel words constructed of non-native consonant clusters that were encountered during the training phase (*practiced CC*), and (3) novel words containing novel non-native clusters (*novel CCVCC*)^b. The extent to which participants acquired the procedural memories for articulating the trained phoneme sequences during the training phase was evaluated during the testing phase by comparing performance across the trained and novel word types. We found that gains in performance speed from practicing words with non-native consonant clusters largely generalized to the *practiced CC* words. Practicing the whole word, however, resulted in further performance gains in accuracy over practicing just the clusters.

Our interpretation of these findings is as follows. Utterance duration during speech sequence production has long been associated with *phonological working memory* (PWM) mechanisms (cf. Sternberg, 1978; Klapp, 1995, 2003; Wright, Robin, Rhee, Vaculin, Jacks, Guenther, & Fox, 2009), which are more taxed when more items need to be stored and retrieved.

^b Note that this stimulus set was not designed to test whether the rhyme (nucleus-coda) was a representational unit of phonological processing (a la Fowler *et al.*, 1993).

Our finding of equal utterance durations for the *practiced CCVCC* and *practiced CC* words suggest that these conditions involved the same number of items in PWM. This strongly suggests that the working memory units must not be full syllables – if they were, then the *practiced CCVCC* condition should have had shorter utterance duration than the *practiced CC* condition. Instead, the results favor an onset-nucleus-coda (O-N-C) syllabic frame representation (cf. Shattuck-Hufnagel, 1992) in which a well-learned consonant cluster constitutes a single item (an onset or coda). Thus, both the *practiced CCVCC* and *practiced CC* words consist of three items (or chunks) in PWM, while words containing novel consonant clusters involve five items since consonant cluster units do not exist yet for these words and thus each phoneme from the cluster must be represented as a distinct item.

We further hypothesize that error rates are primarily reflective of the *articulatory motor programs* needed to produce the word rather than PWM mechanisms since working memory demands of producing a single syllable were minimal in the task. Our error rate data indicate that practicing a phoneme sub-string in onset or coda position leads to performance improvements for all syllables containing that sub-string, but that practicing the whole syllable produces even better performance improvements than just practicing the consonant clusters. We account for these results by positing that speech motor programs are learned for any frequently occurring phoneme strings, including not just clusters but also full words/syllables, and the fewer the motor programs that must be sequenced for production, the fewer the errors. Thus, we see the fewest errors for *practiced CCVCC* words (which involve one syllable-sized motor program), the next fewest for *practiced CC* words (which require activation of two cluster-sized motor programs and a vowel motor program), and the most errors for *novel CCVCC* words (which require sequential activation of five phoneme-level motor programs).

The current research provides a further test of these hypotheses by tackling three issues that were not directly addressed by our prior study (Segawa *et al.*, 2019). First, and perhaps most importantly, we did not provide a definitive test between theoretical accounts that posit that the consonant cluster is a unit of storage in PWM versus a unit of articulation because these two levels of representation were conflated in speakers' productions. In the current study, we attempted to isolate the working memory system from the articulation system by instructing speakers to perform a more demanding version of Segawa *et al.*'s motor-sequence learning task, in which they were required to maintain more extended sequences of phonemes in memory prior to the onset of production. Since it is harder to remember speech sequences with more items than sequences with fewer items (e.g., Baddeley, Thomson, & Buchanan, 1975; Acheson & MacDonald, 2009), we expected to observe different patterns of generalization across conditions for different hypothesized working memory unit types (see detailed predictions below). Disentangling the cognitive structures that operate at the working memory and motor programming levels will not only have important theoretical implications for our understanding of the typical speech production process, but may lead to a method to differentially diagnose PWM versus motor execution impairments in speech sequencing disorders such as apraxia of speech (see also, Buchwald *et al.*, 2017).

Second, regardless of whether one assumes that the consonant cluster is a PWM unit or an articulatory motor programming unit, the details of such a representation are only partially evident from the results of Segawa *et al.* (2019) and other studies. Specifically, since a particular cluster in Segawa *et al.* (2019) always appeared in the same syllable position within a word, it is unclear whether this unit, once learned, generalizes to other syllable positions; for example, does learning of a cluster in the syllable onset position generalize to the same cluster in the coda position?

Findings from other studies (albeit using very different motor tasks) suggest that speech motor learning is often contextually specific (Tremblay, Houle & Ostry, 2008; Rochet-Capellan, Richer & Ostry, 2012; cf. Warker & Dell, 2015). Furthermore, studies focusing on the coordination of articulatory movements for *native* consonant sequences have shown that the temporal and spatial production of consonants is influenced by syllable position (e.g., Hardcastle, 1985; Byrd, 1996; Loevenbruck, Collins, Beckman, Krishnamurth, & Ahalt, 1999; Keating, Wright & Zhang, 1999; Byrd, Lee, Riggs, & Adams, 2005; Tiede *et al.*, 2007). Moreover, the observation that serial ordering errors in spontaneous speech are greatly biased to occur between phonemes (or clusters) that occupy the same position in different planned syllables or words further bolsters the view that phonological planning representations and/or motor programming units may be positionally constrained (Hindson & Byrne, 1984; MacKay, 1972; Shattuck-Hufnagel, 1983; Treiman, 1984). A finding that PWM structures or articulatory motor programs for phonemes are sensitive to phonetic context would have important implications for models of speech serial planning and phonetic encoding, as well as for the design of speech motor rehabilitation therapies.

Last, but not least, Segawa *et al.* (2019) focused on motor performance gains without actually measuring the verbal working memory span of participants. Hence, the results only offer speculative support for the role of working memory in task performance. Here we explore whether individual differences in speech motor sequencing show a relation with well-established measures of phonological working memory capacity. Such a finding would be compatible with the view that speakers with a larger working memory capacity can reliably construct and maintain more detailed serial speech plans than those with a smaller working memory capacity (cf. Lee & Redford, 2015).

In the current research, we addressed the foregoing issues by using working memory capacity limits to identify the elementary working memory structures involved in serial speech planning and phonetic encoding. As in Segawa *et al.*, we used a cued motor-sequence learning paradigm in which participants repeatedly produced CCVCC words containing non-native onset and coda clusters. Following learning, however, we tested for generalization by having participants repeat four types of *pairs*^c of CCVCC words involving non-native clusters. The use of word pairs, rather than singletons, during the test blocks forced participants to maintain the second word in working memory while the first word was buffered and concurrently articulated. Thus, accuracy and timing measures from the first word, which involved little or no demand on phonological working memory, provided a window into the motor programs used in speech, whereas measures for the second word provided insight into phonological working memory mechanisms. The pairs of words used in the test blocks were carefully constructed such that they systematically differed in their degree of overlap with those practiced in the training phase, and, therefore, also in how much they taxed verbal working memory.

Speech motor practice is expected to lead to the concatenation of motor elements in the training sequences into larger, cohesive chunks in PWM, thereby reducing the processing load and decreasing the sequencing error rate and/or performance speed over time. Indeed, our sequencing studies employing functional magnetic resonance imaging (fMRI), which collected imaging data during the testing phase, after the training phase has taken place outside of the scanner (Segawa *et al.*, 2015; Masapollo, *et al.*, in prep), found greater activation in working memory related regions (inferior frontal sulcus (pIFS), pre-supplementary motor area, anterior insula, and intraparietal sulcus) during the production of novel words compared to trained words. Since sequences with

^c During pilot testing, we found that prompting participants to produce longer lists of non-native CCVCC words comprised of either three or four items was too challenging a task.

more chunks (and hence higher processing loads) are expected to lead to more errors, we expected to observe different error patterns for the second word in the pair across the various experimental conditions for different hypothesized working memory unit types. Specifically, if chunking leads to the formation of a generalized working memory representation of the consonant cluster, then we would expect speakers to exhibit better (and/or faster) performance of novel words that contain the practiced clusters relative to novel syllables with novel clusters. If, however, working memory units code clusters based on their serial position in a word/syllable (i.e., onset versus coda position), then we would expect performance of novel words containing practiced onsets and codas to exhibit better (and/or faster) performance than novel words containing practiced clusters in an unpracticed syllable position. Alternatively, if speakers store and retrieve syllable-sized working memory units, then speakers should exhibit better (and/or faster) performance when producing practiced words but should show no improvements when only the onset/coda clusters are practiced.

2. Materials and Methods

2.1 Participants. Sixteen students (6 males, aged 18-25 years, mean age = 20.4 years [$SD = 2.0$]) from Boston University were recruited and paid for participating in two testing sessions. An additional three participants were tested but excluded from analysis due to equipment failure [2] or experimenter error [1]. Participants reported normal (or corrected-to-normal) vision and no history of hearing, speech, language or neurological deficits. All were native, monolingual speakers of standard American English with no previous experience with any of the languages used in the stimulus creation (see following text). We assessed each participant's profile using the Language Experience and Proficiency Questionnaire (LEAP-Q; Marian, Blumenfeld, & Kaushanskaya, 2007). Participants gave informed consent in accordance with the human-subjects policies of Boston University.

To characterize participants' verbal working memory capacity, we administered two subtests from the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgeson, & Rashotte, 1999): 1) Memory for digits, which measures the extent to which an individual can repeat a series of numbers (presented auditorily) ranging in length from two to eight digits; 2) Non-word repetition, to measure an individual's ability to repeat non-words (also presented auditorily) that range in length from three to 15 phonemes. To successfully repeat the digits and non-words, an individual must create, store, and maintain a phonological planning representation robust enough to support subsequent articulation.

2.2 Stimuli. The stimuli consisted of four sets of monosyllabic CCVCC non-words (four words/set). As shown in Table 1, all items contained non-native (i.e., phonotactically-illegal) syllable-initial (onset) and syllable-final (coda) consonant clusters. While all of the individual consonants occur in the English phonemic inventory, the particular combination or serial ordering of the segments does not occur in English but does occur in some other natural human language. The non-native clusters were taken from a variety of language and language families including Hebrew, Leti and Taba, Romani, Polish, Lithuanian, Romanian, Georgian, Tepehua, Hungarian, and Pima (see Segawa, 2013; Segawa *et al.*, 2015, for details). None of the participants had prior experience with any of the languages in which these phonotactic sequences are used.

--- [Insert Table 1 about here] ---

To create the prompts for the cued sequence production task, a male native speaker of standard American English was recorded producing the four sets of words. The model speaker was phonetically trained and had previously practiced producing the sequences until each stimulus could be executed fluently (i.e., without vowel epenthesis or phoneme omissions, swaps, or substitutions). Since we were concerned with learning of non-native phonotactics rather than sub-

phonemic allophonic details, productions were not judged on how natural they sounded in the languages from which they were derived. All recordings took place in a sound-attenuated booth. Speech was recorded directly to a computer using Praat software (Boersma & Weenink, 2020) via a lapel microphone (Shure, SM93) connected to a pre-amplifier (44.1-kHz sampling rate, 32-bit quantization). The speaker recorded multiple randomized repetitions of each token. From these repetitions, one instance of each token was selected on the basis of acoustic similarity in voice pitch (f_0) to the other stimuli in the set. Using Praat, all recorded tokens were matched for peak intensity and duration (i.e., 480-ms) without changing f_0 .

2.3 Procedure and design. The experiment consisted of a training phase followed by a transfer test phase. In the training phase, participants were asked to repeat an isolated CCVCC word on each trial. In the test phase, participants were asked to repeat pairs of transfer CCVCC words that overlapped to varying degrees with the those produced in the training phase; in both cases, participants were asked to repeat aloud the word(s) which were presented both auditorily over noise-cancelling headphones and visually using orthography (as shown in Table 1). The training phase consisted of six blocks of trials over two consecutive days (four on day one and two on day two). Each training block contained 10 repetitions of each word, for a total of 40 trials per block. The test phase consisted of two blocks of trials performed on day two after completing the final two training blocks. Each test block contained 10 repetitions of each transfer word pair (shown in Table 1) from four stimulus categories (conditions): (1) *practiced CCVCC* pairs (i.e., pairs comprised of words that were previously encountered in the training phase), (2) *practiced OC* word pairs (i.e., pairs of novel words that contained non-native consonant clusters that appeared in the same local phonetic context [onset or coda position] in the training words), (3) *practiced CC* word pairs (i.e., pairs of novel words that contained non-native clusters that appeared

in the training words but in a different syllable position [onset or coda position]), and (4) *novel* *CCVCC* word pairs (i.e., pairs of novel words with novel clusters that were not encountered in the training words). This resulted in a total of 80 productions in each test block. Participants produced the target word (or word pairs) in a pseudorandom order. Participants were randomly assigned to one of two experimental groups, which were trained with different *CCVCC* words. As shown in Table 1, group one was trained with “shkizg”, “kshapk”, “zvupf,” and “bdesch”; group two was trained with “shkupk”, “kshezg”, “zvisch,” and “bdepf.” During the subsequent test phase, participants were asked to produce each trained cluster in novel words in both onset position and coda position to assess the contextual specificity of motor-sequence learning.

The experiment was programmed in MATLAB (MathWorks Inc., Natick, MA) using the Audio System and Psych Toolboxes. Participants were seated in a chair in front of a laptop (Lenovo ThinkPad X61s) computer screen in a sound-treated laboratory room that was dimly lit. The auditory stimuli were presented over headphones (Sennheiser, HD 280 Pro) at a comfortable listening level and utterances produced by participants were recorded with a lapel microphone (Shure, SM93) connected to the computer via a MOTU Microbook audio interface. Utterances were recorded using MATLAB.

Each trial consisted of the following sequence of events. First, the orthographic display of the target word(s) appeared in the center of the screen in tandem with its corresponding auditory prompt. Participants only heard each prompt once. In the training trials, the visual display time for each text stimulus was synchronized with the duration of the associated audio files (i.e., 480- ms). In the test trials, both text stimuli appeared side-by-side and were displayed for 2,210-ms – this duration was calculated from the onset of the first auditory stimulus to 1,000-ms after the

offset of the second auditory stimulus (this included an inter-stimulus interval of 250-ms)^d. Then, after the offset of the visual stimuli, a pure tone was presented for 50 ms. The time between the offset of the visual stimulus and tone onset was randomly jittered between 1,500-ms and 2,000-ms in the training trials and between 2,500-ms and 3,000-ms in the test trials. This tone served as a “Go” signal for the participant to repeat the target word(s) as clearly and accurately as possible. Utterances were recorded for 3,000-ms in the training trials and 5,000-ms in the test trials. Syllables were randomized across trials. We opted to combine the text with the audio presentations because prior studies indicate that listeners tend to perceive non-native consonant clusters as epenthesized disyllabic sequences in an audio-only mode (e.g., Dupoux, Kakehi, Pallier, Hirose, & Mehler, 1999; Berent, Steriade, Lennertz, & Vaknin, 2007; Dupoux, Parlato, Frota, Hirose, & Peperkamp, 2011). Moreover, other research (Davidson, 2010) that directly examined the effects of stimulus input modality (audio only vs. audio and text) on participants’ ability to produce non-native consonant clusters found that the presence of text led to an improvement in overall task performance.

Participants were instructed to repeat the target word(s) as clearly and accurately as possible as soon as they heard the tone. They were also instructed to attempt to eliminate any vowel-like insertions between consonants within a cluster, a common response when producing novel illegal consonant clusters (cf. Davidson, 2006). Several familiarization trials with experimenter feedback were included at the start of the experiment to confirm that participants understood the task instructions and were able to perform the task. The sequences used during these initial practice trials were not used at any point in the rest of the study.

^d Pilot testing revealed that the task during the test phase was too challenging without giving participants additional time (after the offset of the second auditory stimulus) to process the visual text stimuli, suggesting that constraints from reading processes may influence task performance.

Because participants were not provided with online feedback about their performance, they had to learn the novel sequences through a trial-and-error process using a combination of motor exploration and performance evaluation. That is, speakers attempted to produce a given sequence by exploring different methods of moving their articulators, and then evaluated the results of those movements using a combination of auditory and somatosensory perceptual feedback signals. Whether or not the vocal tract maneuvers were ultimately successful in achieving a speech target determined whether it should be repeated.

2.4 Data processing. We used a combination of Praat and custom MATLAB software to perceptually rate and acoustically measure onsets and offsets of syllables by viewing the waveform and spectrogram and listening to the audio files. Each utterance was coded by a trained phonetician, blinded to experimental condition, for seven possible error subtypes: (1) gross disfluency (i.e., productions in which a participant omitted, repeated, or restarted an utterance); (2) unrecognizable from target; (3) phoneme deletion/omission; (4) phoneme insertion (i.e., one or more segments were added); (5) phoneme substitution; (6) incorrect ordering of phonemes; (7) vocoid epenthesis (i.e., truncated vowel-like sounds between consonants within a cluster, evidenced by periodic peaks and a visible second formant in the spectrogram; cf. Wilson, Davidson & Martin, 2014; Buchwald, Calhoun, Rimikis, Lowe, Wellner, & Edwards, 2019).

As in Segawa *et al.* (2019), we considered vocoid epenthesis errors to be errors in fluency (in the sense of sounding somewhat different than a native speaker producing the clusters, as if with a strong foreign accent) rather than errors in phoneme sequencing. Previous work examining the production of non-native consonant sequences demonstrates that epenthetic vowels arise from inter-gestural mistiming (Davidson, 2005, 2006; Buchwald, Calhoun, Rimikis, Lowe, Wellner, & Edwards, 2019); a transitional vowel is produced when the achievement of a consonantal

constriction does not temporally overlap with the release of the previous tautosyllabic consonantal constriction. Since the primary goal of the current study was to investigate the cognitive processes involved in selecting the proper sequence of motor gestures, rather than the processes involved in articulatory timing, we focused our analyses on sequencing errors (subtypes 1-6). Mean error rates for each participant were calculated as the percentage of trials that contained one or more errors.

In addition to error rates, we also used production timing measures that have been widely used in prior studies (e.g., Sternberg, 1978; Klapp, 1995, 2003; Wright *et al.*, 2009) to probe the nature of working memory sub-units for motor “chunks,” namely utterance duration and reaction time (RT). Duration (i.e., time from utterance onset to offset) and RT (i.e., time from the offset of the Go signal to utterance onset) were automatically labeled for each produced word based on sound pressure level thresholds, then hand-checked. For the test trials, we also computed the inter-item-intervals (i.e., time from the offset of the first word production to the onset of the second word production).

3. Results

A. Training trials. Our first set of analyses confirmed the presence of motor-sequence learning in the training trials by examining the time course of improvement in three performance measures – sequencing error rates, utterance durations, and RTs – over the two days of speech motor practice. For each word, we computed scores for each performance measure by averaging the values obtained on the first five and last five training trials on day one and the first five training trials on day two. Duration and RT measures were only analyzed for the first or last five utterances coded as *properly sequenced* productions (see above) on each day. These scores were then pooled and averaged across words within each time point and within each participant. Figure 1 shows the results of these analyses. Separate analyses of variance (ANOVAs) were performed on the mean

sequencing error rates, durations, and RTs with time as a within-subjects factor (five trials on day one vs. last five trials on day one vs. first five trials on day two). In these and all subsequent ANOVAs, Greenhouse-Geisser corrections were applied when appropriate and partial eta-squared effect sizes were calculated for all main effects and interactions. Post-hoc pairwise comparisons were reported as significant at the .05 level.

Significantly improved performance was found for all three measures, verifying that learning occurred for the training words. Specifically, the ANOVA performed on sequencing error rates^e (shown in Figure 1A) revealed a highly significant main effect of time [$F(2,30) = 17.906, p < .001, \eta^2_p = 0.544$]. Post-hoc t -tests performed on the pairwise differences indicated that participants produced utterances with fewer errors between the first five [$M = 49.6; SD = 24.5$] and last five training trials on day one [$M = 27.5; SD = 19.9; t(15) = 4.745, p < .001, d = 0.99$]. These performance gains were retained overnight as mean error rates were not significantly different between the last five training trials on day one and the first five training trials on day two [$M = 27.5; SD = 19.7; t(15) = .000, p = 1.000, d = 0$].

The ANOVA performed on utterance durations (shown in Figure 1B) indicated that there was also a significant main effect of time [$F(2,30) = 3.765, p = .035, \eta^2_p = 0.201$]. Post-hoc t -tests performed on the pairwise differences indicated that participants got faster at executing their utterances between the first five [$M = .74; SD = .10$] and last five training trials on day one [$M = .71; SD = .09; t(15) = 2.382, p = .031, d = .31$], but that the last five training trials on day one and the first five training trials on day two [$M = .70; SD = .09$] were statistically equivalent [$t(15) = .890, p = .388, d = .11$]. Taken together, these results provide clear evidence that participants

^e See *Supplementary Materials* for further details regarding time-course data and analyses of syllable position effects.

showed improvements in both performance accuracy and speed over multiple training blocks, and that these gains are retained following an overnight delay without further speech motor practice.

For mean RTs (shown in Figure 1C), we again found a significant main effect of time [$F(2,30) = 24.747, p < 0.001, \eta^2_p = 0.613$]. Post-hoc t -tests performed on the pairwise differences indicated a reliable learning effect, such that participants got faster at initiating their utterances between the first five [$M = .97; SD = .17$] and last five training trials on day one [$M = .88; SD = .19; t(15) = 3.469, p = .003, d = .49$], and faster still between the last five training trials on day one and the first five training trials on day two [$M = .79; SD = .17; t(15) = 3.338, p = .004, d = .49$]. The latter finding demonstrates that additional off-line improvements in initiation speed occurred over time without practice. Analogous overnight performance enhancements have been reported in a number of motor-sequence learning studies outside of the realm of speech (e.g., finger tapping tasks). The contribution of sleep-mediated memory consolidation to these facilitation effects is supported by a number of studies (e.g., Walker, Brakefield, Morgan, Hobson, & Strickgold 2002; Walker, Brakefield, Hobson, & Strickgold, 2003), although this interpretation remains controversial (for discussion, see Brawn, Fenn, Nusbaum, & Margoliash, 2010; Pan & Rickard, 2015). Nevertheless, given these findings, we then proceeded to examine generalization of these performance gains to the novel, untrained syllables.

-- [Insert Figure 1 about here] --

B. Test trials. Our second set of analyses assessed transfer of learning to the novel word pairs in the test phase by examining differences in four dependent measures – sequencing error rates, utterance durations, RTs, and inter-item intervals – between the different experimental conditions (*practiced CCVCC* vs. *practiced OC* vs. *practiced CC* vs. *novel CCVCC*). In the analyses performed on sequencing error rates and durations, we also directly compared

performance for the two different stimulus items (first item vs. second item in word pairs) within each condition since the second word is expected to rely most on PWM mechanisms because of its serial position. Table 2 provides the mean frequency of each error subtype in each condition for each stimulus item. As in Segawa *et al.* (2019), the most common sequencing error was the omission of one or more phonemes in the target syllable.

Sequencing error rate. Figure 2 illustrates the mean sequencing error rates pooled and averaged (across subjects) as a function of condition and stimulus item. As the figure shows, participants (unsurprisingly) had some difficulty remembering and producing the pairs of words and generated a high number of sequencing errors. Critically, however, error rates systematically differed across conditions and stimulus items. An ANOVA on these error rates – condition (*practiced CCVCC* vs. *practiced OC* vs. *practiced CC* vs. *novel CCVCC*) X stimulus item (first item vs. second item in syllable pairs) – showed a significant effect of stimulus item [$F(1,15) = 26.241, p < 0.001, \eta^2_p = 0.636$]: Participants produced fewer errors when executing the first item [$M = 53.1; SD = 19.6$] compared to the second item [$M = 72.2; SD = 18.9$] in the syllable pairs. This is consistent with other findings in the literature that recall tends to be better for early list items than later list items in verbal working memory tasks (Baddeley, 1986; Burgess & Hitch, 1992). In this case, participants were forced to maintain the second word in working memory during concurrent storage and articulation of the first word, which in turn, may have interfered with storage of the second word. An alternative possibility is that participants may have simply paid a greater amount of attention to the linguistic form of the first word in the planned utterance.

The effect of condition was also significant [$F(3,45) = 27.720, p < 0.001, \eta^2_p = 0.649$], as was the predicted interaction [$F(3,45) = 7.979, p < 0.001, \eta^2_p = 0.347$]. Simple effects tests on the stimulus item X condition interaction revealed that there was a significant effect of condition on

both the first syllable [$F(3,45) = 31.844, p < 0.001, \eta^2_p = 0.680$] and the second syllable [$F(3,45) = 11.010, p < 0.001, \eta^2_p = 0.423$]. Post-hoc t -tests on the pairwise comparisons for the *first* syllable indicated that the mean error rates for the *practiced CCVCC* syllables [$M = 20.0; SD = 22.5$] were significantly lower than the *practiced OC* [$M = 51.8; SD = 29.9; t(15) = -5.193, p < .001, d = 1.2$], *practiced CC* [$M = 59.3; SD = 28.6; t(15) = -6.498, p < .001, d = 1.5$], and *novel CCVCC* syllables [$M = 81.2; SD = 16.6; t(15) = -13.453, p < .001, d = 3.0$]. In addition, the mean error rates for the *practiced OC* syllables were significantly lower than the *novel CCVCC* syllables [$t(15) = -4.825, p < .001, d = 1.2$], and the mean error rates for the *practiced CC* syllables were lower than the *novel CCVCC* syllables [$t(15) = -3.732, p = .002, d = 0.93$]. Although, the *practiced OC* and *practiced CC* error rates were not significantly different from each other [$t(15) = -.864, p = .401, d = .25$], there was a small benefit to having practiced producing the clusters in the same syllable position. Overall, the error rate results for the first syllable mirror our prior findings using only a single test syllable (Segawa *et al.*, 2019): syllables practiced in their entirety show the lowest error rates, while practicing only a subset of the syllable (in this case the consonant cluster in either the same or different syllable position) resulted in somewhat lower error rates than fully novel syllables but higher error rates than fully practiced syllables.

The pairwise comparisons for the *second* syllable indicated that the mean error rates for the *practiced CCVCC* syllables [$M = 49.3; SD = 36.6$] were significantly lower than the *practiced OC* [$M = 73.1; SD = 26.5; t(15) = -2.911, p = .011, d = .74$], *practiced CC* [$M = 90.6; SD = 15.2; t(15) = -4.522, p < .001, d = 1.47$], and *novel CCVCC* syllables [$M = 75.6; SD = 20.3; t(15) = -3.992, p = .001, d = .88$]. However, practicing a subset of the syllable did not improve error rates over fully novel syllables: the *practiced OC* and *novel CCVCC* error rates were not significantly different from each other [$t(15) = -.389, p = .703, d = .10$], and the error rate for the *practiced CC*

syllables was actually higher than that for the *novel CCVCC* syllables [$t(15) = 2.818, p = .013, d = .83$]. In addition, the mean error rates for the *practiced OC* syllables were significantly lower than the *practiced CC* syllables [$t(15) = -2.369, p = .032, d = .81$]. Collectively, these results suggest that consonant clusters are positionally encoded in phonological working memory structures but not motor programming units.

Duration of individual motor speech elements. As already discussed, production timing measures during sequence production have been associated with working memory processes (e.g., Sternberg, 1978; Klapp, 1995; Wright *et al.*, 2009), which are more taxed when more sub-units (or chunks) need to be concatenated and stored. We therefore reasoned that *temporal* aspects of sequence generation (i.e., utterance duration and initiation speed) should increase with the number of subunits (in our case, the number of sub-units in each word/syllable) in PWM.

As can be seen in Figure 2, participants often produced a sequencing error on one of the stimulus items within a given syllable pair, especially for the *practiced CC* and *novel CCVCC* conditions, which severely limited the number of properly sequenced productions that could contribute to the temporal measurements. To increase our statistical power, we opted to examine generalization of the production timing measures based on the mean durations, RTs, and inter-item-intervals obtained for each word pair on the first five test trials, regardless of whether both items were properly sequenced or not. This provided a gross measure of how comfortable participants were with producing these non-native sequences following training. Durations were pooled and averaged within each condition and stimulus item and within each subject. RTs and inter-item intervals were also all pooled and averaged within each condition and within each subject.

Figure 3 shows the mean utterance durations (across subjects) as a function of condition. The ANOVA performed on mean durations revealed significant main effects of stimulus item [$F(1,45) = 18.069, p = .001, \eta^2_p = 0.546$], such that the first syllable was executed faster [$M = .65; SD = .10$] than the second syllable [$M = .72; SD = .12$]. There was also a main effect of condition [$F(3,45) = 3.433, p = .025, \eta^2_p = 0.186$] and a significant interaction effect [$F(3,45) = 7.754, p < .001, \eta^2_p = 0.341$].

Simple effects tests on the stimulus item X condition interaction revealed that there was a significant effect of condition on the performance speed of the second syllable [$F(3,45) = 9.681, p < 0.001, \eta^2_p = 0.392$], but not the first syllable [$F(3,45) = 1.216, p = 0.315, \eta^2_p = 0.075$]. The lack of a significant duration difference between conditions for the first syllable is somewhat surprising given that our prior study using single test syllables (Segawa *et al.*, 2019) found that practicing either the full syllable or the onset or coda cluster resulted in lower durations than fully novel syllables. Overall, mean utterance duration for the first syllable in the current study was longer than for the isolated syllable in the prior study [$t(25) = -2.169, p = .040, d = .89$].

The duration pattern for the second syllable in the current study mirrored those for the single syllable in our prior study, namely that practicing onset and coda clusters led to duration reductions compared to fully novel syllables that were statistically indistinguishable from the duration reductions for fully practiced syllables. Specifically, follow-up *t*-tests on the pairwise comparisons for the second syllable indicated that the mean durations for the *practiced CCVCC* syllables [$M = .67; SD = .10$] were significantly faster than the *practiced CC* [$M = .75; SD = .11; t(15) = -5.417, p < .001, d = .76$] and *novel CCVCC* syllables [$M = .77; SD = .14; t(15) = -3.895, p < .001, d = .82$]. However, the differences between the mean durations for the *practiced CCVCC* syllables and *practiced OC* syllables [$M = .70; SD = .11$] did not reach significance [$t(15) = -1.852,$

$p = .084, d = .28$]. In addition, the mean durations for the *practiced OC* syllables were significantly faster than both the *practiced CC* syllables [$t(15) = -3.281, p = .005, d = .39$] and the *novel CCVCC* syllables [$t(15) = -2.591, p = .020, d = .55$]. The *practiced CC* and *novel CCVCC* durations were not significantly different from each other [$t(15) = -.740, p = .471, d = .15$].

-- [Insert Figure 3 about here] --

Reaction time and inter-item-interval. Figure 4 shows the mean RTs and inter-trial-intervals (across subjects) as a function of condition. An ANOVA analysis of RT scores with experimental condition (*practiced CCVCC* vs. *practiced OC* vs. *practiced CC* vs. *novel CCVCC*) as a within-subjects factor was performed on utterances produced during the first five test trials of each condition. There was no main effect of condition [$F(3,45) = 1.920, p = .140, \eta^2_p = 0.113$], indicating that the reaction time for producing the first syllable did not significantly depend on condition. In contrast, an ANOVA analysis of inter-trial intervals revealed a highly significant main effect of condition [$F(3,45) = 7.383, p < .001, \eta^2_p = 0.330$]. Post-hoc *t*-tests performed on these pairwise differences indicated that participants initiated the second stimulus item faster for the *practiced CCVCC* syllables [$M = .32; SD = .16$] than the *practiced CC* [$M = .40; SD = .13$; $t(15) = -3.441, p = .004, d = .54$] and *novel CCVCC* syllables [$M = .43; SD = .14; t(15) = -3.540, p = .003, d = .74$], but not for the *practiced OC* syllables [$M = .35; SD = .17; t(15) = -1.601, p = .130, d = .18$]. Inter-item-intervals for the *practiced OC* syllables were also significantly faster than the *novel CCVCC* syllables [$t(15) = -2.485, p = .025, d = .51$] but not significantly faster than the *practiced CC* syllables [$t(15) = -1.847, p = .085, d = .33$]. In sum, the pattern of the delay prior to onset of the second syllable (the inter-trial interval) across conditions mirrored the pattern for second syllable duration: practicing onset and coda clusters led to inter-trial interval reductions

566 compared to fully novel syllables that were statistically indistinguishable from the inter-trial
567 interval reductions for fully practiced syllables.

568 -- [Insert Figure 4 about here] --

569 *Duration of entire sequence of motor speech elements.* In much of the literature on working
570 memory and motor-sequence production (e.g., Sternberg, 1978; Klapp, 1995; Wright *et al.*, 2009),
571 the focus has been on RT before the first element, as well as overall duration of the entire sequence
572 of motor elements (rather than the duration of individual elements, as reported above). The data
573 and arguments from these studies (albeit using different paradigms and tasks) have given rise to
574 two main claims: (1) RT for the first item does not depend on the number of working memory sub-
575 units (or “chunks”) in each item, since the motor program for the first item can be retrieved and
576 unpacked prior to the onset of the Go signal^f, and (2) overall sequence duration should increase
577 with the number of sub-units in working memory. The first claim, that RT should be the same
578 across all experimental conditions, was confirmed in both the present experiment (Figure 3, left
579 panel) as well as in our prior study (Segawa, *et al.*, 2019).

580 As for the second claim, we know this to be the case from Segawa, *et al.* (2019) since
581 overall duration was the same as element duration in that experiment (i.e., participants produced
582 singletons rather than word pairs during test). Recall, in that study, that the duration for *practiced*
583 *CCVCC* and *practiced OC* words were statistically equivalent to one another, and shorter than that
584 of the *novel CCVCC* words. This finding is compatible with the view that well-learned consonant
585 clusters constitutes a single item (an onset or coda) in PWM; both the *practiced CCVCC* and
586 *practiced OC* words consist of three working memory elements, while words containing novel

^f RT in a choice reaction time paradigm, on the other hand, would depend on the number of sub-units in the syllable since the sub-units cannot be unpacked until the Go signal indicates which syllable to produce (Klapp, 1995; Klapp, 2003).

consonant clusters involve five items since consonant cluster units do not exist yet for these words and thus each phoneme from the cluster must be represented as a distinct item.

To examine further whether this is the case for the word pairs in the present experiment, we conducted an additional analysis in which we computed the mean overall duration of word pairs during test trials as a function of experimental condition (*practiced CCVCC* vs. *practiced OC* vs. *practiced CC* vs. *novel CCVCC*). Overall duration was calculated by summing the duration of the first word, the inter-item-interval, and the second word duration. Figure 5 [left panel] shows the results of this calculation based on participants' first five production attempts, regardless of whether the utterance was properly sequenced. An ANOVA conducted on these duration measures with experimental condition as a within-subjects factor revealed a main effect of condition [$F(3,45)=8.404, p < .001, \eta^2_p = 0.359$]. Post-hoc *t*-tests revealed a significant difference between the mean duration of practiced CCVCC words pairs [$M = .1.62; SD = .26$] and practiced CC [$M = 1.81; SD = .28; t(15) = -4.352, p = .001, d = -.58$] and novel CCVCC word pairs [$M = 1.82; SD = .28; t(15) = -4.044, p = .001, d = -.61$]. The *practiced OC* [$M = 1.71; SD = .32$] and *practiced CC* durations were also significantly different from each other [$t(15) = -2.285, p = .037, d = -.26$]. All other post-hoc comparisons were not significant ($p > .05$). Additionally, Figure 5 [right panel] shows the results of this calculation based only on the first five production attempts that were perceptually judged to be properly sequenced, although there was insufficient data to perform formal statistical tests. Nevertheless, the results of the aforementioned analyses further bolster the view that *practiced CCVCC* and *practiced OC* words contain three chunks in PWM, corresponding roughly to onset-nucleus-coda, whereas *novel CCVCC* words contains five chunks in PWM, corresponding to individual phonemes.

-- [Insert Figure 5 about here] --

Relationship to standardized working memory scores. Our final set of analyses assessed the relationship between standardized measures of phonological working memory capacity and overall task performance in the test phase. Correlational analyses among each of the CTOPP digit recall and non-word repetition scores and the mean number of sequencing errors for each stimulus item (first word vs. second word) were performed. No correlations emerged among the digit recall scores and the mean number of sequencing errors produced on either the first item ($r = -.34, p = .19, n = 16$) or second item in the word pairs ($r = -.36, p = .16, n = 16$).

The correlation among the non-word repetition scores and the mean number of sequencing errors produced was significant for the second word ($r = -.60, p = .01, n = 16$) but not for the first word ($r = -.34, p = .19, n = 16$). A Fisher's r -to- z transformation was then performed to test for a potential difference in the size of these two correlations. Using either a one-tailed or two-tailed test of significance, these correlations were not found to significantly differ ($z = -0.86, p > .05$), however, contra the hypothesis that production of the second syllable is more dependent on PWM mechanisms. Furthermore, it is important to note that because participants produced more sequencing errors on the second word than the first word (Figure 2), there is also more variation and hence more statistical power to observe a correlation.

Although the foregoing results do not strongly support the notion that the production of the second word relies more heavily on phonological working memory than the first word, we should be careful not to draw firm conclusions from these analyses. It is possible that there simply were not a sufficient number of participants to have the power to detect a difference in size between the correlations. Another possibility is that we may need to use a more thorough test of verbal working memory (and potentially more stimuli) to capture meaningful differences.

4. Discussion

In the current study, we investigated the degree to which components of newly learned words containing non-native consonant clusters (practiced one at a time) generalized to transfer word pairs. The primary difference between production of the first and second words in the test phase of our protocol is that the second syllable must be held in PWM while the first syllable is being produced. Therefore, performance differences across conditions for the second syllable compared to the first presumably reflect properties of PWM mechanisms. Within this view, the present error rate results strongly imply that PWM differentiates between a consonant cluster in one syllabic position (onset or coda) and the same cluster in a different syllabic position. In fact, when participants were asked to produce a practiced cluster in a different syllable position, their performance deteriorated; this interference effect can be seen by the higher error rate for the *practiced CC* condition compared to the *practiced OC* and *novel CCVCC* conditions for the second word (Figure 2). Furthermore, improvements in the duration of the second word were seen only for words in which novel clusters appear in the same location as they appeared in the training phase. This is evidenced by the finding that second syllable durations in the *practiced CCVCC* and *practiced OC* conditions are shorter than for the *practiced CC* condition, with the *practiced CC* condition showing no improvement in duration over fully novel (*novel CCVCC*) syllables (Figure 3). The same pattern was seen in the analyses of the inter-trial intervals (basically equivalent to second syllable reaction time in our protocol; see Figure 4) and overall duration of the word pairs (see Figure 5), again highlighting the importance of syllabic position constraints on PWM. Such findings suggest that, during the early stages of speech motor-sequence learning, adjacent tautosyllabic consonants bind together into unified working memory units that are phonologically differentiated (onset vs. coda).

In contrast to the second syllable results, error rates for the first syllable exhibit a pattern indicating that improvements from practicing a consonant cluster in one syllable position generalize to novel syllables in which that cluster appears in a different syllable position (evidenced by equal error rates for the *practiced OC* and *practiced CC* conditions in Figure 2), with both of these conditions showing less improvement in accuracy than practicing the entire syllable (*practiced CCVCC* in Figure 2). These findings support the view that, unlike working memory structures, the motor programming units for speech production are not affected by the syllable position in which a newly learned phoneme subsequence (in this case a non-native consonant cluster) is learned; this “motor knowledge” can be applied any time the subsequence appears in future utterances, regardless of syllable position. Thus, PWM appears to utilize an onset-nucleus-coda syllabic frame structure, whereas the motor system appears to use a syllable-frame-independent representation of common phoneme sub-sequences.

Figure 6 provides a possible account of these findings, based on the gradient order DIVA (GODIVA) model of speech sequencing advanced by Guenther and his colleagues (Bohland *et al.*, 2010; Guenther, 2016). According to this model, the to-be-articulated segments in a planned utterance are temporarily stored in a phonological working memory repository (or buffer). During the production of native-language speech, syllables are represented by up to three chunks in this repo: an onset consisting of one or more initial consonants, a nucleus (vowel), and a coda consisting of one or more final consonants (O-N-C representation). We hypothesize that this representation is used for any syllable that utilizes native consonant clusters or highly-practiced non-native clusters, as schematized in the *practiced CCVCC* and *practiced OC* conditions of Figure 6 for the phonotactically illegal syllable BDEPK. When producing a syllable containing novel non-native clusters, the system is forced to represent each phoneme individually in PWM

(*novel CCVCC* condition in Figure 6). Thus, a fully novel CCVCC syllable requires five chunks in PWM compared to three for novel CCVCC syllables that utilize learned clusters and three for fully learned CCVCC syllables. Utterance duration in GODIVA depends on syllable complexity, specifically the number of chunks (or motor elements) for each syllable that must be retrieved and unpacked from PWM prior to production of the syllable, a relationship supported by numerous prior motor sequencing studies (e.g., Sternberg, 1978; Klapp, 1995, 2003; Wright *et al.*, 2009). According to this account, utterance duration should be longest for the *novel CCVCC* condition, with the *practiced OC* and *practiced CCVCC* conditions having the same duration; indeed, this is the pattern we found for utterance duration in both the current study and Segawa *et al.* (2019). Furthermore, because this account differentiates phonological and motoric learning processes, it may help explain why some individuals with apraxia of speech (AOS), namely those with primarily motoric deficits, improve their productions of consonant clusters with practice, while individuals with AOS who display primarily phonological deficits do not (Buchwald *et al.*, 2017).

-- [Insert Figure 6 about here] --

However, even if this account of serial speech sequencing turns out to be correct, we are still left with the deeper question as to why PWM structures, but not the motor programming units, appear to be contextually specified. One possibility is that higher-level working memory processes are shaped and constrained by linguistic experience to a greater degree than lower-level articulatory processes. Phonological units differ across languages and the brain becomes fine-tuned to the units of the language of exposure early in development (Kuhl, Ramirez, Bosseler, Lin, & Imada, 2014), and although some aspects of articulatory behavior are clearly affected by specific linguistic experience (e.g., Byrd *et al.*, 2005; Beddor, Harnsberger, & Lindemann, 2002; Tiede *et al.*, 2007), humans (and non-human animals) can (and must) learn to execute motor programs for

a wide range of sequential motor behaviors (e.g., typing keyboard sequences, playing a sport or musical instrument) that are not constrained by linguistic structure or rules.

In the current study, both duration and error rates were significantly lower for words practiced in their entirety during the training sessions compared to fully novel syllables. However, for novel syllables consisting of non-native consonant clusters that were practiced but in different syllables, error rates were significantly higher than for fully practiced syllables, while duration for these stimuli was just as low as for fully practiced sequences. The GODIVA model accounts for this difference by positing that duration measures are indicative of the number of chunks for each sequence in PWM, whereas articulatory error rates are indicative of the number of motor programs needed to produce the sequence. However, these findings also raise the possibility that there may be a dissociation between learning how to execute articulatory timing information (as measured by duration) and the proper sequence of articulatory motor gestures (as measured by error rates). That is, different aspects of sequence production may be learned on different time-scales^g and mediated by different cognitive processes and neural substrates. Interestingly, the GODIVA model does propose that prefrontal medial areas (left pre-supplementary motor area, left supplementary motor area) are recruited in coordinating the speech articulators in time to achieve motor goals in sequence, while lateral areas (left inferior frontal sulcus, left ventral premotor cortex) are thought to be recruited to generate speech motor programs for articulation. Further studies using an integrated combination of articulatory kinematic and functional brain-imaging methods are needed to provide a direct test of this claim, however, and isolate the neural substrates underlying articulatory errors versus utterance duration.

^g See *Supplementary Materials* for additional information on the time-course of speech motor-sequence learning.

One unexplained aspect of our findings is that of why we failed to observe any reliable timing differences across conditions for the first syllable (shown in Figure 3), unlike in Segawa *et al.* (2019). Our task was identical to that one used by Segawa and colleagues except that participants also had to buffer a subsequent word during concurrent articulation of the first word. Thus, somehow the timing differences documented by Segawa *et al.* washed out when there was a subsequent word stored in PWM. From our second syllable results, we reasoned that gains in performance speed seem to have to do with PWM processes. Thus, perhaps the “first” syllable in the Segawa *et al.* study was held in working memory longer but was processed more rapidly in the current study in order to minimize interference from the second syllable.

As well, the finding that, practicing a consonant cluster in one syllable position generalizes to novel syllables in which that cluster appears in a different syllable position (Figure 2 [left panel]), runs contra to previous reports that speech motor learning is contextually specific (Tremblay *et al.*, 2008; Rochet-Capellan *et al.*, 2012), and is somewhat surprising given that the temporal and spatial production of (native-language) consonant clusters (and their corresponding sensory outcomes) is known to be affected by syllable position (e.g., Hardcastle, 1985; Byrd, 1996; Loevenbruck *et al.*, 1999; Keating *et al.*, 1999; Byrd *et al.*, 2005; Tiede *et al.*, 2007). We might, therefore, speculate that during speech motor practice, participants learn higher-level patterns of coupling or coordination among articulators that can be flexibly assembled across different phonetic contexts.

Although cluster production was found to generalize to novel syllables containing those clusters, the results also showed that participants produced roughly twice as many errors in the *practiced OC* and *practiced CC* conditions compared to the *practiced CCVCC* condition (see Figure 2). There are at least two possible explanations for this later finding. One possibility is

that, during the initial stages of speech motor-sequence learning, speakers bind together the individual vocal tract movements associated with adjacent consonants into a unified action, or motor “chunk,” but that larger syllable-sized chunks are eventually formed in addition to consonant cluster-sized units. An alternative possibility, however, is that the relevant sequencing sub-units or chunks are actually onset-vowel or vowel-coda (rhyme) units. Indeed, there is a body of evidence supporting the later possibility.

Research on the interface between linguistic representation and speech production has demonstrated that the relative timing and stability of articulatory gestures (for native-language sequences and structures) changes systematically as a function of numerous contextual factors. One of these is syllable position (e.g., Browman & Goldstein, 1988; Byrd, 1996; Byrd *et al.*, 2005; Tiede *et al.*, 2007). Early research, using X-ray microbeam data, found that the temporal coordination between syllable-initial (onset) consonants and the syllable’s vowel differs from that of syllable-final (coda) consonants and the syllable’s vowel (Browman & Goldstein, 1988). In particular, it was found that the timing of the onset as a whole with respect to the vowel remained relatively stable, regardless of the number of consonants and the composition of a given onset cluster (i.e., “C-center” effects). In contrast, this cluster-vowel timing pattern did not emerge with codas. Subsequent studies, using both electropalatography (EPG) and electromagnetic articulography (EMA), obtained similar patterns with several onset clusters and languages and also showed that onset clusters tend to be implemented with less variable inter-gestural timing than coda clusters (e.g., Byrd, 1996; Byrd *et al.*, 2005; Pastatter & Pouplier, 2017). On the basis of these findings, some theoretical accounts have proposed that the motor programs for onsets and vowels are fused together as cohesive action units, or motor “chunks,” at least at some level of the speech production process (for discussion, see Goldstein, Byrd, & Saltzman, 2006; Pastatter &

Poupier, 2017). Such findings are relevant to the current research in that it is unknown whether one could transfer learning of non-native cluster coordination from onsets to codas and vice versa. Unfortunately, however, we are unable to directly address this issue without detailed, kinematic measures of the participants' articulatory movements, although we have begun to investigate gestural coordination for non-native productions in ongoing experiments using electromagnetic articulography (Cheng, Masapollo, Hagedorn, & Buchwald, in progress; Masapollo, Kearney, & Guenther, in progress). Additionally, a strong test of the so-called "C-center" hypothesis in the present context would require additional stimulus conditions, including *practiced CCV* and *practiced VCC* words. Future experiments will be designed with this issue in mind.

One important methodological limitation of the present study is that we solely measured changes in motor performance using perception-based segmental transcription and simple acoustic measures of utterance duration. However, this approach requires transcribers to make *categorical* decisions regarding the segments that speakers produce, and thus does not permit *quantitative* analysis of the presence or magnitude of various articulatory gestures. In other experimental studies designed to examine the nature of speech errors in both normal and disordered speakers (albeit using different speaking tasks and stimulus materials), researchers have provided compelling evidence that errors are often partial or gradient (see, e.g., Mowrey & MacKay, 1990; Goldrick & Blumstein, 2006; Goldstein, Poupier, Chen, Saltzman, & Byrd, 2006; Hagedorn, Proctor, Goldstein, Wilson, Miller, Gorno-Tempini, & Narayanan, 2017). Kinematic data from tongue and lip movements during sequencing errors elicited in our task could help provide further insights into whether such errors reflect limitations in PWM or incomplete control of gestural coordination. If errors derive from immature motor implementation rather than a limited working memory store, then we predict that speakers will generate truncated vocal tract constrictions

(which may be acoustically masked to transcribers). Else we predict that errors arise at a higher organizational level of speech planning whereby sequences of phonological units are assembled and temporarily buffered in the phonological store.

The transcription methods used in the current study also provide a limited window on speech motor learning itself since they provide an indirect measure of articulator movement characteristics among cluster elements (such as inter-gestural timing) and how they change as a function of speech motor practice. Moreover, other research on speech production indicates that the intended goals (or “targets”) of speech production are somatosensory, as well as acoustic, in nature (e.g., Tremblay, Shiller, Ostry, 2003; Golfinopoulos, Tourville, Bohland, Ghosh & Guenther, 2011), and that co-articulatory overlap can weaken or even obliterate acoustic cues for consonants (especially plosives) produced in clusters (Stevens & Keyser, 2010; Perkell, 2012). A complete understanding of speech motor-sequence learning, therefore, will require data on both acoustics and articulation. Ongoing work in our laboratory using electromagnetic articulography is aimed at characterizing how the articulatory activity that occurs within the inner reaches of the vocal tract dynamically changes during motor-sequence learning.

In conclusion, the present findings add to a vast and illuminating body of literature examining how speakers represent, plan and execute sequences of speech movements (as recently reviewed in Guenther, 2016). In moving toward a theory of language and speech production that fully explicates the organization and execution of speech sequences, future work should consider how working memory structures and sensorimotor programs for speech might differ across human languages, especially those that do not have tautosyllabic consonant clusters and/or a phonetically-transparent orthographic writing system (e.g., Japanese or Mandarin). Is it possible that the mere presence of text stimuli in our procedure and the one used by Segawa *et al.* (2019) may have biased

814 speakers to “visually chunk” or segment non-native phoneme sequences in a particular way. In
815 additional to potential reading processing effects, it is also not yet known whether and how these
816 units might vary in pre-literate children learning to talk, or in speakers with disorders of speech
817 sequencing (e.g., stuttering, apraxia of speech). Future studies in our laboratory will focus on
818 addressing these issues.

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1021 **Tables and captions**

Table 1: International phonetic alphabet (IPA) transcription and orthography for speech stimuli used to elicit the syllable-initial (onset) and syllable-final (coda) cluster targets (underlined). Each column represents the stimuli used in the four different experimental conditions. Each row represents the training and test stimuli used for each of the two experimental groups (see text for further explanation).

1027 **Table 2:** Mean error rates in the test blocks by error subtype, word type, and stimulus item.

1028

Figures and captions

Figure 1: Bar plots of the mean performance measures (across words and subjects) from the training blocks as a function of time (first five trials on day one vs. last five trials on day one vs. first five trials on day two). (Left panel) Mean percentage of sequencing errors. (Middle panel) Mean durations of properly sequenced utterances. (Right panel) Mean RTs of properly sequenced utterances. Error bars represent standard error of the mean. Abbreviations: *m* = marginally significant, * = significant ($p < .05$), ** = significant ($p < .01$), *** = significant ($p < .001$).

Figure 2: Bar plots of the mean sequencing error rates (across word pairs and subjects) for the first five trials in the test blocks (on day two) as a function of experimental condition (*practiced CCVCC*, *practiced OC*, *practiced CC*, and *novel CCVCC*) and stimulus item (first word vs. second word). Error bars represent standard error of the mean. Abbreviations: *m* = marginally significant, * = significant ($p < .05$), ** = significant ($p < .01$), *** = significant ($p < .001$).

Figure 3: Bar plots of the mean utterance durations (across word pairs and subjects) for the first five trials in the test blocks (on day two) as a function of experimental condition (*practiced CCVCC*, *practiced OC*, *practiced CC*, and *novel CCVCC*) and stimulus item (first word vs. second word). Error bars represent standard error of the mean. Abbreviations: *m* = marginally significant, * = significant ($p < .05$), ** = significant ($p < .01$), *** = significant ($p < .001$).

Figure 4: Bar plots of the mean reaction times and inter-item-intervals (across subjects) for the first five trials in the test blocks (on day two) plotted as a function of experimental condition

(*practiced CCVCC*, *practiced OC*, *practiced CC*, and *novel CCVCC*). Error bars represent standard error of the mean. Abbreviations: *m* = marginally significant, * = significant ($p < .05$), ** = significant ($p < .01$), *** = significant ($p < .001$).

Figure 5: Bar plots of the mean overall duration of word pairs (i.e., first word duration + inter-item-interval duration + second word duration) during test trials as a function of experimental condition (*practiced CCVCC* vs. *practiced OC* vs. *practiced CC* vs. *novel CCVCC*). Error bars represent standard error of the mean. Abbreviations: *m* = marginally significant, * = significant ($p < .05$), ** = significant ($p < .01$), *** = significant ($p < .001$).

Figure 6: Schematic of the GODIVA model's account of sub-syllabic sequencing in the *novel CCVCC*, *practiced OC*, and *practiced CCVCC* conditions. G_x = articulatory gesture for phoneme *x*. The blue squares/circles with bold outlines in the lower tier refer to motor programming units.

Mean Sequencing Error Rates

Mean Utterance Duration

Supplementary Material for:

Dissociation between phonological working memory structures and motor programming units during speech motor-sequence learning

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S.1 Time-course information in speech motor-sequence learning

Another common analysis method used to examine the time-course of motor-sequence learning involves comparing average performance (e.g., rate of sequence completion) over some equivalent duration or number of trials within the training phase. This type of calculation would allow researchers to compare performance for each training block relative to the other blocks in order to identify early versus late stages of learning. Figure S1 plots each of our motor performance measures – mean sequencing error rates, utterance duration, and reaction time – across the six training blocks (four on day one and two on day two).

S.1.1. Dissociation between execution of articulatory timing and phonological content

As figure S1 shows, the overall time-course of improvement of sequencing error rates (top panel) and utterance duration (middle panel) differ. Specifically, considerable improvements in error rates occur very rapidly within the first training block, whereas gains in duration do not emerge until the final block of training on day one. This finding suggests that speakers may learn different

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aspects of sequence production on different time scales; the ability to select and generate the proper sequence of articulatory motor gestures (as measured by error rates) appears to start quickly, but the execution of articulatory timing information (as measured by utterance duration) may take longer to establish. Using electromagnetic articulography, ongoing studies are examining gestural coordination in non-native sequence productions more carefully (Cheng, Masapollo, Hagedorn, & Buchwald, in progress; Masapollo, Kearney, & Guenther, in progress).

The aforementioned finding is also compatible with claims that the execution of articulatory timing and phonological content are mediated by different neural substrates (Bohland *et al.*, 2010; Guenther, 2016). Specifically, it has been proposed that prefrontal medial areas (left pre-supplementary motor area, left supplementary motor area) are recruited in coordinating the speech articulators in time to achieve motor goals in sequence, while lateral areas (left inferior frontal sulcus, left ventral premotor cortex) are thought to be recruited to generate speech motor programs for articulation.

S.1.2. Post-delay gains in motor sequence performance

As figure S1 shows, there is a trend for the production timing measures – mean utterance duration and reaction time – to show post-delay gains between the end of training on day one (block 4) and the start of training on day two (block 5). Analogous off-line improvements in performance have been reported in other types of motor-sequence learning studies (albeit using different tasks, e.g., finger-tapping) and have been hypothesized to depend on sleep-mediated memory consolidation (see, e.g., Walker *et al.*, 2002). However, other have argued that these types of post-delay gains may simply be an artifact of data averaging in the calculation of pre-post gain scores (for discussion, see Brawn *et al.*, 2010; Pan & Rickard, 2015). For example, fatigue build up might give rise to the worsening of sequence performance at the end of a long training session, which in

turn, might affect pre-post gain difference scores. In the present case, however, the time-course plots suggest that there is no performance fatigue worsening performance between the end of training on day one, consistent with the hypothesis that sleep may help to enhance some aspects of motor performance. Ongoing work in our laboratory is testing the hypothesis that sleep quality/duration plays an important role in encoding newly acquired speech motor sequences into long-term procedural memory. Specifically, we are examining whether sequence performance following sleep is better than performance after an equivalent period of time during wakefulness.

S.1.3. Incomplete motor learning

Figure S1 (top panel) indicates that, by the end of training, the mean sequencing errors rates are roughly 25 percent, which is still relatively high. Additionally, Figure 3 (in the main text) indicates that the average *practiced CCVCC* word duration is roughly 650 msec. Both of these findings suggest incomplete motor learning, assuming the average adult speech rate of four syllables/second (Kent, 2000; Guenther, 2016). However, we are not making the claim that, following two days of speech motor practice, speakers execute the *practiced CCVCC* words in a manner that is identical to native-language speech sequences. Rather, the present study captures an early aspect of the learning process (analogous to the earliest stages of second language learning in adulthood) and the extent to which those early performance gains generalize to novel, transfer words.

S.2 Effects of syllable position on speech motor-sequence learning

We conducted an additional analysis to test for potential effects of syllable position (syllable-initial [onset] clusters vs. syllable-final [coda] clusters) as such effects are suggested by some theories of speech production, especially Articulatory Phonology (see, e.g., Browman & Goldstein, 1988, 1995; Byrd, 1995, 1996; Keating, Wright, & Zhang, 1999; Byrd, Lee, Riggs, & Adams, 2005; Bohland, Bullock & Guenther, 2010). Specifically, we examined the time course of improvement

in the mean sequencing error rates for onset and coda clusters over the two days of speech motor practice. We performed an analysis of variance (ANOVA) with time (five trials on day one vs. last five trials on day one vs. first five trials on day two) and syllable position (onset clusters vs. coda clusters) as within-subjects factors. The results (shown in Figure S2) revealed a significant main effect of time [$F(2,60) = 8.523, p < .001, \eta^2_p = .221$] as well as an interaction effect involving syllable position [$F(2,60) = 14.477, p < .001, \eta^2_p = .325$]. The effect of syllable position was not significant [$F(1,30) = .515, p = .478, \eta^2_p = .017$].

Simple effects tests on the time X syllable position interaction revealed that there was an effect of time on sequencing error rates for codas clusters [$F(2,30) = 14.397, p < .001, \eta^2_p = .490$], but not onset clusters [$F(2,30) = 2.495, p = .099, \eta^2_p = .143$]. Follow-up *t*-tests on the pairwise comparisons for *coda* clusters indicated that subjects produced fewer sequencing errors between the first five [$M = 35.0; SD = 37.2$] and last five trials [$M = 12.0; SD = 17.5$] on day one [$t(15) = 3.789, p = .002, d = 1.00$], and between the first five trials on day one and the first five trials on day two [$M = 9.0; SD = 14.8; t(15) = 5.566, p < .001, d = 1.18$]. The difference in mean error rates between the last five trials on day one and the first five trials on day two was not significant [$t(15) = .618, p = .546, d = .18$]. Although the factors that influence this effect of syllable position are not entirely clear, we hypothesize that speakers may focus their attention on articulating early list versus late list motor elements in a planned speech sequence.

Supplementary References

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117

118 **Figure S1.** Motor performance measures across training blocks. Top panel: Mean percent sequencing error rates.
 119 Middle panel: Mean utterance duration (s; for properly sequenced productions only). Bottom panel: Mean reaction
 120 time (s; for properly sequenced productions only). Each data point represents the mean performance measure
 121 (averaged across words and subjects) for each training block (10 repetitions/training word). Error bars represent
 122 standard errors of the mean. The vertical dashed black line divides the first four training blocks performed on day one
 123 from the last two training blocks performed on day two.

Figure S2. Boxplots of sequencing error rates as a function of syllable position (syllable-initial [onset] clusters vs. syllable-final [coda] clusters) and epoch in training phase (first five productions on day one vs. last five productions on day one vs. first five productions on day two). *** = $p < .01$.