# Lexical and sub-lexical knowledge influences the encoding, storage, and articulation of nonwords

Short title: Lexical knowledge and nonwords

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Abstract

Nonword repetition (NWR) has been used extensively in the study of child language. Although lexical and sub-lexical knowledge is known to influence NWR performance, there has been little examination of the NWR processes (e.g., encoding, storage, articulation) that may be affected by lexical and sub-lexical knowledge. We administered 2- and 3-syllable spoken nonword recognition and nonword repetition tests on two independent groups of 31 children (M=5;07). Spoken nonword recognition primarily involves encoding and storage, whereas NWR involves an additional articulation process. The influence of lexical and sub-lexical knowledge was determined by examining the amount of lexical errors produced. There was a clear involvement of long-term lexical and sub-lexical knowledge in both spoken nonword recognition and NWR. In spoken nonword recognition, twice as many errors involved selecting a foil that contained a lexical item (e.g., yashukup) over a foil that contained only nonsense syllables (e.g., yashunup). In repetition, over 30% of errors changed a nonsense syllable to a lexical item. Our results show that long-term lexical and sub-lexical knowledge is pervasive in NWR – any explanation of NWR performance must therefore consider the influence of lexical and sub-lexical knowledge throughout the whole repetition process, from the encoding of nonwords to the articulation of them.

Keywords: nonword repetition, encoding, articulation, phonological working memory, lexical knowledge.

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# Introduction

If a child is to attain an accomplished use of their native language, then they must first learn the vocabulary of that language. Vocabulary learning is at least a two stage process. The first stage is learning the word boundaries from incoming speech that does not ordinarily contain pauses. The second stage is the learning of words in a meaningful way. Word learning involves the temporary storage of the word in phonological working memory, where learning processes can act upon the word for subsequent storage in long-term memory, and lexical access processes can retrieve the word for later articulation. It is on the second stage of vocabulary learning that the current paper is focused. Extensive research (e.g., Dollaghan, Biber & Campbell, 1995; Gathercole & Adams, 1993; Munson, Kurtz & Windsor, 2005) has been conducted in word learning using nonword repetition (NWR), where nonwords varying along a number of dimensions (e.g., stress, length) are presented to the child who must repeat the nonwords aloud. The task is an extremely good predictor of language ability (e.g., Gathercole & Baddeley, 1989; Cheung, 1996) and involves the ability to encode, store, and articulate the spoken nonword, amongst other processes (Coady & Aslin, 2004).

## Nonword repetition research

NWR tests were originally designed to examine phonological working memory, a temporary store for auditory information. Research showed that adults with impaired phonological working memory had difficulty in learning word-nonword pairs compared to word-word pairs (Baddeley, Papagno, & Vallar, 1988). Words would be expected to have some form of representation in long-term memory whereas nonwords would not, leading to the belief (at the time) that impaired performance on word-nonword pairs was primarily due to nonword learning being reliant on phonological working memory. Gathercole and Baddeley (1989) supported the phonological working memory account by finding that 4-5 year olds' NWR performance declined as nonword length increased. Longer nonwords place more of a burden on phonological working memory and therefore have an increased probability of being incorrectly repeated. Subsequent research showed further support by finding nonword length effects for 2-3 year olds (Gathercole & Adams, 1993) and 7-11 year olds (Archibald & Gathercole, 2006).

However, it quickly became clear that even phonologically novel words had strong links to long-term lexical and sub-lexical knowledge. For the purposes of this paper, lexical knowledge refers to phoneme sequences that correspond to a known lexical item or morpheme, and sub-lexical knowledge refers to phoneme sequences that form part of a known lexical item or morpheme. Gathercole (1995) re-analysed children's responses to her set of nonwords based on adult ratings of the wordlikeness of each nonword. Children showed superior repetition accuracy for nonwords that adults rated high in wordlikeness over nonwords that adults rated low in wordlikeness. The nonwords that adults rated high in wordlikeness show a greater number of lexical items or morphemes (e.g., <u>thick</u>ery, sladd<u>ing</u>) than the nonwords that adults rated low in wordlikeness (e.g., glistow, woogalamic). Wordlikeness effects have also been shown for other sets of nonwords (e.g., Frisch, Large, & Pisoni, 2000; Munson, Kurtz, & Windsor, 2005).

There is also a sub-lexical influence on repetition performance. Nonwords constructed from high frequency phoneme sequences are easier to repeat than nonwords constructed from low frequency phoneme sequences (e.g., Munson 2001; Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997). Although frequency and wordlikeness have been shown to have a strong relationship (Frisch, Large, & Pisoni, 2000), they have also been shown to exert independent influences on repetition performance (Munson, Edwards, & Beckman, 2005).

In order to test the influence of phonological working memory, any help from long-term lexical and sub-lexical knowledge needs to be minimised. Munson, Kurtz, and Windsor (2005) therefore suggest that nonwords be constructed from low frequency phoneme sequences that do not contain any lexical items or morphemes. However, since low frequency phoneme sequences clearly exist in spoken language, their components are not precluded from having some form of representation as long-term sub-lexical knowledge. Frisch, Large, and Pisoni (2000) also suggest that even nonwords comprising low frequency phoneme sequences can still activate lexical knowledge.

Gathercole and colleagues (e.g., Gathercole, 1995, 2006; Gathercole, Frankish, Pickering, & Peaker, 1999) used redintegration (Schweickert, 1993) as an explanation for the influence that lexical and sub-lexical knowledge has on NWR. Any spoken input is placed in phonological working memory, where it decays after approximately

2,000 ms unless it is rehearsed (Baddeley & Hitch, 1974). If the information in phonological working memory becomes degraded in quality (e.g., if there was a large amount of information placed in phonological working memory or the information remained there for longer than 2,000 ms) then there are two processes that can be applied to help repair the degraded information. First, lexical knowledge can be used to ‘fill in’ the missing parts. For example, if only the initial phoneme of the nonword ‘trumpetine’ was degraded, knowledge of the lexical item ‘trumpet’ could repair the /t/. Second, sub-lexical knowledge, in the form of phonological similarity, can be used to repair degraded information[1]. For example, the final phoneme /k/ of the nonword ‘neek’ could be repaired because the nonword rhymes with ‘week’. Note that when a spoken input becomes degraded in quality, it can still retain some information. For example, if the /b/ of the nonword ‘rubid’ became degraded in quality but retained the fact that it was a consonantal stop, then it could be correctly repaired using the lexical item ‘bid’ or incorrectly repaired using the lexical items ‘did’ and ‘kid’. However, it could not be repaired using lexical items such as ‘lid’ and ‘hid’ since they do not begin with a consonantal stop.

Redintegration was originally used to explain the greater serial recall accuracy of word lists over nonword lists (Hulme, Maughan, & Brown, 1991). The application of redintegration to NWR (using the original conception of redintegration as described above) is because nonwords involve a sequence of sounds that are initially unknown to the listener, and hence nonword processing can be viewed as serial recall of a phoneme sequence. When viewed as such, NWR shows the same type of primacy and

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[1] Although Schweickert (1993) does not explicitly state that sub-lexical information is used to repair degraded information, he does indicate its use: “detailed knowledge of the features of phonemes in the context of other phonemes would be useful” (p. 173).

recency effects that are encountered in the serial recall of words (Gupta, 2005) and overall NWR performance shows a strong relationship to serial recall performance (Gupta, 2003).

The redintegration account makes specific predictions regarding NWR performance: (a) redintegration is most likely to benefit nonwords that are wordlike or that contain high frequency phoneme sequences, because they have more in common with existing lexical and sub-lexical knowledge; and (b) as the quality of a nonword held in phonological working memory decreases, the likelihood of long-term lexical and sub-lexical involvement increases. Prediction (a) has already been supported by the wordlikeness and frequency research reported above, but is also supported in a broader capacity by Dollaghan, Biber, and Campbell (1995). They found improved NWR performance for nonwords containing lexical items as opposed to nonwords without (e.g., <u>bath</u>esis versus <u>fath</u>esis), consistent with the idea that lexical knowledge is more beneficial as nonwords become more wordlike. However, they also found that errors in NWR often involved substituting a nonsense syllable for a lexical syllable, consistent with the idea that lexical (and possibly sub-lexical) knowledge is used to repair the decayed representation of nonwords. To our knowledge, prediction (b) has not been directly tested and is one focus of the current study. The quality of a stored nonword in phonological working memory can be manipulated by varying the length of the nonword, since long nonwords are more prone to decay relative to short nonwords. Taking into account the results of Dollaghan, Biber, and Campbell (1995) therefore, as nonword length increases, one should also expect an increase in NWR errors that substitute a nonsense syllable for a lexical item due to the increased involvement of lexical (and possibly sub-lexical) knowledge.

The clear indication from the literature covered thus far is that NWR performance is influenced by both phonological working memory and long-term lexical and sub-lexical knowledge. However, there are three key processes involved in NWR (other processes may be involved but we consider the following as the key processes, as do Coady & Aslin, 2004): accurate perception and encoding of the spoken nonword, together with its temporal sequence; efficient storage of the phoneme sequence; and the preparation and execution of speech-motor processes to articulate the phoneme sequence. For the purposes of the current study, we combine the first two processes such that NWR involves encoding/storage and articulation. Since tests of NWR performance examine the child's articulated response (i.e., after encoding/storage and articulation have taken place), it is unclear whether the interaction between phonological working memory and long-term lexical and sub-lexical knowledge occurs at the encoding/storage stage, the articulation stage, or both. The redintegration account predicts no lexical or sub-lexical involvement at the stage of encoding/storage since redintegration occurs at the later point of retrieval (e.g., Gathercole, 1995; Thorn, Gathercole, & Frankish, 2005; see also Hulme, Roodenrys, Schweickert, Brown, Martin, & Stuart, 1997). That is, redintegration is hypothesised to occur at a late stage in NWR – when the nonword is retrieved from memory for articulation – rather than at an early stage, such as during encoding of the incoming sound patterns.

If a nonword task is administered that does not involve articulation, then the influence that long-term lexical and sub-lexical knowledge has on encoding/storage can be examined. The results of the encoding/storage nonword task can then be compared to the influence that long-term lexical and sub-lexical knowledge has on the traditional nonword repetition task that involves encoding/storage and articulation. While we accept that the ‘additive’ nature of this hypothesis suggests that encoding, storage, and articulation are sequential processes, any differences in performance between the articulation-excluded and articulation-included nonword tasks nevertheless must indicate additional processes that are involved in articulation over and above the ability to encode and store a nonword.

Encoding/storage and articulation have been compared previously within the context of word production. For example, Rossmeissl and Theios (1982) recorded response times in word production where participants either read aloud words immediately or read them aloud after a delay. It was assumed that during a delay, participants can encode and store the material and therefore the delay condition should only involve articulation. There was a large reduction in response latency in the delay condition, suggesting that the no-delay condition involved encoding, storage, and articulation, whereas only articulation was involved in the delay condition. Balota and Chumbley (1985) further examined the effect of a delay until word production. By manipulating word frequency, they found that high frequency words were produced more quickly than low frequency words under various temporal delays. Taken together, these two studies illustrate that the articulation process must involve long-term lexical (and possibly sub-lexical) knowledge since frequency effects emerged when both encoding and storage were minimised. However, studies of spoken word recognition indicate that long-term lexical (and possibly sub-lexical) knowledge is also involved in encoding (Norris, McQueen, & Cutler, 2003). Recognising a word primarily involves lexical access and encoding, with minimal need for storage and no requirement for articulation. Word recognition studies show superior response times for high frequency words over low frequency words (e.g., Brysbaert, Lange, & Wijnendaele, 2000; Forster & Chambers, 1973). For word stimuli at least, long-term lexical (and possibly sub-lexical) knowledge must influence both encoding and articulation.

However, encoding/storage and articulation have not been examined thoroughly in the production of nonwords, and yet without their examination we cannot be certain where interactions between phonological working memory and long-term lexical and sub-lexical knowledge may lie. We suggest that two tasks are required to examine the influence of lexical and sub-lexical knowledge on both encoding/storage and articulation. Conducting a spoken nonword recognition task on an item-by-item basis excludes articulation, emphasising the role of encoding/storage (other processes will be involved but encoding/storage should be primary). Conducting a nonword repetition task includes articulation, emphasising any additional processing over and above encoding/storage.

## Spoken nonword recognition research

Although there are studies that present several to-be-remembered spoken nonwords for later recognition (e.g., Gathercole & Pickering, 1999), we know of no study that examines spoken nonword recognition on an item-by-item basis in a way that is analogous to NWR. One possible exception is Swingley and Aslin (2007) who trained 1.5 year olds on spoken nonwords that related to specific pictures before a later item-by-item recognition test (by examining gaze duration when presented with the associated picture and an unassociated one, together with the spoken nonword). For our purposes, the most pertinent spoken nonword recognition study is that of Frisch, Large, and Pisoni (2000), who examined serial spoken nonword recognition in adults.

Participants rated 72 nonwords for wordlikeness before later being given a recognition test involving the original 72 nonwords plus 72 foils. Providing support for long-term lexical and sub-lexical influences in encoding/storage, they found improved spoken nonword recognition performance for nonwords that contained high frequency phoneme sequences relative to nonwords that contained low frequency phoneme sequences. Interestingly, no effect of nonword length on spoken nonword recognition was found – consistent with research in spoken word recognition (e.g., Frederikson & Kroll, 1976) but in contrast to the NWR literature that consistently finds length effects (e.g., Gathercole & Baddeley, 1989; Jones, Gobet, & Pine, 2007; Jones, Tamburelli, Watson, Gobet, & Pine, in press).

There is also literature on speech perception that supports long-term lexical and sub-lexical influences, at least for the encoding of incoming sounds. By examining ambiguous sounds in Dutch, Norris, McQueen, and Cutler (2003) found that the categorisation of the ambiguous sound was dependent upon the lexical context of the stimuli. For example, the sound of the final /f/ in druif (grape) was altered to be between /f/ and /s/ on a continuum but was almost always perceived as /f/ because of its context in relation to the remainder of the word. Pitt and McQueen (1998) showed that sub-lexical knowledge also affected the processing of English-based nonwords. By manipulating the transitional probabilities of vowel-consonant biphones, they found that ambiguous consonants were more likely to be perceived as the consonant that most often followed the vowel in English.

## The current study

We conduct spoken nonword recognition and NWR on independent groups of 5-6 year olds using the same set of 2- and 3-syllable nonwords for each task. The two tasks are designed to assess the long-term lexical and sub-lexical involvement in encoding/storage and articulation, and to test the redintegration predictions outlined earlier. We use 5-6 year old children for two reasons. First, a pilot study has shown that 5-6 year old children are old enough to successfully complete both spoken nonword recognition and nonword repetition, while at the same time we know that children of this age are unable to reliably use any memory strategies such as rehearsal (Gathercole & Adams, 1994). This is important because both tasks, in part, require the child to remember nonwords. Minimal use of memory strategies therefore results in more reliance on phonological working memory and lexical/sub-lexical knowledge when completing the tasks. Second, at 5-6 years of age, both phonological working memory and lexical/sub-lexical knowledge are strong predictors of vocabulary learning. Up to the age of five, the best predictor of vocabulary learning is phonological working memory (Gathercole & Baddeley, 1989), and at the age of six and above, the best predictor is lexical/sub-lexical knowledge (Gathercole, Willis, Emslie & Baddeley, 1992).

The spoken nonword recognition task presents each nonword followed by three further nonwords – the same (target) nonword, a lexical foil that substitutes one phoneme of the target nonword to create a syllable that is a lexical item, and a non-lexical foil that substitutes one phoneme of the target nonword to create another nonsense syllable. The NWR task presents the original nonwords for the children to repeat aloud. A forced pause is introduced between hearing the nonword and repeating it that is equivalent to the time lapsed between hearing the original nonword and hearing the target in the spoken nonword recognition test.

For spoken nonword recognition, the use of lexical foils allows us to examine long-term lexical and sub-lexical involvement in encoding/storage. If there is no long-term involvement, then any errors on the task should involve an equal number of lexical and non-lexical foil selections. For NWR, repetition errors that change a nonsense syllable into a lexical item show the clearest influence of lexical and sub-lexical knowledge. We use the term lexical error to denote the selection of a lexical foil in the spoken nonword recognition task and the substitution of a nonsense syllable for a lexical item in the NWR task. An increase in lexical errors in the repetition task over the spoken nonword recognition task therefore indicates the likely involvement of long-term lexical and sub-lexical knowledge in the articulation process.

The design of the current study allows us to examine several research questions that have not yet been examined in the domain of nonword processing:

1. The extent to which encoding/storage and articulation are influenced by lexical and sub-lexical knowledge. Current NWR studies indicate that lexical and sub-lexical knowledge influences repetition performance, but as yet we do not know whether this occurs primarily at the encoding/storage stage, the articulation stage, or both. We can answer this question by comparing the number of lexical errors produced in spoken nonword recognition versus the number of lexical errors produced in NWR.

2. Whether the influence of lexical and sub-lexical knowledge increases as the quality of a stored nonword decreases. The redintegration account predicts that for NWR, lexical and sub-lexical knowledge exerts a greater influence as the quality of a nonword declines. As the influence of lexical and sub-lexical knowledge increases, so should the proportion of repetition errors that are classified as lexical errors. We can answer this question by (for example) comparing the proportion of errors that are classed as lexical errors across 2-syllable and 3-syllable nonwords, the latter of which are more prone to decay due to their phonemic length. If a similar pattern of results also occur for spoken nonword recognition, then redintegration, or another similar process, must occur at an earlier stage than retrieval.

3. The extent to which errors in NWR are explained by encoding/storage and the extent to which errors in NWR are explained by articulation. Currently, studies of NWR base their results on repetition accuracy that we know involves encoding/storage and articulation. Hence there is no way of determining whether the source of NWR errors lie with encoding/storage or with articulation. We can answer this question by comparing accuracy in spoken nonword recognition versus accuracy in NWR to begin to identify the relative contributions of encoding/storage and articulation in NWR performance.

# Method

## Participants

64 children were recruited from three primary schools within a 9-mile radius north of Nottinghamshire. Two children were removed from the analyses as they failed to perform within normal ranges on the British Picture Vocabulary Scale Version 2 (BPVS-II, Dunn, Dunn, Whetton, & Burley, 1997). The remaining 62 children (28m, 34f; 5;03 – 6;09, M=5;07) were native speakers of English and had no learning, speech or hearing difficulties, as reported by their school teacher.

## Materials

### Creation of nonwords

Fifteen 2-syllable (5-7 phonemes in length) and fifteen 3-syllable (7-8 phonemes in length) nonwords were created. In order for all nonwords to be perceived as plausible English words, we ensured that (a) the nonwords followed the predominant stress pattern for 2-syllable words (strong-weak e.g., geris [ˈgerɪs]) and one of the predominant stress patterns for 3-syllable nonwords (strong-weak-weak e.g., heburin [ˈhebərɪn]); and (b) all of the constituent biphones within each nonword existed in the child's vocabulary. We extracted biphone frequencies from the Children's Printed Word Database (CPWD, a database containing frequency counts of the printed word vocabulary of 5-9 year old children, Masterson, Stuart, Dixon, & Lovejoy, 2010) and ensured that each biphone had a frequency of at least 10. Although the CPWD is a summary of children's written word frequencies, as far as we are aware no such database exists for children's spoken English. Note that we ensured that all nonwords were non-lexical by constructing nonwords that contained no grammatical morphemes and no syllables that existed as lexical items in the CPWD.

In order for the spoken nonword recognition test to be of sufficient difficulty, we used only nonwords that contained low frequency biphones. We compared the constituent biphones of the nonwords to the biphones from a random sample of 30 of the lowest frequency (3 occurrences per million) words in the CPWD (matched for stress pattern, length in syllables, and length in phonemes). For 2-syllable items, the nonword biphones had a significantly lower average log frequency ($M$ = .43 vs. $M$ = .54; $t(28) = 7.13$, $p < .001$). The same was true of 3-syllable nonwords ($M$ = .47 vs. $M$ = .57; $t(28) = 5.59$, $p < .001$) (average log frequency was computed using the method of Luce and colleagues: Jusczyk, Luce, & Charles-Luce, 1994; Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997; Vitevitch & Luce, 1998). Note that by using nonwords containing low frequency phoneme sequences and that have no lexical or morphological components, we minimise the influence of lexical and sub-lexical knowledge. If lexical errors still persist in spoken nonword recognition and NWR, then the influence of lexical and sub-lexical knowledge is likely to be prevalent for all types of nonword.

Creation of foils

The spoken nonword recognition test presents each nonword succeeded by three further nonwords: the original nonword (the target), a lexical foil and a non-lexical foil. The lexical and non-lexical foils for each nonword were created by changing the initial phoneme of the last syllable to either create a final syllable that was a lexical item that existed in the CPWD or a final syllable that was a nonsense syllable different from that of the target. For example, the nonword yashudup had the lexical foil yashukup and the non-lexical foil yashunup. The phoneme change could differ by place of articulation, manner of articulation, voice, or a combination of these. In the example, /d/ and /k/ differ by place and voice, and /d/ and /n/ differ only by manner of articulation – since the phoneme used to create a lexical syllable differs by two features from the original phoneme whereas the phoneme used to create a non-lexical syllable differs by one feature, the lexical syllable might be easier to distinguish from the original. We therefore ensured that foil selections were not influenced by the number of phoneme features that change when creating non-lexical and lexical syllables (non-lexical phoneme features: $M = 2.13$, $SD = .75$; lexical phoneme features: $M = 2.16$, $SD = .72$; $t(28) = .17$, $p = .869$).

Position of the stimuli

For the spoken nonword recognition test, the 15 nonwords at each syllable length were randomly split into three groups of 5 nonwords. The first group had the target in the first position, the second group had the target in the second position, and the third group had the target in the third position. The relative positions of the lexical and non-lexical foils were counterbalanced (e.g., when the target was in the first position, the lexical foil occurred in position two twice and in position three thrice).

There was no difference between the nonwords at each position in terms of number of phonemes, spoken duration, or average log frequency ($p$=.25 or higher). We also ensured that the nonwords at each length and position contained a similar number of neighbours. All neighbours were totalled for each syllable in a nonword (neighbours being defined as words within the CPWD that differed by only one phoneme to the nonsense syllable). There was no difference in the number of neighbours for nonwords in each different position for both 2-syllable nonwords ($F(2,12) = .03$, MSE = 71.57, $p = .972$) and 3-syllable nonwords ($F(2,12) = .29$, MSE = 39.07, $p = .765$).

Recording of the stimuli

The nonwords and their foils were recorded onto a Sony ICD-MX20 digital voice dictaphone by the second author who was native to Nottingham. All nonwords were converted to MP3 format using Sony Digital Voice Editor, version 3.1 (available from http://esupport.sony.com/). The nonwords were edited using Audacity (http://www.audacity.sourceforge.net/) such that the original nonword was followed by a pause of 1.2s, followed by the foils and target separated by .7s pauses. The 2-syllable nonwords had a mean spoken duration of .8s and therefore the temporal duration until hearing the target nonword was 2.0s, 3.5s, and 5.0s when the target appeared in the first, second, and third positions respectively (2.2s, 3.9s, and 5.6s for the 3-syllable nonwords which had a mean spoken duration of 1.0s). The order of the sets of nonwords plus foils was randomised to produce two sound files for each nonword length: the randomised order and the reverse of this order.

For the NWR test each nonword was succeeded by a pause and then a beep (the children were asked to wait for the beep before repeating the nonword). The pause duration matched the temporal duration until the target of the relevant nonword was heard in the spoken nonword recognition test. For example, the target for the nonword virel appeared in the first position, and therefore the nonword virel was followed by a 1.7s pause and a .3s beep in the NWR test. Two sound files were produced for each nonword length that matched the randomised order of nonwords in the spoken nonword recognition test. Figure 1 gives an illustration of the presentation of stimuli for both spoken nonword recognition and NWR.

FIGURE 1 ABOUT HERE

Design

The type of test (spoken nonword recognition, NWR) was a between subjects variable and nonword length (2-syllables, 3-syllables) was a within subjects variable. For spoken nonword recognition, the position of the target ($1^{st}$, $2^{nd}$, $3^{rd}$) was also a within subjects variable; for NWR the pause duration (2.0s, 3.5s, and 5.0s for 2-syllable stimuli, 2.2s, 3.9s, and 5.6s for 3-syllable stimuli) was also a within subjects variable.

Procedure

All children were tested individually in a quiet area of their school. The sound files were played to each child using a Sony ICD-MX20 digital voice dictaphone connected to Creative Inspire T10 portable speakers.

Children were randomly allocated to either the spoken nonword recognition group or the NWR group and given standardised instructions together with an example trial (instructions and example differed depending on whether spoken nonword recognition or NWR was being carried out). Once the child had completed the example, and had confirmed to the experimenter that they understood the task, the testing began.

The session for each child consisted of all stimuli at one nonword length followed by the BPVS-II followed by all stimuli at the other nonword length. The presentation order of the 2-syllable and 3-syllable stimuli was counterbalanced.

For spoken nonword recognition, the child was required to say whether the original nonword matched the first nonword that they heard, the second or the last. Children's responses were noted by the experimenter. For NWR, the child repeated the nonword as accurately as possible after hearing the beep. Responses were recorded onto a Sony ICD-MX20 digital voice dictaphone for later transcription.

## Results and Discussion

We first analyse the results for spoken nonword recognition, followed by the nonword repetition results, and finally a comparison between the two. Note that the children in the spoken nonword recognition condition and the children in the nonword repetition condition had very similar levels of vocabulary knowledge as evidenced by their standardised BPVS-II scores (spoken nonword recognition: $M$ = 101.87, $SD$ = 10.95; nonword repetition: $M$ = 103.13, $SD$ = 11.20; $t(60) = .45$, $p = .656$).

### Spoken Nonword Recognition

During the collection of the data, a problem was discovered with one of the nonwords, reldufop, the nonword foil for which was relduthop. The recording of the nonword foil resulted in the phoneme /th/ being almost indistinguishable from /f/ and therefore reldufop was removed from all analyses.

Verification of data

Participants' selection of the target was significantly above chance levels at each position of the target and for each nonword length (all $p < .001$), indicating that the children were not simply guessing among the three options.

Analyses

Figure 2 shows the percentage selection of the target (i.e., the original nonword), lexical foil, and non-lexical foil at each position and for each nonword length. A 2 (nonword length: 2- or 3-syllables) x 3 (position: 1, 2, or 3) x 3 (foil type: target, lexical, non-lexical) repeated measures ANOVA was carried out on the data. Note that by including foil type as a variable, no independent effects of nonword length, position, and the interaction between the two are seen (collapsing the data across foil type will always total 100% since it includes the percentage selections of the target, lexical, and non-lexical foils). There was a significant effect of foil type ($F(2,60) = 114.44$, $p < .001$, $\eta_p^2 = .79$) with post-hoc Bonferroni tests indicating the target was selected more often than both the lexical and non-lexical foils (both $p < .001$), and lexical foils were selected more often than non-lexical foils ($p < .001$). There was also a significant interaction between nonword length and foil type ($F(2,60) = 10.17$, $p$ <

.001, $\eta_p^2 = .25$). We confirmed that the interaction reflected not only a higher number of target selections for 2-syllable stimuli over 3-syllable stimuli ($t(30) = 3.46$, $p = .002$), but also a lower number of lexical foil selections for 2-syllable stimuli over 3-syllable stimuli.

The interaction between position and foil type only approached significance ($F(4,120) = 2.38$, $p = .056$, $\eta_p^2 = .07$), indicating a slight decrease in target selections (and hence an increase in foil selections) at position two. The position of the target did not significantly influence its recognition. The three way interaction was not significant ($F(4,120) = .39$, $p = .815$, $\eta_p^2 = .01$).

FIGURE 2 ABOUT HERE

The spoken nonword recognition results confirm the involvement of phonological working memory, long-term lexical and sub-lexical knowledge, and the interaction of the two in the encoding/storage of nonwords. First, the significant decline in target selections for 3-syllable nonwords relative to 2-syllable nonwords shows the involvement of phonological working memory – 3-syllable nonwords are longer in duration and therefore have to be maintained in phonological working memory for a longer period of time until the target is heard. Children are therefore susceptible to length effects in the spoken recognition of nonwords, whereas adults are not (Frisch et al., 2000). Second, the number of lexical foil selections significantly outweighed the number of nonword foil selections, showing that lexical and sub-lexical knowledge must be involved in the encoding/storage of nonwords. Third, as nonword length increased, there was a significant increase in lexical foil selections – indicating an interaction between phonological working memory and long-term lexical and sub-lexical knowledge. Because 3-syllable stimuli are more likely to be degraded in quality, there is more emphasis placed on long-term lexical and sub-lexical knowledge to support their representation in phonological working memory. That is, a decrease in the quality of a stored nonword leads to an increase in the likelihood that a nonword containing a lexical syllable will be erroneously selected as a nonword target.

## Nonword repetition

### Verification of data

The nonword responses were transcribed into the phonetic alphabet of the CMU Pronouncing Dictionary by the second author. The reliability of the transcriptions was assessed using a pseudo-random sample (to include at least one child from each school) of five children (16%). These samples were subsequently transcribed by (a) a researcher working on an unrelated project who has experience in transcribing nonword repetitions, and (b) a trained linguist. Phoneme-by-phoneme inter-rater reliability was 87% for the transcriptions produced by inter-rater (a) and 91% for the transcriptions produced by inter-rater (b).

### Repetition analyses

We defined a lexical error as any error that involved a syllable in a nonword being changed for a syllable that occurred in the CPWD – that is, we only considered as a lexical error those words that are likely to be in the child's vocabulary. To be as consistent as possible to the spoken nonword recognition results, the percentage of lexical errors were calculated by dividing the number of nonwords repeated with a lexical error by the total number of nonword repetitions in each condition (i.e., number of lexical errors / number of correct nonword repetitions + number of repetitions involving a lexical error + number of repetitions involving a non-lexical error). All analyses in this section use a 2 (nonword length: 2 or 3-syllables) x 3 (pause duration: short, medium, or long) repeated measures ANOVA.

Figure 3 shows the percentage of repetitions containing a lexical error for nonwords at each length and pause duration. There was no effect of nonword length ($F(1,30) = .27$, $p = .609$, $\eta_p^2 = .01$) but a significant effect of pause duration ($F(2,60) = 5.11$, $p = .009$, $\eta_p^2 = .15$), with post-hoc Bonferroni tests indicating that there were more lexical errors made at the longest pause duration compared to both the short duration ($p = .041$) and medium duration ($p = .040$). These results indicate an interaction between phonological working memory and long-term lexical and sub-lexical knowledge (e.g., via redintegration). As the representation of nonwords in phonological working memory decrease in quality, the involvement of long-term lexical and sub-lexical knowledge increases. For the current study, it is at the longest temporal duration that nonwords become sufficiently degraded in quality for long-term lexical and sub-lexical knowledge to be used as an aid to repetition. However, the same is not true when comparing short and long nonwords, where the proportion of lexical error does not differ. We will return to the issues surrounding the lexical error/nonword length data in the discussion.

FIGURE 3 ABOUT HERE

There was a significant interaction between nonword length and pause duration ($\underline{F}(2,60) = 4.18$, $\underline{p} = .020$, $\eta_p^2 = .12$), caused by the 3-syllable nonwords at a medium pause duration. Because the repetition accuracy at this length and duration is relatively high (see Table 1 later), there is a relatively low number of lexical errors.

We also examine repetition accuracy. A nonword was repeated accurately if all constituent phonemes were correctly articulated, and was regarded as inaccurate if one of more phonemes were incorrectly repeated. Table 1 shows the mean percentage of nonwords correctly repeated for each pause duration and length of nonword. There was a significant effect of nonword length ($\underline{F}(1,30) = 22.72$, $\underline{p} < .001$, $\eta_p^2 = .43$), such that 2-syllable nonwords were repeated more accurately than 3-syllable nonwords. There was also a significant effect of pause duration ($\underline{F}(2,60) = 6.48$, $\underline{p} = .003$, $\eta_p^2 = .18$), with post-hoc Bonferroni tests indicating greater accuracy for both the short and medium pause durations over the long pause duration ($\underline{p} = .036$ and $\underline{p} = .006$ respectively). However, there was also a significant interaction between nonword length and pause duration ($\underline{F}(2,60) = 10.53$, $\underline{p} < .001$, $\eta_p^2 = .26$), caused by the relatively high repetition accuracy for 3-syllable nonwords with a medium pause duration.

The accuracy results are similar to the spoken nonword recognition results in that accuracy is lower as nonword length increases. However, in spoken nonword recognition there was no effect of the position of the target foil whereas in repetition, a long delay until repeating a nonword causes a reduction in accuracy. One possible reason for the lack of a position effect in spoken nonword recognition may be rehearsal. Although the children themselves are unlikely to be rehearsing material (Gathercole & Adams, 1994), the spoken nonword recognition task provides some rehearsal of information since the two foils only differ from the target by one phoneme.

TABLE 1 ABOUT HERE

Spoken Nonword Recognition versus Repetition

One of the main purposes of the current study is to examine performance differences across spoken nonword recognition and NWR. First, we examine lexical errors across spoken word recognition and NWR; and second, we examine accuracy. To make the analyses more tractable, the data are collapsed by position/pause duration. We only consider effects involving the type of task, since task comparison is the main area of interest (for errors, all other effects will have been covered earlier).

Figure 4 shows the 2- and 3-syllable lexical error data for spoken nonword recognition and repetition. A 2 (task type: spoken nonword recognition or repetition) x 2 (nonword length: 2 or 3-syllables) mixed ANOVA is carried out on the data with task type being the between subjects variable. Importantly, there is a significant effect of task type ($\underline{F}(1,60) = 14.17$, $\underline{p} < .001$, $\eta_p^2 = .19$), showing that spoken nonword recognition involves fewer lexical errors than NWR. Previous research, together with the current study, shows that lexical errors are prevalent in NWR. However, previous research did not indicate whether the source of lexical errors in NWR is attributed to the encoding/storage process or the articulation process. We can now address this issue. The design of the current study aimed to minimise any differences in encoding/storage across spoken nonword recognition and NWR. Given that the encoding/storage of material should be similar across the two tasks, the additional lexical error seen in NWR must be produced by lexical and sub-lexical knowledge infiltrating the articulation process. The encoding/storage and the articulation of nonwords are both influenced by lexical and sub-lexical knowledge.

There is an interaction between task type and nonword length ($\underline{F}(1,60) = 5.19$, $\underline{p} = .026$, $\eta_p^2 = .08$). As Figure 4 and the individual analyses for each type of task show, for spoken nonword recognition there is an increase in lexical errors as nonword length increases from 2-syllables to 3-syllables; the same is not true for NWR, where lexical errors are stable across 2- and 3-syllables.

FIGURE 4 ABOUT HERE

Figure 4 shows the accuracy data for spoken nonword recognition and NWR. There was a clear effect of task type ($\underline{F}(1,60) = 63.23$, $\underline{p} < .001$, $\eta_p^2 = .51$) showing that spoken nonword recognition showed superior accuracy to NWR. There was no interaction between task type and nonword length ($\underline{F}(1,60) = .35$, $\underline{p} = .556$, $\eta_p^2 = .01$). Adding an articulatory component causes a significant decrease in accuracy, with accuracy almost halving when moving from spoken nonword recognition to NWR.

## Summary

Previous research has shown a long-term lexical and sub-lexical involvement in NWR performance (e.g., Munson, 2001; Munson, Kurtz, & Windsor, 2005). However, NWR involves various processes such as encoding/storage and articulation. To our knowledge, no previous study has examined which of the processes involved in NWR are affected by long-term lexical and sub-lexical knowledge. The current study targeted encoding/storage and articulation within the same nonword study and using the same set of stimuli. A spoken nonword recognition task was hypothesised to involve at least a significant encoding/storage component but no articulation component; and a NWR task was hypothesised to involve encoding/storage and articulation as significant processes. For spoken nonword recognition, there were significantly more lexical errors than non-lexical errors, indicating the influence of long-term lexical and sub-lexical knowledge in the encoding/storage of nonwords. In NWR, approximately 30% of repetitions involved a lexical error, indicating an involvement of lexical and sub-lexical knowledge in encoding/storage, articulation, or both. Importantly, there were a significantly higher number of lexical errors for NWR than for spoken nonword recognition. Since the principal difference between the two tasks is an additional process of articulation for NWR, encoding/storage and articulation must both be influenced by long-term lexical and sub-lexical knowledge.

At the end of the introduction we outlined three research questions that, to our knowledge, have not yet been addressed in nonword research. The current study has been able to address each of these questions. First, encoding/storage and articulation are both influenced by lexical and sub-lexical knowledge. In fact, our results show that almost twice as many lexical errors are produced in NWR over spoken nonword recognition, illustrating that the addition of an articulation component almost doubles the number of lexical errors.

Second, the influence of lexical and sub-lexical knowledge increases as the quality of a stored nonword decreases. As the burden of holding a nonword in phonological working memory increases, there is an increased reliance on long-term lexical and sub-lexical knowledge to bolster the representation of the nonword. For spoken nonword recognition, the selection of lexical foils increased as the length of the nonword increased; for repetition, there were more lexical errors as the delay until repeating a nonword increased. Note that these results occur even though the nonword stimuli were low in frequency, non-lexical, and non-morphological – thus showing that long-term lexical and sub-lexical knowledge is pervasive in tests involving nonwords.

Third, errors in NWR are caused by both encoding/storage and articulation. Not surprisingly, accuracy was greater when children were asked to recognise spoken nonwords than when they were asked to repeat them. In fact, children were approximately twice as accurate in recognising spoken nonwords as they were in repeating them. However, children still made errors in spoken nonword recognition – approximately half as many as for NWR. Up to half of the errors produced in NWR tasks may therefore be caused by problems in encoding/storing sound patterns rather than in articulating them. Although this assertion must be treated cautiously – the tasks presented here used a delay and also the spoken nonword recognition task is not a pure encoding/storage task given there was a selection process involved – the findings nevertheless suggest there is some utility in breaking down the NWR task into its components processes to establish where errors occur.

Our study also tests the redintegration account of NWR. Redintegration predicts that long-term lexical and sub-lexical knowledge is used at the point of retrieval to aid the representation of decayed nonwords in phonological working memory. As the pause duration until repeating a nonword increases, the number of repetitions involving a lexical error should increase due to greater decay. Similarly, long nonwords would be expected to decay more than short nonwords due to their length, and hence their repetitions should involve a greater number of lexical errors. The results fit with the first of these predictions. As pause duration increased, the number of lexical errors also increased – particularly for the longest pause duration. However, there was no difference between 2-syllable and 3-syllable nonwords in terms of the number of lexical errors. The spoken nonword recognition results also present problems for a redintegration account. Since redintegration occurs at the point of retrieval, there should be little influence of lexical and sub-lexical knowledge for a task that should require minimal retrieval. However, there was a clear effect of lexical and sub-lexical knowledge during the spoken recognition of nonwords. Redintegration or a similar process must occur earlier than at the point of retrieval. Other researchers have indicated that redintegration may be involved at earlier stages of the repetition process (see Hulme et al., 1997; Roodenrys, Hulme, Lethbridge, Hinton, & Nimmo, 2002; Thorn, Gathercole, & Frankish, 2005).

Finally, there is one interesting finding regarding lexical errors: length effects are seen for spoken nonword recognition but not for NWR. It would therefore appear that for nonword tasks that primarily involve encoding/storage, the extent of lexical error is determined by the level of decay of nonwords in phonological working memory. However, for tasks that involve an articulatory component, articulation processes over-ride any length effects caused at other stages. There is certainly a precedent for the latter view. Jones et al. (in press) examined nonword repetition in both typically developing children and children with specific language impairment, finding that both groups of children showed no influence of nonword length on lexical error production. In fact, the predictor of lexical errors during repetition was the lexical neighbourhood size of the nonwords involved. In the current study, the nonwords in each condition were matched for neighbourhood size, which is a possible reason that the number of lexical errors were equal for both 2-syllable and 3-syllable nonwords. In nonword repetition, therefore, the articulation process is the key determiner of lexical errors – a process that is primarily influenced by lexical neighbourhood.

The results presented here show that long-term lexical and sub-lexical knowledge is pervasive in both the spoken recognition and repetition of nonwords, even for those containing low frequency phoneme sequences. That is, encoding/storage and articulation processes are influenced by long-term lexical and sub-lexical knowledge irrespective of the frequency of the nonword biphones. Any theory of NWR performance must explain the interaction process between long-term lexical and sub-lexical knowledge and phonological working memory – for all types of nonword and throughout the whole repetition process, including encoding, storage, and articulation.

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Table 1. Mean percentage of nonwords repeated accurately for each pause duration and length of nonword (standard deviations in parentheses).

| | Nonword length | |
|---|---|---|
| Pause duration | 2-Syllable | 3-Syllable |
| Short | 48.92 (22.33) | 30.11 (21.70) |
| Medium | 40.00 (19.32) | 44.52 (24.06) |
| Long | 40.65 (18.96) | 20.65 (20.32) |

FIGURE CAPTIONS

Figure 1. Example of the presentation of stimuli for both spoken nonword recognition and nonword repetition. In the example, the target foil appears as the second of the three foils, and so the pause length for nonword repetition is adjusted to cater for this.

Figure 2. Percentage selection of target and foils at each position in spoken nonword recognition, for 2-syllable and 3-syllable stimuli. For labels on the x-axis, letters indicate the foil type (T=Target, L=Lexical foil, N=Non-lexical foil) and numbers indicate the position of the foil (1, 2, or 3). Error bars indicate standard error.

Figure 3. Percentage of lexical errors at each pause duration in nonword repetition, for 2-syllable and 3-syllable stimuli. Error bars indicate standard error.

Figure 4. Lexical errors and accuracy for spoken nonword recognition and repetition, for 2-syllable and 3-syllable stimuli. Error bars indicate standard error.

FIGURE 1

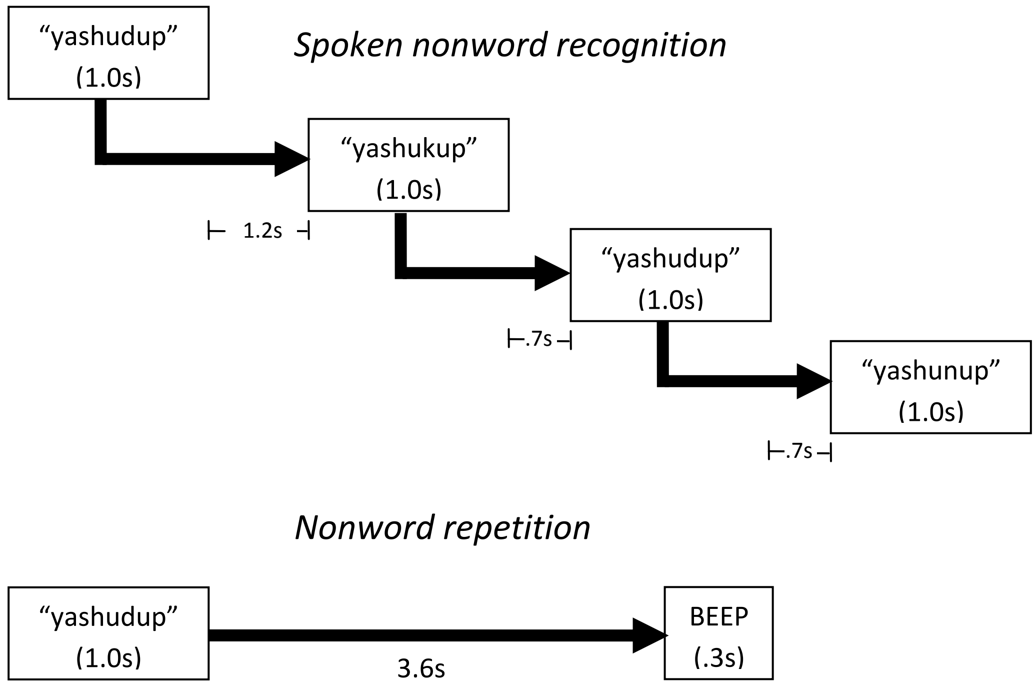

"yashudup"
(1.0s)
Spoken nonword recognition
"yashukup"
(1.0s)
1.2s
"yashudup"
(1.0s)
.7s
"yashunup"
(1.0s)
.7s
Nonword repetition
"yashudup"
(1.0s)
3.6s
BEEP
(.3s)

FIGURE 2

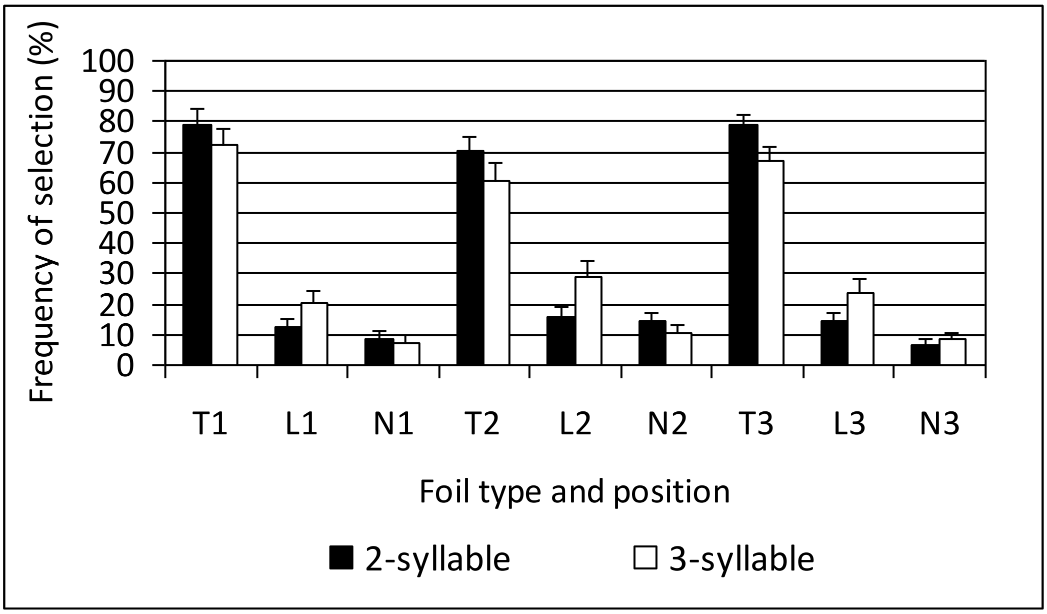

Frequency of selection (%)
100
90
80
70
60
50
40
30
20
10
0
T1
L1
N1
T2
L2
N2
T3
L3
N3
Foil type and position
2-syllable
3-syllable

FIGURE 3

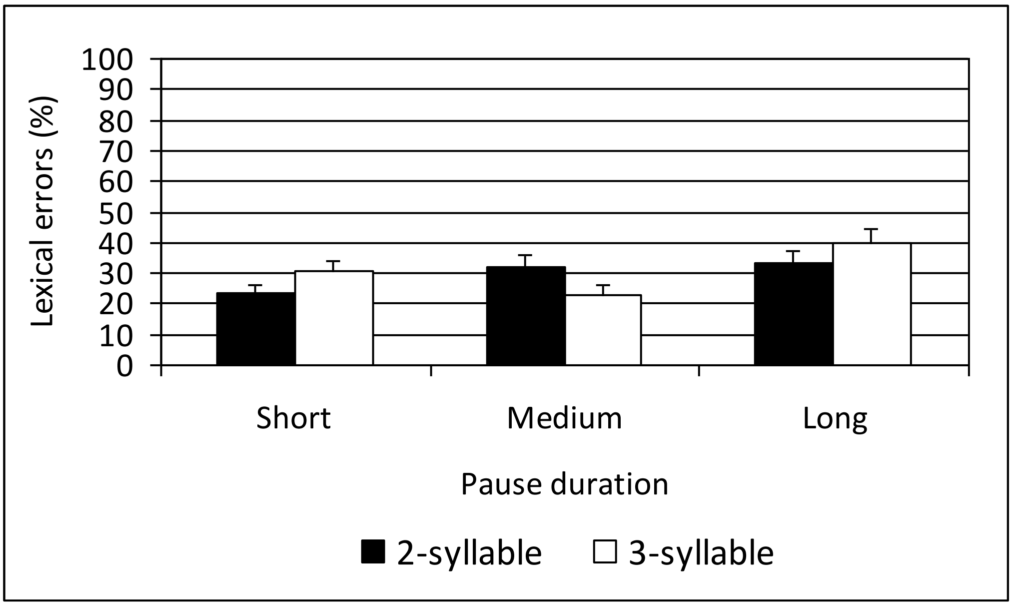
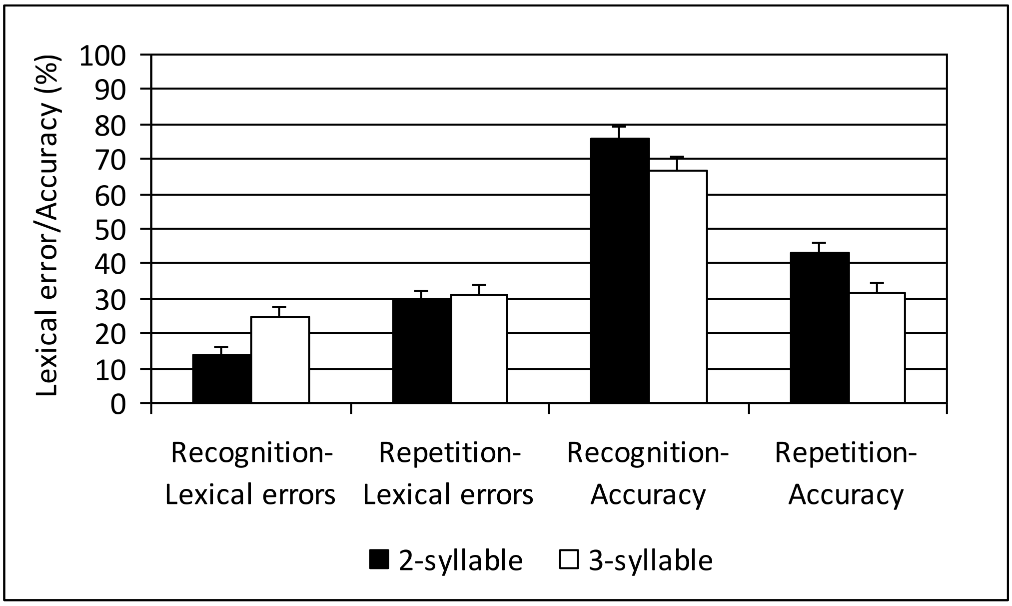

100
90
80
70
60
50
40
30
20
10
0
Lexical errors (%)
Short
Medium
Long
Pause duration
2-syllable
3-syllable

FIGURE 4


100
90
80
70
60
50
40
30
20
10
0
Lexical error/Accuracy (%)
Recognition-
Lexical errors
Repetition-
Lexical errors
Recognition-
Accuracy
Repetition-
Accuracy
2-syllable
3-syllable