

# Multisyllabic nonwords: More than a string of syllables

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Nonword repetition is closely associated with the learning of the phonological form of novel words. Several factors influence nonword repetition performance such as short-term memory, phonotactic probability, lexical knowledge, and prosodic factors. The present study examined the influence of list duration, coarticulation, and prosody on nonword repetition by comparing naturally articulated multisyllabic nonwords to multisyllabic nonwords formed by concatenating syllables produced in isolation and serial lists (experiment 1), to multisyllabic forms that incorporated either valid or invalid coarticulatory information (experiment 2), and to multisyllabic forms either with or without common English within-word stress patterns (experiment 3). Results revealed superior recall for naturally articulated nonwords compared to lists of matched duration or sequences with invalid coarticulatory cues. Within-word stress patterns also conveyed a repetition advantage. The findings clearly establish that the coarticulatory and prosodic cues of naturally articulated multisyllabic forms support retention. © 2009 Acoustical Society of America. [DOI: 10.1121/1.3076200]

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## I. MULTISYLLABIC NONWORDS: MORE THAN A STRING OF SYLLABLES

The ability to repeat multisyllabic nonwords (nonword repetition) has been linked to new word learning in both children (Gathercole *et al.*, 1992) and adults (Atkins and Baddeley, 1998; Gupta, 2003), and in both native (Gathercole and Baddeley, 1989) and foreign language learning (Masoura and Gathercole, 1999, 2005; Service, 1992). Such findings have led to widespread interest in understanding the cognitive processes that underlie nonword repetition. Nonword repetition was first proposed as a relatively pure index of phonological short-term memory (STM) capacity (Gathercole and Baddeley, 1989, 1993). Reports that nonword repetition accuracy decreases with increasing nonword length (Gathercole *et al.*, 1994) and forms a classic serial recall curve (Archibald and Gathercole, 2007a; Gupta, 2005) are consistent with this position. Not all of the available evidence can be explained by STM, however.

Several studies have demonstrated that characteristics of the nonwords themselves influence performance, such as the extent to which the nonwords resemble real words (Gathercole, 1995), the prosodic structure of the nonword (Roy and Chiat, 2004), the phonotactic probability of the inherent phonemes (Edwards *et al.*, 2004), and the articulatory complexity of the nonword (Archibald and Gathercole, 2006). One area that has not been explored as closely concerns the extent

to which the coarticulatory information inherent in multisyllabic nonwords influences repetition accuracy. The studies reported in the present paper investigated three factors that may influence nonword repetition, nonword duration, coarticulatory cues, and within-word prosodic patterns.

The role of STM in nonword repetition has been investigated by comparing performance on this task to a classic immediate serial recall paradigm. In a recent study, typically developing children aged 6–12 years repeated nonword syllable lists presented either as whole multisyllabic forms or as lists of individual syllables for serial recall (Archibald and Gathercole, 2007a). Consistent with previous findings (Gupta, 2005), a serial recall curve was found for both conditions. Interestingly, the results clearly established more accurate repetition of the naturally articulated multisyllabic nonwords than lists of (equivalent) syllables presented individually, at least for this age range.

Why should multisyllabic nonwords be easier to recall than lists of individual syllables? One possibility lies in the temporal difference between the conditions. In the study of Archibald and Gathercole (2007a) overall stimulus duration was greater in the serial recall paradigm due to the pause time between list items. Attempting to retain information in STM for longer periods may lead to greater loss for two reasons. One explanation relates to the suggestion that the contents of STM spontaneously decay over time in order to allow for continuous updating and removal of information no longer needed (e.g., Baddeley, 1986; Cowan, 1999). According to this view, lists of longer duration will be subject to greater loss over time resulting in greater forgetting in the longer serial recall lists than the shorter nonword repetition

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condition. A second view holds that when several elements are held in STM simultaneously, interference arises such that representations may become degraded (e.g., [Nairne, 2002](#)). It follows from this that opportunities for interference will be greater when information is retained for longer periods.

An additional factor is the effect of coarticulation, the overlap in the articulation of sound gestures for consecutive segments of an utterance ([MacNeilage, 1980](#)). Coarticulatory information is known to influence speech perception. For example, listeners can predict the following vowel when presented with only the aperiodic portion of the consonants that preceded it (e.g., [Nittrouer and Whalen, 1989](#); [Tjaden and Sussman, 2006](#)); listeners are faster and more accurate at identifying a vowel when the preceding sounds contain appropriate coarticulatory information (e.g., [Martin and Bunnell, 1981, 1982](#)); and listeners have more difficulty identifying vowels when coarticulatory information is distorted such as in speakers with apraxia of speech ([Southwood et al., 1997](#)). It therefore appears that coarticulatory cues enhance listeners' ability to perceive the identity of later occurring segments in a way that maximizes the efficiency and speed of speech perception ([Ostreicher and Sharf, 1976](#)). It has been suggested that the absence of coarticulatory cues across word boundaries may account for the decrease in immediate sentence recall observed in synthetically as compared to naturally produced speech ([Paris et al., 2000](#)).

Coarticulatory cues are available across syllables in multisyllabic nonword repetition but not in serial list recall paradigms. Bidirectional coarticulatory effects across syllables from one vowel (V) to the preceding vowel (i.e., anticipatory effects) and to the vowel of the next syllable (i.e., carry-over effects) have been documented physiologically, acoustically, and perceptually ([Sharf and Ohde, 1981](#)). Coarticulatory effects have been found to be influenced by the intervening consonants ([Bell-Berti and Harris, 1976](#); [Hansen, 2003](#)), syllable stress ([Cho, 2004](#)), and the language spoken ([Beddor et al., 2004](#)). For example, languages with a dense vowel space such as American English have been found to allow more V-to-V coarticulation than languages with sparser vowel spaces ([Choi and Keating, 1991](#)). The effect of syllable structure on V-to-V coarticulation has also been studied, to some extent. Greater anticipatory than carry-over effects have been observed for open consonant (C)-vowel syllables (CV) such as those employed in the present study ([Modarresi et al., 2003](#)). Other studies, however, have reported no effect of syllable structure on V-to-V coarticulation ([Mok et al., 2007](#)).

There is growing evidence that the prosodic pattern of a nonword also influences immediate recall. Stress patterns have been found to affect repetition both for English ([Gupta et al., 2005](#); [Reeves et al., 2000](#); [Roy and Chiat, 2004](#)) and Japanese speakers ([Yuzawa and Saito, 2006](#)), and for typically developing and language impaired children ([Chiat and Roy, 2007](#); [Gallon et al., 2007](#)). Typically, errors are more frequent for weak than strong syllables with prestress syllables being the most vulnerable (e.g., [Roy and Chiat, 2004](#)). Our previous study of nonword repetition and serial recall ([Archibald and Gathercole, 2007a](#)) was not designed to investigate the influence of prosodic factors. Indeed, all of the

syllables in the multisyllabic nonwords contained tense vowels and were produced with equal-stress-across-syllables. This design served the dual purpose of improving the acoustic saliency of all syllables, and reducing the "wordlikeness" of the nonwords thereby making them resistant to support from long-term lexical knowledge ([Dollaghan and Campbell, 1998](#)). Nevertheless, a suprasegmental contour at the level of the whole nonword would have been present in the multisyllabic forms and may have led to improved recall. The extent to which suprasegmental or within-word stress patterns may facilitate the retention of multisyllabic forms over syllable lists remains unclear.

This paper presents three experiments aimed at investigating the role of phonetic information in nonword repetition performance. In these experiments, we manipulate list duration, coarticulatory information, and prosodic cues within a standard nonword repetition task. In each experiment adults recalled nonword CV syllable strings of matched phonological content under different conditions that manipulated temporal, coarticulatory, or prosodic aspects of the signal. Recall accuracy of naturally articulated multisyllabic nonwords was compared to multisyllabic strings of equal duration without coarticulatory cues in experiment 1, multisyllabic forms with and without valid coarticulatory cues in experiment 2, and multisyllabic forms with and without within-word stress in experiment 3. More accurate recall of natural nonwords and sequences with valid coarticulatory information would point to the role of coarticulation in supporting retention. And better performance on multisyllabic forms with within-word stress patterns would reflect the positive influence of prosodic information.

## II. EXPERIMENT 1

In the first experiment, participants repeated syllable strings presented as naturally articulated multisyllabic nonwords, in serial recall lists with one syllable presented at a rate of one per second, and as strings derived by concatenating individually produced CV syllables to obtain a multisyllabic nonword form of equivalent duration to the naturally articulated nonwords. One aim of experiment 1 was to establish the recall advantage of nonword repetition in an adult group. A second goal was to equate the temporal duration of naturally articulated multisyllabic nonwords and syllable strings through the use of simple concatenation. Less accurate performance on the serial recall lists but equivalent performance on the multisyllabic forms would point to the increased trial duration in serial recall as a significant detriment to performance. Superior repetition of naturally articulated than concatenated multisyllabic forms may reflect the importance of coarticulatory cues in enhancing recall.

### A. Method

#### 1. Participants

Twenty-four students participated in the present experiment (mean age=17.43 years, range=16.83–18.67). Participants were from a local sixth form in York, England and were completing their final year of high school. English was the native language of all participants.

TABLE I. Syllables used to construct stimuli for experiments 1 and 3.

Practice trials							
/faʊ/	/dʒaʊ/	/ga/	/va/	/tʃaɪ/	/uɔɪ/	/vəʊ/	
Experimental trials							
/kaɪ/	/kəʊ/	/daʊ/	/pɔɪ/	/teɪ/	/ba/	/gi/	/ku/
/faɪ/	/vəʊ/	/maɪ/	/mɔɪ/	/veɪ/	/ta/	/tʃi/	/fu/
/yaɪ/	/tʃəʊ/	/taʊ/	/dɔɪ/	/tʃeɪ/	/da/	/yi/	/vu/

## 2. Procedure

All participants completed a repetition task under three conditions: repeating naturally spoken nonwords (*natural nonwords*), *concatenated syllables*, and *syllable sequences*. Order of presentation of the conditions was counterbalanced, with eight participants completing each of three presentation orders. In each condition, eight experimental trials preceded by two practice trials consisting of five CV syllables were presented. The five-syllable length was chosen based on pilot testing indicating this sequence length resulted in adequate numbers of errors to yield accuracy rates below ceiling in most participants. The CV syllables comprising the lists were constructed from a pool of phonemes excluding the eight consonants that are late acquired (Shriberg and Kwiatowski, 1994). Only tense vowels were included so that the multisyllabic nonwords could be produced with roughly equal-stress-across-syllables (Dollaghan and Campbell, 1998), thereby minimizing prosodic differences among conditions. The resulting pool of 30 CV syllables, generated by combining 13 consonants and 8 vowels, are shown in Table I. Twenty-four syllables were selected for use in the experimental trials. The remaining six syllables were employed in the practice trials, with the exception that one syllable from the experimental pool was also used to construct the practice items in order to fulfill the criteria described below for sequence construction.

For each condition, the eight sequences were created by combining the syllables from the 24-syllable pool for the experimental tasks with the following constraints: No phonemes were repeated within a sequence; each vowel occurred in each ordinal position for each task; any syllables recurring in a condition occurred in a different ordinal position. Note that each syllable string across all conditions was unique in order to eliminate implicit learning that may arise from the repetition of identical items. A digitized recording was made of a female speaker producing the syllables in isolation and the multisyllabic nonwords.

Presentation of the experimental stimuli was controlled by a specialized computer program written in VISUAL BASIC (Microsoft Corporation, 2003). For the syllable sequence task, the participant was asked to listen to each sequence of sounds and repeat them in the same order. The syllable sequences were presented at the rate of one every 1 s for serial recall. For the natural nonwords' and concatenated syllables' conditions, the participant was told that they would hear a made-up word and asked to repeat it back immediately. All responses were recorded digitally and phonetically transcribed by the first author, a trained speech language pathologist.

The average duration of the syllables in the syllable sequence condition was 456 ms ( $SD=38.87$ ); the total trial duration of each sequence including pauses was approximately 3500 ms. The average duration of the natural nonwords was 2040 ms ( $SD=47.10$ ). The concatenated syllables were created such that each individual syllable was 408 ms, and the total trial duration was 2040 ms, equal to the mean length of the naturally produced nonwords. The concatenated syllables were created by compressing each of the relevant syllables from the syllable sequence condition to 408 ms using the time warp similarity function in GOLDWAVE (Gold-wave Inc., 2003), which overlaps similar sections of audio to reduce length, and then concatenating the five syllables in sequence with no intervening silence. Thus, the natural nonword and concatenated syllables' trials each presented continuous speech strings of equal duration, but the concatenated syllables were not naturally coarticulated.

## B. Results and discussion

Recall accuracy for each syllable in the natural nonword, concatenated syllables, and syllable sequence conditions was scored using a strict serial order criterion according to which a unit was only scored as correct if it was recalled in its original position within the sequence. Table II summarizes the syllable accuracy data for all of the reported experiments. Figure 1 plots the experiment 1 accuracy results for each recall type and serial position. An initial two-way analysis of variance (ANOVA) (recall type  $\times$  serial position) completed on the syllable accuracy data revealed significant main effects for task,  $F(2,46)=11.829$ ,  $p<0.001$ ,  $\eta_p^2=0.34$ , and position,  $F(4,92)=80.806$ ,  $p<0.001$ ,  $\eta_p^2=0.78$ . The interaction failed to reach significance,  $F(8,184)=1.788$ ,  $p=0.082$ ,  $\eta_p^2=0.07$ . For the effect of recall type, pairwise comparisons with Bonferroni corrections indicated that syllable accuracy was significantly greater in the natural nonword than either the concatenated syllables ( $p<0.001$ ) or syllable sequence conditions ( $p=0.013$ ) while the latter two conditions did not differ ( $p>0.05$ ). Within-subject contrasts revealed a significant quadratic function for the main effect of position corresponding to standard primacy and recency effects across conditions. The results were also subjected to an item analysis, with the syllables at different serial positions treated as the random factor. Significant effects included recall type,  $F2(2,8)=7.125$ ,  $p=0.017$ ,  $\eta_p^2=0.664$ , and position,  $F2(4,8)=37.742$ ,  $p<0.001$ ,  $\eta_p^2=0.95$ , but not the interaction,  $F2(8,105)=0.507$ ,  $p>0.05$ ,  $\eta_p^2=0.04$ . In pairwise comparisons between recall types, there was one significantly different pair: Accuracy was greater in the natural

TABLE II. Syllable accuracy for each serial position and recall type across three experiments.

Recall type	Total		Serial position									
			1		2		3		4		5	
			<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Experiment 1 ( <i>n</i> =24)												
Natural nonwords <sup>a</sup>	21.08	7.08	6.46	1.59	4.33	1.71	2.88	1.80	2.92	2.02	4.50	1.69
Concatenated syllables <sup>b</sup>	16.25	5.24	5.08	1.47	3.58	1.79	2.54	1.74	2.00	1.62	2.92	1.35
Syllable sequences	17.17	4.30	5.67	1.17	4.17	1.34	2.50	1.32	1.67	1.05	3.17	1.93
Experiment 2 ( <i>n</i> =14)												
Naturally coarticulated <sup>c</sup>	16.93	2.20	6.07	1.33	4.14	1.75	2.14	1.35	1.71	1.44	2.86	1.66
Spliced valid	16.07	5.62	5.14	1.66	3.93	1.64	3.07	1.59	1.71	1.33	2.21	1.37
Spliced invalid	12.00	4.57	3.64	1.74	2.50	1.23	2.00	1.47	1.21	1.31	2.21	1.37
Experiment 3 ( <i>n</i> =14)												
Stressed nonwords	20.79	7.22	5.43	1.70	4.29	2.30	3.36	1.55	3.14	1.79	4.57	1.83
Neutral prosody <sup>a</sup>	17.36	7.42	5.57	2.10	3.86	1.99	2.64	1.91	1.86	1.41	3.43	1.95
Concatenated syllables <sup>b</sup>	15.21	7.19	5.07	1.64	2.57	2.03	2.50	2.07	2.29	2.13	2.79	1.72

<sup>a</sup>Constitutes the same recall type of the same items.

<sup>b</sup>The concatenated syllables of experiment 1 were compressed prior to splicing whereas those of experiment 2 were not compressed.

<sup>c</sup>Constitutes the same recall type as in (a) but different phoneme sequences.

nonwords' than the concatenated syllables' condition ( $p = 0.034$ ; all remaining comparisons,  $p > 0.05$ ).

In this experiment, recall accuracy was significantly greater when repeating naturally articulated nonwords than nonwords of equal duration created by concatenating single syllables or lists of single syllables. These results clearly establish a recall advantage for multisyllabic nonwords over syllable strings of matched content in adults, replicating previous findings for children (Archibald and Gathercole, 2007a). The more accurate repetition of naturally articulated nonwords than concatenated syllables of matched duration indicates that the multisyllabic benefit is not simply due to the more rapid presentation of multisyllabic forms over syllable lists, ruling out explanations related to temporal decay in the serial list paradigm as the source of the difference. One possible explanation of the superior repetition in the natural nonword than concatenated syllable conditions in the present experiment relates to the synthetic manipulation (compression) of the concatenated syllables. Experiment 3 addresses this issue by providing a replication of this finding without the synthetic manipulation. A more interesting possibility is that the naturally articulated nonwords provide additional cues to support retention, and experiment 2 was designed to address one potential source of such cues, coarticulation.

### III. EXPERIMENT 2

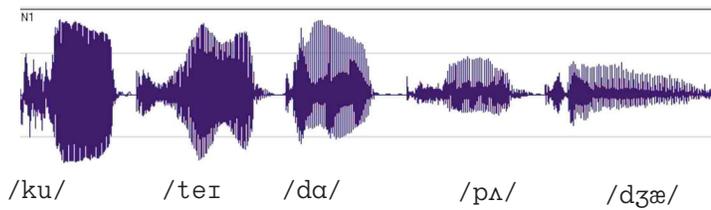
Results of experiment 1 established that the repetition advantage for multisyllabic nonwords does not lie in the shorter overall duration of such stimuli. One suggestion has been that multisyllabic forms contain additional phonetic signals of segmental structure in the form of coarticulatory and prosodic cues. These cues may in turn facilitate a richer encoding of multisyllabic sequences. Experiment 2 was designed to investigate the extent to which coarticulatory information influences nonword repetition. In this experiment,

adults recalled nonword strings as naturally articulated multisyllabic nonwords, multisyllabic nonwords in which each syllable was spliced from a different repetition in a way that maintained coarticulatory information, and as multisyllabic nonwords in which each syllable was spliced in a way that created invalid coarticulatory information. As this experiment represents one of the first investigations of coarticulation in nonword repetition, invalid coarticulatory cues were maximized by producing the required target syllable in a different sequence where phonemes in adjacent syllables were maximally different from the target. For example, selected consonants differed from the target sequence in place and manner of articulation, and voicing. That is, if the target syllable was preceded by a syllable containing a back, voiceless plosive, /k/, it was produced in a context preceded by a labiodental, voiced fricative, /v/. Similarly, if the target syllable was followed by a high front vowel, /i/, it was produced in a context followed by a low back vowel, /a/.

As the aim of experiment 2 was to focus on coarticulatory cues, it was necessary to control prosodic information in the nonwords. In order to achieve this, items in both spliced conditions were created such that each syllable was cut and pasted into an appropriate ordinal location. For example, the initial syllable of a given nonword was always derived from the initial syllable of the original nonword. This process assured that each syllable was prosodically valid, eliminating the possibility that differences in performance were due to intonation and duration cues that were inappropriate for a syllable in a given position. It should be noted also that the use of phonologically equivalent nonwords across all three conditions ensured that phonological content did not influence any set of items to differing extents.

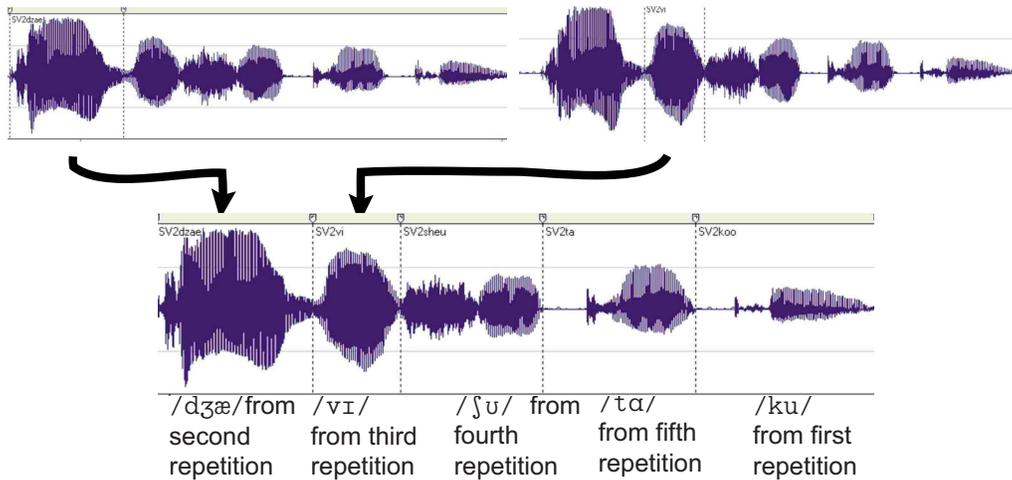
The inclusion of two spliced conditions, containing either valid or invalid articulatory information, addressed the concern that nonword repetition performance could be weak-

a) Repetition 5 of /kutɛɪdɑpɒdzæ/ for natural nonwords (no splicing)



b) Creating spliced valid nonword /dʒævɪʃutaku/

second repetition of /dʒævɪʃutaku/      third repetition of /dʒævɪʃutaku/



c) Creating spliced invalid nonword /tʊvɪgɪtʃeɪdɑ/

first repetition of /tʊkɑbɒvædzʊ/

second repetition of /gɑvɪbɑkɑgʊ/

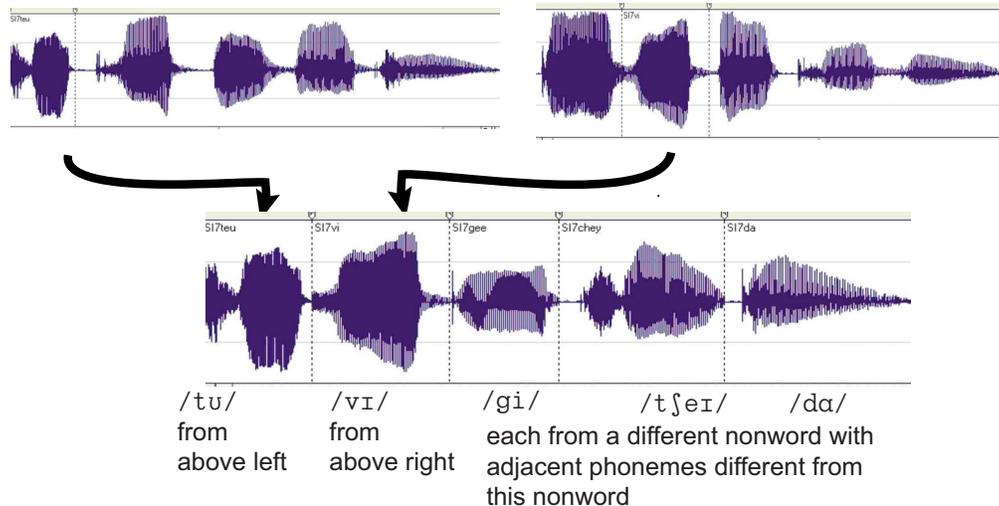


FIG. 1. (Color online) Examples of an item created for each condition.

ened simply due to the presence of spliced syllables. That is, although care was taken to splice syllables in a way that retained the naturalness of the nonwords, the act of splicing the waveform could nevertheless have disrupted the signal in a way that would lead to less accurate repetition. This would be indicated by equally poor repetition accuracy in the spliced conditions containing valid and invalid coarticulatory information. In contrast, if performance was poorer in the invalid condition, it would indicate that coarticulatory cues do, in fact, influence recall in nonword repetition.

## A. Method

### 1. Participants

Fourteen adults ranging in age from 18 to 35 years from the London, ON community were recruited to participate in the present experiment. All spoke English as their primary language.

### 2. Procedure

All participants completed a repetition task under three conditions, the repetition of naturally produced nonwords

TABLE III. Syllables used to construct stimuli for experiment 2.

				Practice trials			
/fʊ/	/wʌ/	/gɑ/	/jʊ/				
				Experimental trials			
/kæ/	/ʃʊ/	/vɪ/	/pʌ/	/teɪ/	/bɑ/	/gi/	/ku/
/fae/	/dʊ/	/kɪ/	/ʃʌ/	/veɪ/	/tɑ/	/tʃi/	/fu/
/dʒæ/	/tʊ/	/tʃi/	/dʌ/	/tʃeɪ/	/dɑ/		

(naturally coarticulated) and multisyllabic forms spliced from either valid (*spliced valid*) or invalid (*spliced invalid*) contexts. Condition order was counterbalanced across participants such that there were three orders with eight participants each. Items were created following the same principles as employed in experiment 1. CV syllables were constructed from 11 consonants and 8 vowels chosen because they could be paired with phonemes of highly contrastive articulation, reliably segmented in the acoustic waveform, and create nonwords in CV structures. The vowels corresponded to the extreme points of English vowel space: high-mid front, /i,ɪ,eɪ/, high back, /u,ʊ/, mid back, /ʌ/, low front, /æ/, or low back, /ɑ/, and the consonants included /p,b,t,d,k,g,f,v,ʃ,tʃ,dʒ/. There were a total of 26 syllables, 4 of which appeared only in the practice trials (see Table III).

A digitized recording was made of an adult female speaker producing seven repetitions of each nonword. The first and seventh repetitions were rejected in order to eliminate prosodic differences that typically occur for initial and final items in a list. The remaining repetitions were used to create the auditory stimuli in each condition as follows: For the naturally coarticulated condition [Fig. 2(a)], the ten items (two practice and eight trials) were used as recorded, two each from the first through fifth repetitions of the respective nonword.

The target items for the two spliced conditions were phonologically equivalent to those in the natural nonword condition. However, stimulus tokens were constructed by segmenting the recordings of nonwords into individual syllables and re-splicing them. Syllables were segmented by finding the offset of the vowel at the end of each syllable on the acoustic waveform using the software program SOUND FORGE 6.0 (Sonic Foundry Inc., 2002). The spliced valid condition consisted of syllables re-spliced from different tokens of the same nonword item [see Fig. 2(b)]. For example, the first syllable was taken from the first token, the second from

the second token, and so on. Order of syllable selection was counterbalanced across stimulus items. Note that this splicing scheme maintained the validity of coarticulatory information in the nonword since each syllable had been produced in the same phonetic context to which it was spliced. In contrast, the spliced invalid stimuli contained spliced syllables taken from five-syllable nonwords in which adjacent syllables had phonemes with highly contrastive articulation demands from those of the target stimulus [Fig. 2(c)]. That is, none of the syllables in the stimulus word had originally been produced with the same adjacent phonemes as the target. For example, to create the spliced invalid nonword /kuʃʊtʃeɪtavi/, the syllable /ku/ was taken from the nonword /kudɪbɑgʊteɪ/, where /di/ is distinguished from the target second syllable—/ʃʊ/—in terms of place, manner, and voice of the consonant, and place of the vowel. Similarly, /ʃʊ/ was taken from /væʃʊbɑgɪfu/, where /væ/ is similarly distinguished from the target first syllable /ku/, and /bɑ/ from the target third syllable /tʃeɪ/, and so on. Note that additional five-syllable sequences were recorded as necessary to provide appropriate syllables to construct target stimuli. The same process was employed for selecting syllables to be spliced as in the valid condition above.

It should be noted that the splicing procedures were identical for the valid and invalid conditions; thus any detriment caused by the act of splicing would be equivalent across both conditions. Nevertheless, it was the case that the syllable transitions were less smooth for the invalid than valid conditions. In order to ensure that the resulting invalid sequences were perceived as the target sequence, a trained research assistant unaware of the correct forms or nature of the experiment phonetically transcribed the spliced invalid nonwords. For 11 of the 50 syllables, changes in the oral aperture related to anticipatory coarticulatory processes occurring before vowel offset resulted in the perception of the presence of an additional consonant. That is, the syllable, /ku/, spliced from the sequence /kudi./ was perceived as /kud/ despite the fact that the alveolar closure had not yet been achieved. The change in the oral aperture leading to this misperception was clearly visible as a change in the vowel's acoustic waveform. This section of the waveform was attenuated to eliminate the misperception. On average, the duration of the attenuation was 0.06 s ( $SD=0.03$ ). While this process maintained the invalid coarticulatory cues and duration, it reduced opposing coarticulatory information.

Stimulus presentation was controlled by the same computer software program as employed in experiment 1. Participant responses were digitally recorded and phonetically transcribed. Recall accuracy in the naturally coarticulated,

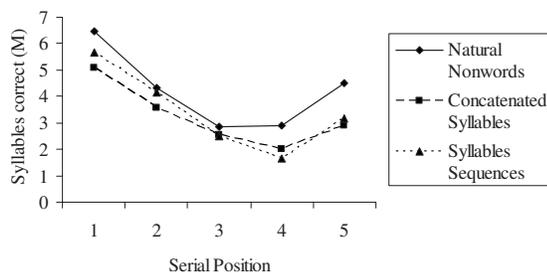


FIG. 2. Mean syllable accuracy (out of eight trials) at each serial position for the natural nonwords, concatenated syllables, and syllable sequences conditions.

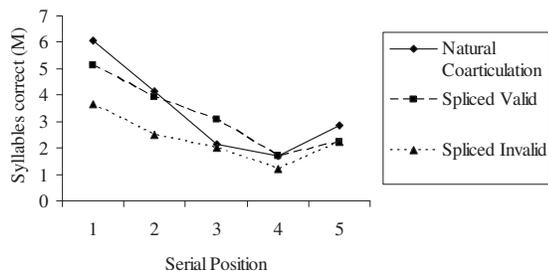


FIG. 3. Mean syllable accuracy (out of eight trials) at each serial position for the naturally coarticulated, spliced valid, and spliced invalid nonword conditions.

spliced valid, and spliced invalid conditions was scored by the first author using the same serial order criterion as employed in experiment 1.

## B. Results and discussion

Figure 3 plots the experiment 2 accuracy data across serial position for each recall type (naturally coarticulated, spliced valid, and spliced invalid). An initial two-way ANOVA (recall type  $\times$  serial position) completed on the syllable accuracy data revealed a significant main effect of recall type,  $F(2, 26) = 13.860$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.52$ , and position,  $F(4, 52) = 46.346$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.78$ , and a significant interaction,  $F(8, 104) = 3.059$ ,  $p = 0.004$ ,  $\eta_p^2 = 0.19$ . For the main effect of recall type, pairwise comparisons with Bonferroni correction revealed significantly less accurate performance in the spliced invalid condition than both the naturally coarticulated ( $p = 0.001$ ) and spliced valid conditions ( $p = 0.002$ ) while the latter two conditions did not differ ( $p > 0.05$ ). The effect of recall type on serial position was investigated using simple pairwise  $t$ -tests. There was no difference in the recency effects across conditions as evidenced by no task differences at the fourth and fifth serial positions ( $p > 0.05$ , all cases). Primacy effects were significantly reduced in the spliced invalid condition as indicated by significantly less accurate performance in this than either of the other two conditions at positions 1 and 2 and at position 3 compared to the spliced valid condition,  $t(13) > 2.4$ ,  $p < 0.05$ , all cases. In the corresponding items analysis, there was a significant main effect of position,  $F(2, 4, 8) = 15.023$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.88$ . The task term did not reach significance,  $F(2, 8) = 2.657$ ,  $p = 0.13$ ,  $\eta_p^2 = 0.40$ , likely a reflection of the low power in the item analysis as a result of the small number of items. Importantly, the effect size for the task term in the item analysis was comparable to the F1 ANOVA and the means reflected a similar trend with higher proportions of participants repeating syllables accurately in the naturally coarticulated ( $M = 0.42$ ;  $SD = 0.27$ ) and spliced valid conditions ( $M = 0.40$ ;  $SD = 0.24$ ) compared to the spliced invalid task ( $M = 0.32$ ;  $SD = 0.24$ ). The interaction was not significant,  $F(8, 105) = 1.077$ ,  $p > 0.05$ ,  $\eta_p^2 = 0.08$ .

Thus, syllable accuracy was greater in the two conditions presenting valid coarticulatory information (naturally coarticulated and spliced valid nonwords) compared to the spliced invalid condition. These results demonstrate the positive influence of valid over invalid coarticulatory cues in immediate repetition. It is possible that coarticulatory pro-

cesses enable a richer encoding of temporary phonological representations because they transmit information about more than one phoneme at a time (Lieberman *et al.*, 1967). One interesting aspect of the present results is the finding that there was very little cost to the splicing of the acoustic waveform in that recall accuracy did not differ between the naturally coarticulated and spliced valid conditions. Recent evidence has demonstrated superior repetition for natural vs synthetic speech (e.g., Humes *et al.*, 1993). Nevertheless, the present findings suggest that immediate repetition processes can withstand small disruptions to the acoustic waveform. Such a skill may be adaptive, as it would assist with recognition of highly similar (but not identical) acoustic forms.

The coarticulatory effect in the present experiment was more pronounced in the primacy portion of the recall curve. The presence of primacy and recency effects in nonword repetition has been established previously (Gupta, 2005), as have differential primacy and recency effects in immediate recall generally (Cowan *et al.*, 2002; Oberauer, 2003). Typically, primacy effects are attributed to an automatic attentional gradient operating during encoding such that items presented first receive more attention and therefore are encoded (and recalled) more accurately (e.g., Brown *et al.*, 2000; Farrell and Lewandowsky, 2002; Oberauer, 2003; Page and Norris, 1998). The present findings suggest that the presence of valid coarticulatory information may further enhance encoding especially when the attentional gradient is highest.

These findings indicate that the more accurate recall of multisyllabic forms than syllable lists relates, at least in part, to the coarticulatory information inherent in the multisyllabic strings. Experiment 3 investigates the influence on retention of another factor that differs between these forms, prosody.

## IV. EXPERIMENT 3

Prosodic structure has been found to play a role in nonword repetition (Gallon *et al.*, 2007; Roy and Chiat, 2004; Yuzawa and Saito, 2006). Nevertheless, experiments 1 and 2 were designed to minimize prosodic influences on recall by employing equal-stress-across-syllables. It could be argued that such stimuli remain list-like leading to the underestimation of the importance of processes related to the learning of more plausible novel words. Experiment 3 was designed to examine the influence on nonword repetition of information inherent to more plausible nonwords, prosodic information. In this final experiment, stress patterns common to five-syllable words in English were imposed on nonwords creating within-word stress contours. This condition was compared to the naturally articulated nonwords employed in the previous experiments that had neutral prosody (i.e., equal-stress-across-syllables). An aprosodic condition was also created by concatenating syllables recorded in isolation. In order to avoid the temporal and manipulated confound present in experiment 1, the isolated syllables were produced with a naturally short duration such that no compression was required and the sequence duration was not significantly longer.

Graded and decreasing performance across all three of these conditions, within-word stress, neutral prosody, and

aprosodic nonwords, would provide strong evidence of the positive influence of prosodic information on immediate recall of multisyllabic forms. More accurate recall in the within-word stress relative to the neutral prosody conditions would point to the importance of syllable level prosodic information rather than strictly a suprasegmental benefit.

## A. Method

### 1. Participants

The 14 adults who participated in experiment 2 also completed experiment 3. Order was fixed such that all participants performed experiment 2 first, with a 5-min break between sessions.

### 2. Procedure

All participants completed a repetition task under three conditions, the repetition of naturally produced nonwords with within-word stress (*stressed nonwords*), naturally produced nonwords with equal-stress-across-syllables (*neutral prosody*), and an aprosodic condition (*concatenated syllables*). Condition order was counterbalanced across participants such that there were three orders with eight participants each. The phonological form of items was the same as those employed in experiment 1 (which differed from those in experiment 2).

A digitized recording was made of an adult female speaker producing four repetitions of each syllable sequence used in the stressed nonword and neutral prosody conditions, and the item was selected from either the second or third repetition. Note that fewer repetitions were needed because the items were not spliced from different repetitions but taken as a single production. Items in the stressed nonword condition were produced with one of three stress patterns common to English multisyllabic words [i.e., weak (W)-strong<sup>1</sup> (S)-WS<sup>2</sup>W as in “accumulation;” S<sup>2</sup>WS<sup>1</sup>WW as in “hippopotamus;” S<sup>1</sup>WWS<sup>2</sup>W as in “qualification”]. Items in the neutral prosody condition were produced with equal-stress-across-syllables. For the concatenated syllables’ condition, syllables were naturally produced in isolation with short duration so that the average duration of the syllable string once concatenated ( $M=1.91$  s,  $SD=0.08$ ) would be equivalent to that of the stressed nonword condition ( $M=1.85$  s,  $SD=0.17$ ;  $t(18)=-1.105$ ,  $p>0.05$ ). This procedure eliminated the need to artificially compress syllable length as occurred in experiment 1. Note that the items in the neutral prosody group had the longest average duration ( $M=2.08$  s,  $SD=0.08$ ) compared to either of the other two conditions,  $t(18)>3.9$ ,  $p<0.05$ , both cases.

Stimulus presentation was controlled by the same computer software program as employed in experiment 1. Participant responses were digitally recorded and phonetically transcribed. Recall accuracy was scored by Archibald using the same serial order criterion as employed in experiment 1.

## B. Results and discussion

Figure 4 plots the experiment 3 syllable accuracy data across serial positions for the stressed, neutral, and concatenated syllables’ conditions. An initial two-way ANOVA (re-

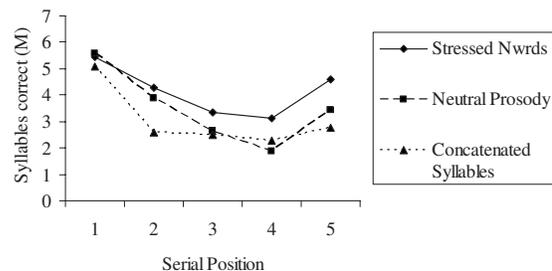


FIG. 4. Mean syllable accuracy (out of eight trials) at each serial position for the stressed nonwords’, neutral prosody, and concatenated syllables’ conditions.

call type  $\times$  serial position) completed on the accuracy data revealed significant effects of recall type,  $F(2, 26)=14.266$ ,  $p<0.001$ ,  $\eta_p^2=0.52$ , position,  $F(4, 52)=18.107$ ,  $p<0.001$ ,  $\eta_p^2=0.58$ , and recall type and position,  $F(8, 104)=2.071$ ,  $p=0.045$ ,  $\eta_p^2=0.14$ . Pairwise comparisons with Bonferroni correction for recall type revealed significantly more accurate repetition in the stressed than both the neutral ( $p=0.009$ ) and concatenated syllable conditions ( $p=0.003$ ). Also, there was a marginally significant difference between the latter two conditions ( $p=0.066$ ). The interaction was explored through pairwise  $t$ -tests. The most consistent effect was the recency advantage for stressed nonwords compared to both the remaining conditions at serial position 5, and to the neutral nonwords at positions 3 and 4. The reduced primacy effect for the concatenated syllables observed in experiment 1 was present here at position 2. Remaining comparisons were nonsignificant ( $p>0.05$ ). In the corresponding items’ analysis, significant effects were found for recall type,  $F(2, 8)=8.537$ ,  $p=0.01$ ,  $\eta_p^2=0.68$ , and position,  $F(2, 4, 8)=20.426$ ,  $p<0.001$ ,  $\eta_p^2=0.91$ , but not for the interaction term,  $F(2, 8, 105)=0.662$ ,  $p>0.05$ ,  $\eta_p^2=0.05$ . In pairwise comparisons for task type, repetition accuracy was significantly greater in the stressed nonword than concatenated syllables ( $p=0.004$ ). All remaining comparisons were nonsignificant ( $p>0.05$ , all cases).

It should be noted that in one further analysis comparing syllable accuracy for the strong vs weakly stressed syllables in the stressed nonword condition, no significant difference was found between stress types,  $t(26)=-1.206$ ,  $p>0.05$ .

In this experiment, syllable recall was more accurate in the F2 analysis for the within-word stress condition than concatenated syllables and in the F1 analysis than either of the other two conditions, an effect that was greater in the recency portion of the curve. Consistent with previous findings (Roy and Chiat, 2004), within-word prosodic pattern facilitated recall. It could be argued that the presence of a within-word stress pattern increased the wordlikeness of the nonwords, thereby facilitating recall through the lexical effect (e.g., Gathercole, 1995). Lexicality, however, has traditionally been associated with improved primacy rather than recency (e.g., May and Sande, 1982). One explanation of recency effects is the temporal distinctiveness hypothesis, which holds that items presented more recently will be more distinctive on average and thereby enjoy a recall advantage (Brown et al., 2000). It may be that the differential stress patterns across syllables in the stressed nonwords of the

present experiment enhanced their distinctiveness leading to more accurate recall overall, and in the final serial positions, in particular.

It should be noted that experiment 3 essentially replicated the finding from experiment 1 that naturally articulated nonwords were repeated more accurately than concatenated syllables of matched duration. In addition to the more accurate performance on stressed nonwords, the higher scores on the neutral prosody nonwords (equivalent to the natural nonwords; condition in experiment 1) than the concatenated syllables of shorter duration were marginally significant. While this latter result may reflect a smaller effect size due to the elimination of the synthetic manipulation in the concatenated syllables' condition, the marginally significant outcome with this substantially smaller sample size (experiment 3,  $n=14$ ; experiment 1,  $n=24$ ) in favor of the (longer) neutral prosody sequences provides evidence that temporal duration does not account for the nonword repetition advantage. It is possible that a larger sample size may have reduced variability in experiment 3 and lead to significant results matching those of experiment 1.

## V. GENERAL DISCUSSION

The present study examined the influence of three acoustic-phonetic factors—list duration, subphonetic detail, and prosody—on nonword repetition performance. In the first experiment, we compared repetition of naturally articulated five-syllable nonwords to recall of concatenated syllable strings of equal duration but which were created from syllables produced in isolation. In a second experiment, we more closely examined the influence of coarticulatory cues by comparing nonword repetition of multisyllabic nonwords containing either valid or invalid coarticulatory information, and naturally produced nonwords. Finally, we compared multisyllabic forms varying in prosodic detail including common English stress patterns, suprasegmental contours only, and aprosodic forms created by concatenating syllables recorded in isolation. The results established superior immediate recall for multisyllabic nonword forms over single syllable lists in adults. The repetition advantage was not a result of the shorter duration of multisyllabic strings. Valid coarticulatory cues enhanced recall, especially over the first syllables of the nonword. Within-word stress facilitated repetition, particularly over the final positions of the sequence.

These results clearly establish a recall advantage for coarticulated multisyllabic nonwords that cannot be attributed to their overall shorter duration. One reason that multisyllabic nonwords may enjoy a repetition advantage over syllable lists or concatenated syllables is that the structure of the nonwords may promote chunking within STM. It has been suggested that chunks form when stimuli already form a unit or have external punctuation serving to group stimuli (McLean and Gregg, 1967), both of which apply in the case of multisyllabic nonwords. The use of nonwords in the present studies limits long-term memory processes forcing greater reliance on STM estimated to have a capacity of

$4 \pm 1$  chunks (Cowan, 2001). Thus, the five-syllable syllable lists that resist chunking may have been more difficult to recall than multisyllabic forms.

Not only was nonword repetition more accurate than syllable list recall in the present studies, scores were higher when valid coarticulatory information was present in the multisyllabic form. The presence of invalid coarticulatory cues disrupted recall to the greatest extent, as indicated by the lowest performance across the three studies. The coarticulation benefit was a robust finding with valid coarticulatory information preserved despite splicing of the waveform. The greater primacy effect may indicate that coarticulation information enhances encoding, especially when the attentional gradient is highest. Traditionally, primacy effects have been considered to reflect long-term memory support of traces retained in memory for the longest time period (Craik, 1970). It may be that valid coarticulatory information enhances encoding, which in turn facilitates activation of long-term phonological representations.

It is interesting to speculate on how sensitivity to coarticulatory information may influence nonword repetition. One suggestion has been that coarticulation speeds processing because it transmits information about more than one phoneme at a time (Liberman *et al.*, 1967). Speeded processing may have positive effects on speech perception, memory, and language in that inputs may be recognized earlier and additional time afforded for rehearsal and other processing requirements. Relatedly, children with specific language impairment (SLI), an unexplained difficulty learning language, have more difficulty repeating multisyllabic nonwords than single syllable nonword lists (Archibald and Gathercole, 2007b). It may be that children with SLI are less sensitive to, or able to capitalize on, coarticulatory cues in connected speech.

The present findings also indicate that prosodic pattern positively influences immediate repetition of novel word forms. Familiar within-word stress patterns conveyed a marked advantage that was not tied simply to the more accurate recall of strongly stressed syllables. Natural prosodic patterns may further enhance the chunking processes described above by highlighting distinctions between groups of syllables. Increased distinctiveness between syllables may account for the greater recency effect observed in the present study as well.

One other possible explanation of the prosodic advantage in the present study relates to list position. It is well established in serial recall research (e.g., Treiman and Danis, 1988) that migrated or transposed units in responses are much more likely to move to similar prosodic locations (i.e., a word-initial phoneme exchanges with a word-initial rather than word-final phoneme). It may be that the presence of fewer syllables with equivalent stress markings in the within-word stress condition in the present study decreased opportunities for same-position moves compared to the other conditions with equal-stress-across-syllables.

## VI. CONCLUSION

Nonword repetition was examined in three studies exploring the influence of nonword duration, coarticulatory in-

formation, and prosodic cues. The results indicate that phoneme strings presented as a multisyllabic form rather than an isolated syllable list are more accurately recalled. This advantage cannot be readily explained by STM accounts related to temporal decay. Both the presence of valid coarticulatory information and within-word stress patterns enhanced recall. Coarticulatory effects were observed over the primacy portion of the recall curve whereas prosodic influences were linked to greater recency. These findings suggest that several processes operating in conjunction in new word learning enable rich encoding and retention of novel phonological forms facilitating transfer to long-term memory. It may be that individuals with word learning deficits such as those with SLI are impaired in one or more of these processes.

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