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The effects of cognitive – linguistic variables and language experience on behavioural and kinematic performances in nonword learning

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Abstract

The aim of the present study was to investigate the effect of cognitive – linguistic variables and language experience on behavioral and kinematic measures of nonword learning in young adults. Group 1 consisted of thirteen participants who spoke American English as the first and only language. Group 2 consisted of seven participants with varying levels of proficiency in a second language. Logistic regression of the percent of correct productions revealed short-term memory to be a significant contributor. The bilingual group showed better performance compared to the monolinguals. Linear regression of the kinematic data revealed that the short – term memory variable contributed significantly to movement coordination. Differences were not observed between the bilingual and the monolingual speakers in kinematic performance. Nonword properties including syllable length and complexity influenced both behavioral and kinematic performance. The findings supported the observation that nonword repetition is multiply determined in adults.

Keywords

Nonword repetition; cognitive-linguistic; lip aperture variability

The ability to repeat novel phonological strings is considered to be a critical skill for language learning. Studies of nonword learning suggest that the task is sub-served by several cognitive - linguistic systems including, phonological *storage* or short-term memory (e.g. Gupta, 2004), phonological *processes* or strength of long-term sublexical representations mediated by vocabulary size and resulting phonological knowledge (e.g. Storkel et al., 2006; Majerus, Poncelet, Van der Linden, & Weekes, 2008), nonword repetition skills (e.g. Gathercole, 2006), and finally, an intact speech motor system (e.g. Aichert & Ziegler, 2004). Gathercole (2006) described nonword learning as a primitive mechanism that is mediated by phonological storage and is available throughout the lifespan. The aim of the present study is to investigate nonword learning in adults to study the effects of the different cognitive – linguistic variables and language experience on behavioral and kinematic measures of task performance.

Although the involvement of the different sub-systems is critical to nonword learning, the varying influences is much debated. For instance, differences have been reported in the

relevance of phonological storage vs. processes. A reliance on phonological storage would indicate dependence on phonological short-term rather than on long-term memory, i.e., vocabulary size, for better task performance. Research findings support a role for vocabulary size in nonword learning in children (e.g. Gathercole & Baddeley, 1989; Storkel, 2001; Storkel, 2004) while short-term memory rather than long-term sublexical representations is considered critical in adults (e.g. Gaskell & Dumay, 2003). Therefore, the primary purpose of this preliminary study is to investigate experimentally the varying contributions of cognitive - linguistic factors, including, short-term and long-term memory processes, on nonword learning in adults. In addition to the cognitive – linguistic factors, nonword learning requires an intact speech motor system and task performance is determined by limitations placed on this system (e.g. Aichert & Ziegler, 2004). Although the speech motor system is known to be involved (e.g. Sasisekaran, Smith, Sadagopan, & Weber-Fox, 2010), careful consideration to the role of speech motor processes in nonword learning has been limited. Thus, a second purpose is to investigate the contributions of the speech motor system and to test for interactions between relevant cognitive variables and speech movement coordination in nonword learning.

The process of nonword learning has been discussed mainly from two perspectives namely, psychological and psycholinguistic (e.g. Gupta, 2003; Gupta & Tisdale, 2009). From the psychological perspective, the phonological loop within Baddeley's working memory model (Baddeley & Hitch, 1974) is considered to be a critical component. Within this framework, the learning of novel words, nonword repetition, and phonological short term memory processes share similar underlying mechanisms and performance in nonword learning can be predicted based on measures of phonological short-term memory. While computational modeling of the data reveals the potential for a causal link (e.g. Gupta and Tisdale, 2009), experimental studies testing the extent of influence and interaction of short-term memory, nonword repetition, and vocabulary size in nonword learning are required.

Gaskell and Dumay (2003) investigated nonword learning in adults using a phoneme monitoring task in which participants were also required to remember the nonwords. The formation of initial lexical representations in short-term memory was tested in a nonword recognition task while integration of new representations with existing lexical representations in long-term storage was tested using a lexical decision task. The results revealed that adults formed new representations immediately (within 12 trials) based on faster recognition of test nonwords while the integration of the new representations with existing ones took longer as indicated by the lack of response time differences between pre- and post-exposure lexical decision task performance. This finding indicated precedence for short-term memory in nonword learning in adults.

Storkel, Armbruster, and Hogan (2006) tested the effects of long-term phonological and lexical level factors, *viz*, phonotactic probability and neighborhood density, on nonword learning in adults. Earlier reports have indicated an advantage for high phonotactic probability and high neighborhood density on nonword learning in children (e.g. Storkel, 2004). Storkel et al. (2006) tested adults for the effects of these variables on partially correct and completely correct productions. The findings revealed that contrary to the effects found in children, nonwords of high phonotactic frequency had a disadvantage rather than an advantage in nonword learning and such an effect was evident in the pattern of errors observed in the partially correct productions. Nonwords with higher neighborhood density had an advantage in the task as evident from the correctly produced nonwords. Thus the findings indicated that both long-term phonological and lexical level factors have varying influences on nonword learning.

In addition to such influences, language experience of the speaker interacts with short-term and long-term memory variables to influence nonword learning. Speakers of more than one language have the advantage of a larger phonological knowledge base. Therefore, it could be hypothesized that the larger phonological knowledge base is an advantage in nonword learning. Majerus et al. (2008) tested French - English bilinguals in a word-nonword paired associate learning task with the nonword following French phonotactics. Participants were also tested for serial order short term memory, vocabulary, and French proficiency. The findings revealed that both short-term memory and long-term phonological knowledge (French proficiency scores) were independent predictors of performance in the paired associate learning task. Papagno and Vallar (1995) tested Italian polyglots (participants knew three languages or more) and non-polyglots in several measures including short-term memory (verbal digit span, nonword repetition), paired associate learning of nonwords, general intelligence, and visuo-spatial memory. The results revealed the groups to be comparable in all of the measures except the verbal short-term memory measure and paired associate learning of nonwords; tasks in which the polyglots scored higher thereby indicating that short-term memory is a critical variable in nonword learning in polyglots.

In summary, studies of nonword learning in adults have recognized several variables as crucial to task performance. These studies have identified both short-term and long-term memory variables in addition to language experience as critical factors. It remains to be seen the varying extent to which differences in measures of phonological short-term memory (e.g. digit span, sentence recall, nonword repetition) influence nonword learning in adults. Furthermore, it is critical to understand the effects of long-term memory measures, such as, vocabulary and resulting phonological knowledge from varying language experiences, and how such variables influence task performance. This can have further implications for our understanding of the different processes sub-serving nonword learning in adults.

From a psycholinguistic perspective, accounting for nonword learning will involve explaining the process within psycholinguistic models, such as, Levelt's speech production model (Levelt, Roelofs, & Meyer, 1999). Within Levelt's model, performance in nonword learning is presumably based on processes associated with encoding of phonemes and syllables at both linguistic and motoric levels. In addition, Levelt et al. (1999) proposed the existence of the syllabary, storage of motor programs, which facilitates the production of frequently occurring syllables in a language. Although motor processes are an integral part of nonword learning, not much attention has been directed towards the influences of such processes on task performance. Behavioral responses can mirror the effects of the linguistic or the speech motor systems on nonword learning and, not many studies have attempted to differentiate these systems in terms of the effects that they bear on nonword learning. Sasisekaran et al. (2010) tested a group of 9 to 10-year-olds and young adults on two consecutive days and measured changes in behavioral responses and speech movement coordination with nonword repetition. They used a measure of movement coordination called lip aperture variability index (LA VAR; Smith & Zelaznik, 2004) in order to study the trial-to-trial variability in movement coordination. The test stimuli were nonwords of increasing phonemic and motoric complexity. Young adults, similar to children, showed short- and longer-term improvements in coordinative consistency with repeated production of complex nonwords. Both groups showed a practice effect, such that later Day 1 trials and Day 2 trials were shorter in duration and more consistent in coordination patterns than Day 1 early trials. Phonemic complexity of the nonwords had a significant effect in that the children showed learning effects on all nonwords that they could produce accurately, while adults showed improvements in performance only for the more complex nonword stimuli. The findings suggest a role for speech motor processes within models of nonword repetition and a need for further testing to understand the effects of nonword complexity on movement coordination.

In another study Charabarty, Goffman, and Smith (2008) tested 21 bilingual Bengali (first language, L1) – English (second language, L2) speakers using Bengali and English sentences in to order to test the effect of language experience on movement coordination. Participants were further subdivided into high and low proficiency in English to study the effect of L2 on movement coordination. The findings revealed that the group was equally consistent in both L1 and L2 contrary to the expectation that they would be more consistent in L1 than L2. This finding was interpreted to suggest that bilingual adults exhibit reduced movement variability during production in both L1 and L2. Furthermore, English proficiency did not have a significant effect on the movement patterns in L2. To date there are no known studies investigating the effects of language experience on movement coordination in a nonword learning task to study if a larger phonological knowledge base in bilinguals offers an advantage in movement coordination during nonword learning.

Summarizing, nonword learning is a process requiring the coordinated action of several sub-processes, linguistic and motoric, critical for task performance. The findings from earlier studies in adults have identified certain areas of nonword learning that require further testing, for instance, the relevance of short-term and long-term memory variables in task performance. Critical caveats also remain in our understanding of the role of the speech motor system in nonword learning and further testing is required to understand the nature of contributions of the speech motor system to nonword learning. For instance, how does the speech motor system accommodate the production of increasingly complex nonwords? Furthermore, coordinated production of complex and lengthy nonwords probably requires cognitive effort. How does the speech motor system interact with the relevant cognitive systems to accommodate the production of complex nonwords? Based on Levelt's model, the existence of the syllabary which contains high frequency syllables stored for production could be used to predict higher movement variability and a higher degree of interaction between the cognitive and speech motor systems for complex and longer nonwords containing low frequency phonemes and syllables; an assumption yet to be tested.

The aim of this preliminary study is to identify the varying effects of the different cognitive – linguistic variables (short-term memory – digit span, sentence recall, nonword repetition; long-term memory – vocabulary) on the behavioral and kinematic performance in a nonword learning paradigm. Language experience of the speaker (monolingual vs. late bilingual) and its influence on behavioral and kinematic components of nonword learning will also be tested. In addition, the use of nonwords varying in syllable length and complexity offers the opportunity to study the effects of such phonemic level factors on nonword learning. The methodology used in the present study is adapted from Smith, Johnson, McGillem, and Goffman (2000) and offers the advantage of measuring LA VAR, a composite measure of spatial and temporal movement variability associated with lip aperture trajectory for repeated productions. With this measure, the kinematic responses associated with nonword repetition performance were investigated in addition to behavioral performance measured as percent correct productions.

Methods

Participants

Participants were twenty adults in the age range of 18 to 35 years who spoke English as the primary language since birth. The first group consisted of thirteen participants (Mean age = 21.2, S.D. = 4.4) who spoke native American English as the first and only language. The second group consisted of seven participants (Mean age = 22.7, S.D. = 2.56) with varying levels of proficiency in a second language identified based on responses to a questionnaire. Group membership for the bilingual group was determined based on two pre-established criteria: a) score of 3 or higher on a self-reported proficiency rating scale (1 = *least*, 5 = *most*

proficient), b) history of formal training in the second language. The mean self-reported proficiency rating for the group was 3.14 ($S.D. = 0.37$). A majority of the participants also reported continued use of second language for 5 hours or more a week ($Mean = 6.7$ hours per week, $S.D. = 5.31$). All participants in Group 2 started learning a second language (Spanish, $N = 4$, Portuguese, $N = 1$, French, $N = 1$, or Russian, $N = 1$) in high school.

Participants were recruited using fliers posted on campus at the University of Minnesota. All participants were undergraduate students at the University who were reimbursed for participation. The experimental protocol was approved by the Institutional Review Board, University of Minnesota. Participant selection was based on responses to a screening form that was used to rule out positive history of language, hearing, and/or neurological deficits, and current usage of drugs likely to affect the outcome of the experiment (e.g. drugs for ADHD and anti-anxiety drugs).

Standardized tests

All participants were administered a series of standardized tests to determine short-term memory, vocabulary, and nonword repetition skills. Participants also passed a hearing screening test performed at .5, 1, 2, 4, and 8 KHz (20dB) in both ears. Normal articulatory structures and movements in both groups were confirmed using the *Oral Speech Mechanism Screening Evaluation-Revised* (OSMSE-R; St. Louis & Ruscello, 1987).

Short-term memory—Short-term memory (digit span + sentence recall, DSSR) was tested using both order and item recall tests—the forward and backward digit span subtest of the Weschler’s Intelligence test (Weschler, 1997) and the sentence recall subtest of the *Clinical Evaluation of Language Fundamentals test - IV* (CELF - IV; Semel, Wiig, & Secord, 1996). For the digit span subtest participants were presented with a series of digits in a specified order with the length of each series increasing progressively. Participants were required to recall the digits in each series in the pre-specified order. For the forward digit span subtest participants were required to recall the series in the forward order and for the backward digit span in the reverse order. For the sentence recall subtest participants were presented with sentences of increasing length and complexity. They had to recall the words within each sentence. Short-term memory was computed as an average of the percent scores from the digit span (forward + backward) and the sentence recall subtests.

Nonword repetition and vocabulary skills—Nonword repetition, a skill deemed critical for nonword learning (Gathercole, 2006), was determined using the Nonword Repetition test (Dolloghan & Campbell, 1998). The Nonword Repetition test was administered to all participants as a baseline measure of the ability to perceive and repeat nonwords. The nonwords spoken by a female native English speaker were pre-recorded and presented over loudspeakers and participants were required to repeat each nonword. The test consisted of a total of 16 nonwords varying in length (1 – 4 syllables) with the nonwords themselves containing tense vowels and consonants acquired early in development (Dollaghan & Campbell, 1998). The nonwords repeated by the participants were recorded and analyzed offline to obtain the total number of correct repetitions (%). Finally, participants were tested for expressive vocabulary using the Expressive vocabulary test (EVT; Williams, 1997). The EVT administration and scoring protocol was edited such that participants were given only one opportunity to name each test stimulus. Prompts were not provided in case a participant did not respond with the correct answer at the first attempt. Raw EVT scores are reported from all participants.

Target Stimuli

Six nonwords varying in number of syllables (6, 4, and 3) and phonemic complexity (simple vs. complex) and the nonword /*mab*/ formed the test stimuli. The complex nonwords consisted of individual phonemes and/or phonemic combinations acquired later in developmental sequence. The first syllable /*mab*/ and the last consonant /*b*/ were identical for all nonwords. This strategy was used to select consistent start and end points for the extraction of oral movement trajectories on the basis of lower lip peak opening velocities for the kinematic analysis. The six syllable nonwords were /*mab*¹*ta*²*ba*³*po*⁴*tee*⁵*ba*⁶/ and /*mab*¹*gra*²*shro*³*plo*⁴*kroo*⁵*ba*⁶/ . These were the longer nonwords with the first nonword consisting of simple and the second consisting of complex phonemic combinations based on the frequency of occurrence of phonemic combinations in English. The four syllable nonwords, /*mab*¹*sko*²*kwee*³*flaib*⁴/ and /*mab*¹*skree*²*splo*³*stroob*⁴/ were similar to two of the nonwords from Sasisekaran, et al. (2010). Again, the first of these nonword consisted of simple and the second consisting of complex phonemic combinations. Finally, the three syllable nonwords /*mab*¹*thwaip*²*fkrob*³/ and /*mab*¹*shfu*²*chloib*³/ were considered to be the most complex as they consisted of novel phonemic combinations non-existent in English. These nonwords were shorter compared to the other two nonword pairs. Again, the second nonword, /*mab*¹*shfu*²*chloib*³/ consisted of phonemes that are motorically challenging and acquired later in developmental sequence. Finally, participants were also required to say the nonword ‘mab’, which was used as a baseline measure for all participants. All participants rated the nonwords on a 7-point rating scale (1 - *least wordlike*, 7 - *most wordlike*) based on the frequency with which the speech sound combinations and length for each nonword were encountered in English. The ratings were 3.80 and 3.84 for /*mabsko**kwee**flaib*/ and /*mabskreesploistroob*/, 3.32 and 3.08 for /*mabtaibapoteeba*/ and /*mabgrashroploikrooba*/, and 2.56 and 2.20 for /*mabthwaipfkrob*/ and /*mabshfuchloib*/ . All stimuli were produced by a native English speaker spoken with an iambic stress pattern with primary stress on the first syllable and secondary stress on the second syllable, e.g. /*mab*_s*ta*_w - *ba*_s*po*_w - *tee*_s*ba*_w/ . The productions were recorded and intensity normalized using the PRAAT (Boersma, & Weenink, 2010) acoustic software and used as test stimuli.

Apparatus

Participants were seated in front of a commercial Optotrak Certus camera (Northern Digital, Waterloo, Ontario) system that allows tracking of movements in 3D with an accuracy of less than 0.1mm. Eight small (7 mm) infra-red light emitting diodes (IREDs) were attached to the participant’s face to track articulatory movements of the upper lip, lower lip, and jaw. Four of the IREDs were mounted on a set of goggles that participants were required to wear during the experimental session. One IRED was placed in the center of the forehead. Together, these five IREDs were used to calculate the 3D head coordinate system (Smith, Johnson, McGillem, & Goffman, 2000), which allowed head movement artifact to be eliminated. The remaining three IREDs were placed one on the vermilion border of the upper lip, one on the center of the lower lip (this marker represents combined actions of the lower lip and jaw), and one on a splint taped to the jaw. The IREDs were fixed to the subject and facing the Optotrak camera such that the movements could be tracked. The IRED motions were sampled at a rate of 250 Hz. A condenser wireless microphone placed approximately 8 cms away from the participant’s mouth and microphone receiver was used to record the acoustic speech signal. This acoustic signal was digitized on an A/D channel of the Optotrak system and was thus synchronized with the movement data. The acoustic signal was digitized at the rate of 16,000 Hz.

Procedure

The experiment consisted of a 1.5 hour session. Two experimenters were present throughout the experimental session and monitored subjects’ performance while providing verbal

feedback on an on-going basis. Participants were instructed that they would hear nonwords at a comfortable loudness. They were asked to listen carefully and repeat each nonword as best as they could. Following instructions, participants were provided practice trials. During practice each nonword was presented five times via loudspeakers. During the first three practice trials participants were presented with visual (written) + audio signal of the nonword. For the fourth and fifth trials, they heard only the audio signal. They were required to use the visual + audio or the audio only signal to assist with accurate nonword production. Productions during practice were monitored and corrected for pronunciation and stress errors. The data indicated that a majority of participants were able to achieve a minimum of two correct productions within the five practice trials. Following practice, participants were instructed that they would hear each nonword several times and were asked to repeat the nonword they hear in the carrier phrase “_____ again”. The carrier phrase was used to control articulatory positions at the ending of the target nonwords.

A total of 22 blocks were presented to all participants. Each block consisted of the seven test nonwords presented once in random order. The nonwords in each block were presented with a 60 second gap between each trial. Participants then completed the experimental task, producing the target items embedded in the carrier phrase. On-going feedback and error correction was provided by both the experimenters for all nonwords across the 22 blocks to ensure an even distribution of effort towards producing all nonwords correctly. Participant's response during each trial was recorded in order to ensure a minimum 8 – 10 correct productions of each nonword as these numbers of trials were minimally required for the kinematic analysis. A maximum of two additional blocks ($22 + 1 - 2$) were presented in case a few additional trials were required beyond the pre-established set of 22 blocks in order to achieve the minimum trim numbers for each nonword for the kinematic analysis.

The procedure required both the experimenters to record the participant errors online during the experiment. The notes from the online coding were later used to analyze the recorded productions offline for errors. Post-experiment, both experimenters listened independently to the recordings and provided offline scores of correct and error productions for the behavioral and kinematic analysis. Consonant, vowel, and stress errors were all recorded for the behavioral analysis. In addition, disfluencies, including sound or syllable repetitions, were also considered as errors. Additionally, correct productions that nonetheless included hesitations or pauses (> 750 ms) and delayed, prompted production or absence of the carrier phrase, were also excluded from the kinematic analysis. Only those productions that both raters agreed upon as being correct were included in the kinematic analysis.

Data Analysis

A detailed description of this analysis can be obtained from Smith et al. (2000) and Smith and Zelaznik (2004). The MATLAB digital signal processing software was used to simultaneously load and analyze the acoustic and kinematic data. Following low pass filtering (cut-off 10 Hz) of the lip displacement signals (both upper and lower lip), the velocity signal was computed from the lower lip displacement signal. Following this, the displacement trajectories associated with 10 correct productions of each nonword were obtained by identifying the correct productions from the 22 blocks and segmenting the corresponding displacement file for each correct production. The velocity signal was used to obtain the start and end point of the displacement trajectory of each correct production. The start point for each segment was the point of maximum opening velocity for /m/ (in the first syllable /mæb/) and the end point was the point of maximum opening velocity of the lower lip opening gesture for /b/ (in the last syllable). The peak velocity regions were easily located by the experimenter, and a MATLAB algorithm selects the peak opening velocity within a user-defined window. Each trim corresponding to a correct production was selected in this manner was then reassessed for fluency and accuracy of extraction by listening to the

associated audio record. If there were more than 10 correct productions of a target nonword, the trajectories associated with the first 10 were used in the data analysis.

Following extraction of the lip displacement trajectories for a set of 10 correct productions corresponding to a nonword, a multi-step analysis was performed using a custom MATLAB programme. First, the lip aperture (LA) signal was obtained by a sample-by-sample subtraction of the lower lip from the upper lip displacement signal. This analysis was carried out to obtain the difference between the upper and lower lip IRED markers as a function of time. Second, the 10 LA trajectories for each nonword were amplitude normalized, which involved subtracting the mean and dividing by the standard deviation. Third, using interpolation, the LA trajectories were time normalized to a fixed record length of 1000 points. Fourth, standard deviation values were calculated at 50 point intervals (2% intervals in relative time) of the normalized waveform. The cumulative sum of the 50 standard deviations was computed to obtain a cumulative spatial and temporal coordinative index called lip aperture variability index (LA VAR; Smith & Zelaznik, 2004). The LA VAR is a measure of the trial-to-trial spatial and temporal variability associated with the lip aperture (LA) trajectory. A higher LA VAR index suggests a greater degree of trial to trial variability in inter-articulatory coordination for nonword production, and vice versa. In addition to LA VAR, the movement duration in real time was computed as the total duration of the LA signal for each target production and was obtained by measuring the duration of each movement trajectory of a nonword from start to end point.

Statistical Analysis

A logistic mixed model analysis (McColloch, Searle, & Neuhaus, 2008) was performed on the behavioral data (percent correct productions) in order to investigate the extent of influence of cognitive - linguistic variables (digit span + sentence recall, nonword repetition, vocabulary size) as covariates on nonword learning. Furthermore, this analysis was also used to study the effect, if any, of language experience (monolingual vs. bilingual late) on nonword learning. Nonword variables including syllable length and complexity were also included in the analysis. Subjects were treated as a random effect. The number of correct and incorrect productions was the dependent variable in this analysis. A second linear regression analysis was performed in order to investigate the effects of language experience, and nonword properties (syllable length, complexity) on movement coordination. Digit span, nonword repetition, and vocabulary were the covariates in this analysis. LA VAR scores were the dependent variable in this analysis. Finally, Pearson correlations were performed between digit span and LA VAR scores for each nonword to determine the extent to which short-term memory may have influenced movement variability.

Results

Short-term Memory, Nonword Repetition, and Vocabulary

Descriptive analysis of the average scores from the memory measure (DSSR) revealed that the monolingual group scored 77.4 % (*S.D.* = 9.0) and the bilingual group scored 80.7 % (*S.D.* = 5.0). Independent samples t-test revealed the group differences to be non-significant, $t(18) = 0.88$, $p = 0.39$, two-tailed. Descriptive analysis of the nonword repetition scores revealed that the monolingual group scored 74.0 % (*S.D.* = 10.2) and the bilingual group scored 75.9 % (*S.D.* = 12.2). Independent samples t-test revealed the group differences to be non-significant, $t(18) = -0.72$, $p = 0.36$. If we adopt a one-tailed alternative analysis of the EVT raw scores revealed that the bilingual group scores lower (*Mean* = 165.4, *S.D.* = 6.5) than the monolingual group (*Mean* = 170.5, *S.D.* = 5.8, $t(18) = 1.79$, $p = 0.04$). The results from the standardized tests were further included as covariates in the regression analysis.

Behavioral Data

Descriptive analysis revealed a lower percent of correct productions for the 3-syllable nonwords ($Mean = 51.0$, $S.D. = 35.2$) compared to the 4-syllable ($Mean = 72.3$, $S.D. = 24.3$) and 6-syllable nonwords ($Mean = 66.2$, $S.D. = 36.0$). The nonword /*mab*/ was produced correctly by all subjects. Across the three nonword lengths, the percent of correct productions for the simple nonwords was higher ($Mean = 79.8$, $S.D. = 23.9$) compared to the complex nonwords ($Mean = 47.0$, $S.D. = 33.2$). The 6-syllable simple nonword /*mabtaibapoteeba*/ received the highest percent of correct productions ($Mean = 90.2$, $S.D. = 11.2$) while the 3-syllable complex nonword /*mabshufchloib*/ received the lowest percent of correct productions ($Mean = 35.4$, $S.D. = 31.6$) followed by the 6-syllable complex nonword, /*mabgrashroploikrooba*/ ($Mean = 42.3$, $S.D. = 36.3$). Descriptive comparison revealed that averaged across the nonwords the bilingual group scored a higher percent of correct productions ($Mean = 73.9$, $S.D. = 29.9$) compared to the monolingual group ($Mean = 58.2$, $S.D. = 33.9$).

Logistic mixed model—The aim of this analysis was to identify the extent of influence of language experience on the percent of correct productions in the nonword learning task. Cognitive-linguistic variables including DSSR, nonword repetition, and vocabulary scores were used as covariates. An indicator variable for language experience was also included as a covariate. Nonword properties including syllable length, complexity and their interaction were included as predictor variables. Subjects are treated as a random effect. Fitting was done using the “lmer” procedure in R, Bates, Maechler and Bolker (2011).

Among the four covariates, only DSSR had a clearly significant effect on the percent of correct nonword productions with a unit increase in DSSR corresponding to a 0.071 ($SE=0.03$) increase in percent correct ($Z = -2.39$, $p = .016$). The effect of language experience was marginally significant ($Beta (S.E.) = -0.89, (.46)$, $Z = -1.9$, $p = .051$), with the monolingual group scoring lower than the bilingual group. The other two covariates were insignificant.

The syllable length-complexity interaction was significant ($X^2 = 56.55$, $df = 2$, $p < .001$). Figure 1 presented the fitted probability of correct nonword production for the six conditions, adjusted for the covariates in the analysis. Percent correct nonword production is higher for simple nonwords than for complex nonwords at each number of syllables. Interestingly, for simple nonwords percent correct production increases with the number of syllables, but for complex nonwords percent correct production is highest for 4-syllables and lower for 3- or 6-syllables.

Kinematic Data

Descriptive analysis of the LA VAR scores revealed higher movement variability for the 3-syllable nonwords ($Mean = 19.1$, $S.D. = 5.8$) compared to the 4-syllable nonwords ($Mean = 16.6$, $S.D. = 5.4$) and the 6-syllable nonwords ($Mean = 17.4$, $S.D. = 6.0$). The control nonword /*mab*/ had an LA VAR score of 6.8 ($S.D. = 3.0$). Analysis of the simple vs. complex nonwords revealed that the movement variability for the complex nonwords ($Mean = 19.2$, $S.D. = 6.0$) was higher compared to the simple nonwords ($Mean = 16.3$, $S.D. = 5.2$). Averaged across the language groups, movement variability for the 4-syllable simple nonword, /*mabskokweeflaib*/ ($Mean = 15.3$, $S.D. = 4.5$) and the 6-syllable simple nonword, /*mabtaibapoteeba*/ ($Mean = 15.6$, $S.D. = 4.7$) were comparable and lower while that for the 3-syllable complex nonword, /*mabshufchloib*/ ($Mean = 19.9$, $S.D. = 5.5$) and the 6-syllable complex nonword, /*mabgrashroploikrooba*/ ($Mean = 20.4$, $S.D. = 6.7$) were comparable and higher. Finally, the mean movement variability for the bilingual group was 17.3 ($S.D. = 5.2$) and the monolinguals group was 17.8 ($S.D. = 6.0$).

Analysis of movement duration revealed that the complex nonword in each length category was longer in duration compared to the simple nonword (4-syllable: /mabskokweeflaib/, *Mean* = 1.37, *S.D.* = 0.16, /mabskreesploistroob/, *Mean* = 1.54 ms, *S.D.* = 0.23; 6-syllable: /mabtaibapoteeba/, *Mean* = 1.33 ms, *S.D.* = 0.13, /mabgrashroploikrooba/, *Mean* = 1.78 ms, *S.D.* = 0.29, 3-syllable: /mabthwaipfkrob/, *Mean* = 1.32 ms, *S.D.* = 0.26, /mabshfujchloib/, *Mean* = 1.64 ms, *S.D.* = 0.24). The duration of the nonword /mab/ was .26 ms (*S.D.* = .039).

Linear Mixed Model—The aim of this analysis was to identify the extent of influence of cognitive and linguistic variables and language experience on LA VAR scores in nonword learning. The covariates and predictors used were the same as for percent of correct productions, but linear model fitting was used rather than logistic. As with the percent of correct productions, LA VAR was associated with DSSR, with a unit increase in DSSR estimated to produce a change in LA VAR of -0.261 , *S.E.* = 0.109, $p < 0.02$. Other covariates were insignificant, in all cases with value of p in excess of 0.15. Unlike the percent of correct production analysis, the number of syllables by complexity interaction was not significant, $p = 0.30$, but both main-effects were significant (for Complexity, $X^2 = 13.14$, $df = 1$, $p = 0.00029$, while for number of syllables $X^2 = 6.59$, $df = 2$, $p = 0.03708$ (See Figure 2). Complexity increases LA VAR by an estimated 3.54 (*S.E.* = 0.97) at each number of syllables. Increase in the number of syllables from 3- to 4- resulted in a decrease in LA VAR scores, *Beta* (*S.E.*) = -3.07 (1.19), $Z = -2.57$, $p < .01$. Increase in the number of syllables from 3- to 6-syllable nonwords resulted in a trend for decrease in LA VAR scores, *Beta* (*S.E.*) = -1.79 (1.22), $Z = -1.46$, $p > .1$.

Correlation of Memory measure and Movement Variability

Pearson product moment correlations were computed to study further the effect of short-term memory on movement variability for individual nonwords. This analysis revealed a negative correlation between DSSR scores and movement variability such that an increase in DSSR resulted in a decrease in movement variability for both the 6-syllable nonwords (/mabtaibapoteeba/, *pearson* $r = -0.54$, $p = .003$, and /mabgrashroploikrooba/, *pearson* $r = -0.58$, $p = .01$), the complex 4-syllable nonword /mabskreesploistroob/, *pearson* $r = -.43$, $p = .03$, and the 3-syllable nonword /mabthwaipfkrob/, *pearson* $r = -0.65$, $p = .001$.

Discussion

The present study was a preliminary investigation of the effects of cognitive – linguistic variables including, short-term memory (digit span and sentence recall), nonword repetition, and long-term memory (vocabulary size) on behavioral and kinematic measures of nonword learning. The study also investigated the effects of language experience on behavioral and kinematic measures of nonword learning. Finally, the nonwords in the present study were varied in syllable length and complexity to examine the effects of these variables on task performance. Logistic mixed modeling of the behavioral data revealed that vocabulary scores are not a significant predictor of nonword learning in adults. The findings also revealed for the first time that short-term memory processes directly influence not just behavioral performance but also movement variability in nonword learning. Furthermore, speakers of varying language experiences showed comparable movement variability associated with nonword production.

Cognitive – Linguistic variables

In this study the contributions of short-term (digit span + sentence recall, DSSR; nonword repetition) and long-term memory processes (vocabulary scores) on nonword learning in adults were investigated. Computational modeling of nonword repetition data has revealed reliance on short-term memory processes in nonword learning (e.g. Gupta & Tisdale, 2004).

The findings revealed that the measure of short-term memory used in this study (DSSR) was a significant variable in determining behavioral performance in nonword learning in adults.

Investigation of the effect of vocabulary scores on nonword learning was also undertaken in this study and the findings revealed that vocabulary scores did not have a significant influence on behavioral performance in adults. Furthermore, analysis of the standardized test results revealed that the bilingual group had lower scores on the vocabulary test. The above findings of reliance on short-term memory rather than long term processes for nonword learning in adults has been demonstrated in several other studies (e.g. Gaskell & Dumary, 2003; Majerus et al., 2008) and highlight the role of short-term memory processes in nonword learning in adults.

The effect of the short-term memory measures was also evident on movement coordination such that for every unit increase in this measure a reduction in movement variability in nonword production was observed. Further correlation between the memory measure and individual nonwords revealed a significant correlation such that increase in this measure was accompanied by a decrease in movement variability for the more complex nonwords including the 6-syllable nonwords and the complex 4-syllable nonword / *mabskreesploistroob*/. This is the first study to demonstrate such a direct effect of cognitive – linguistic variables, such as short-term memory, on speech movement kinematics with varying nonword complexity. Perhaps the short-term memory acts as a buffer in temporarily storing motor programs of the nonwords during repeated production, and with increasing complexity there is a higher reliance on this buffer action to produce coordinated speech movements. Future studies need to take into consideration the effect of this variable on movement coordination in nonword learning.

Language experience

The effects of language experience on nonword repetition performance were measured in this study. The findings revealed a marginally significant difference ($p = .051$) between the bilingual and monolingual groups such that bilinguals had a higher percent of correct productions in the nonword learning task. This marginal significance is consistent with earlier reports of a significant advantage for the bilingual group in nonword learning (e.g. Majerus et al., 2008; Papagno & Vallar, 1995). The present finding of a trend for significant difference between the bilingual and monolingual group, however, should be interpreted with caution as the bilinguals in this study were a heterogeneous group of late bilinguals varying in proficiency and the second language that was spoken. Such differences may have contributed to the observed marginal trend for significance in the behavioral performance. A reason for the observed bilingual advantage in this task is not clearly evident. For instance, although short-term memory played a critical role in task performance, the bilingual group was not significantly different from the monolingual group in this measure while some descriptive differences were observed. Therefore, short-term memory may not be solely attributable to the observed bilingual advantage. Furthermore, the nonwords in the present study were primarily constructed based on English phonotactics rather than the phonotactics of the second language and therefore a broader phonological knowledge base due to experience in two languages in the bilingual group is not attributable to the marginally significant difference between the groups in behavioral performance. Further studies need to take into consideration the several variables including short-term memory and varying levels of proficiency in accounting for a bilingual advantage in nonword repetition.

Analysis of the movement data revealed that a trend for significant group differences similar to the effect observed in behavioral performance was not observed between groups in movement variability thereby indicating that although the bilingual group may have a slight advantage in behavioral performance, the groups were comparable in terms of movement

variability. This finding also suggests that a larger phonological knowledge base in the bilingual group did not necessarily offer an advantage in movement coordination in nonword learning.

Nonword properties

The effects of phonemic level variables on nonword learning were investigated in the present study by varying syllable length and syllable internal phonemic composition. The nonwords were 3-, 4-, or 6-syllables long with the 3-syllable nonwords consisting of phonemic combinations non-existent in English. Furthermore, within each syllable length the nonwords were categorized as phonemically simple or complex based on syllable-internal phonemic composition. The findings indicated that the complexity manipulation used in the present study was successful in challenging task performance. The behavioral data revealed that both syllable length and syllable-internal phonemic composition are critical variables that determine nonword learning in adults. Participants experienced more difficulties with the 3-syllable nonwords that contained phonemic combinations not existing in English compared to the 4- and 6-syllable nonwords. Similarly, a higher percentage of errors were obtained for the complex nonword compared to the simple nonwords in each category. This finding supported the observation that the internal phonemic composition of the nonwords and nonword length are critical variables that determined nonword learning in adults (also see, Gathercole, 2006). Interestingly, the 6-syllable nonword /*mabtaibapoteeba*/ had the highest percentage of correct productions (Mean = 90.2, S.D. = 11.2) of all of the nonwords while the 3-syllable complex nonword, /*mabshufchloib*/ had the lowest percent of correct productions (Mean = 35.4, S.D. = 31.6) thereby indicating that syllable-internal phonemic composition may have a greater influence on nonword learning than the syllable length variable.

Analysis of movement variability revealed higher movement variability or reduced movement coordination for the 3-syllable nonwords compared to the 4-syllable nonwords and a trend for higher movement variability for the 3-syllable compared to the 6-syllable nonwords. Within each length category, a significant effect of complexity was observed such that the movement variability was higher for the complex nonwords compared to the simple nonwords. These findings corroborate earlier reports of an effect of nonword complexity and phonemic composition on speech movement coordination (e.g. Sasisekaran et al., 2010). The finding of higher movement variability for the 3-syllable nonwords with phonemic combinations non-existent in English and for the complex compared to the simple nonwords also offers some preliminary support for the existence of a syllabary or storage of motor programmes for high frequency syllables in a language (Levelt, 1989; 1999). Together, the findings support the observation that nonword properties determine both behavioral and kinematic performance in nonword learning.

Summarizing, the present findings support the observation that nonword learning is multiply-determined and is influenced by short-term memory processes, language experience, and nonword properties. Both behavioral and kinematic performances were influenced to varying extent by these variables. A limitation of the present study is the smaller sample size of bilingual speakers and the heterogeneous nature of this group based on proficiency and the second language spoken. This may have resulted in the observed trend for significance rather than a significant advantage in behavioral performance. Further studies are required comparing monolinguals vs. late bilinguals in nonword repetition performance in order to investigate potential differences in behavioral and kinematic performance. The findings also reveal a role for the speech motor system in nonword learning. While language experience did not contribute to differences in movement variability in nonword learning, nonword properties including syllable length and phonemic complexity were critical variables that determined the response of the speech motor system

to task performance. Finally, the results support the observation that cognitive variables such as short-term memory have a direct influence on movement coordination. Further studies are required to understand the nature of interactions between the cognitive and speech motor systems with the production of increasingly complex nonwords.

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Figure 1. Estimated percent correct productions for nonwords in six conditions, adjusted for four covariates. Error bars give 95% confidence interval.

Figure 2.
Estimated LA VAR in six conditions, adjusted for four covariates. Error bars give 95% confidence interval.