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Differentiating phonotactic probability and neighborhood density in adult word learning

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Abstract

Purpose: The purpose of this study was to differentiate effects of phonotactic probability, the likelihood of occurrence of a sound sequence, and neighborhood density, the number of words that sound similar to a given word, on adult word learning. A second purpose was to determine what aspect of word learning, namely triggering learning, formation of an initial representation, or integration with existing representations, was influenced by each variable.

Method. Thirty-two adults were exposed to 16 nonwords paired with novel objects in a story context. The nonwords orthogonally varied in phonotactic probability and neighborhood density. Learning was measured following 1, 4, and 7 exposures in a picture-naming task. Partially correct (i.e., 2 of 3 phonemes correct) and completely correct responses (i.e., 3 of 3 phonemes correct) were analyzed together and independently to examine emerging and partial representations of new words versus complete and accurate representations of new words.

Results. Analysis of partially correct and completely correct responses combined showed that adults learned a lower proportion of high-probability nonwords than low-probability nonwords (i.e., high-probability disadvantage) and learned a higher proportion of high-density nonwords than low-density nonwords (i.e., high-density advantage). Separate analysis of partially correct responses yielded an effect of phonotactic probability only, whereas analysis of completely correct responses yielded an effect of neighborhood density only.

Conclusions. These findings suggest that phonological and lexical processing influence different aspects of word learning. In particular, phonotactic probability may aid in triggering new learning, whereas neighborhood density may influence the integration of new lexical representations with existing representations.

Key words: word learning, vocabulary, phonotactic probability, neighborhood density

Differentiating phonotactic probability and neighborhood density in adult word learning

Recent models of spoken language processing incorporate two types of form representations: phonological and lexical (e.g., Dell, 1988; Gupta & MacWhinney, 1997; Levelt, 1989; Luce, Goldinger, Auer, & Vitevitch, 2000; Magnuson, Tanenhaus, Aslin, & Dahan, 2003; McClelland & Elman, 1986; Norris, 1994). *Phonological* representations correspond to knowledge of individual sounds with variation across models in the specific sound property chosen (e.g., phonetic features; context specific allophones; phonemes). In contrast, *lexical representations* refer to knowledge of whole words. Most models also incorporate representation of referents or meanings of words, namely *semantic representations*.

When a known word is encountered, it presumably activates these existing representations so that the word can be accurately recognized or produced. In contrast, when a novel word is encountered, it will activate matching phonological representations (assuming that the component sounds are known); however, it will not exactly match any existing lexical or semantic representation. This mismatch between the environment and stored representations in memory likely triggers the formation of a new lexical representation and a new semantic representation (e.g., Carpenter & Grossberg, 1987; Gupta & MacWhinney, 1997). That is, recognition that a novel word is unknown initiates the learning process. At that point, existing phonological representations may potentially aid in maintaining the sound sequence in working memory while a new lexical and semantic representation are created. Moreover, these newly created lexical and semantic representations must form links with related existing lexical and semantic representations, thereby integrating the new representation with old representations in memory. These new representations and links are strengthened over repeated exposures to the novel word (e.g., Gupta & MacWhinney, 1997). When the new representations and links

stabilize, the word is considered mastered, although there may be evidence of gradient knowledge about the new word prior to ultimate mastery (e.g., Capone & McGregor, in press).

This hypothesized scenario is supported by data. Gaskell and Dumay (2003) attempted to differentiate the creation of an initial lexical representation from integration with existing lexical representations in adult word learning. They exposed adults to multisyllabic nonwords derived from real words (e.g., *cathedruke* derived from *cathedral*) in a phoneme monitoring task, where the adults listened to the nonwords and pressed a button if the nonword contained the specified target phoneme. Adults also were instructed that they should try to remember the nonwords. Formation of an initial lexical representation was tested in a recognition task. In the recognition task, participants heard a pair of nonwords (e.g., *cathedruke* and *cathedruce*) and had to decide which nonword they had heard previously (e.g., *cathedruke*). Integration of the new lexical representation with existing lexical representations was tested in a lexical decision task that was administered pre- and post-exposure. In the lexical decision task, the original real words (e.g., *cathedral*) were presented, and participants had to judge whether these words were real words or nonwords. Of interest was the change in reaction time from the pre-exposure test to the post-exposure test. If participants integrated the new lexical representation with existing lexical representations, there should be competition between the new word and the existing word, leading to slower lexical decision times in the post-test as compared to the pre-test. The recognition task results showed that adults accurately recognized the nonwords, indicating that they had created a new lexical representation following relatively minimal exposure (i.e., 12 presentations of the nonword). Moreover, recognition remained accurate following a delay, suggesting that these new lexical representations were retained over time (i.e., after 24 hours and 1 week). However, changes in the post-exposure lexical decision task were not immediately observed. Evidence of competition in the post-exposure lexical decision task only emerged 3-7

days after initial exposure (both with and without additional exposure). Thus, integration of the new representation with existing representations required additional time. In summary, the learning of an initial representation appeared to occur rapidly, but the integration of the new representation with existing representations appeared to be protracted.

Taken together, word learning appears to be comprised of three distinct processes. The first process involves the recognition that a novel word was heard and the resultant triggering of learning. This process has received less attention in previous research, but it is likely critical in naturalistic word learning where presentation of a novel word may not be highlighted in any way (e.g., "Here's a word you probably don't know"). Thus, the learner must detect the mismatch between the novel word and existing lexical representations to initiate learning. The second process involves the creation of a representation of the novel word. These first two processes appear to occur relatively rapidly. The third process involves the integration of the new representation with existing representations, which presumably is more protracted. We propose to build on the results of Gaskell and Dumay (2003) by investigating the influence of existing phonological and lexical representations on these different word learning processes, as indexed by partial versus complete responses.

It has been proposed that insights about processing within each representation can be inferred by observing the behavioral effects of two distinct, but related, form characteristics: phonotactic probability and neighborhood density (Vitevitch & Luce, 1999). *Phonotactic probability* refers to the frequency of occurrence of individual sounds and sound combinations. It is thought that behavioral effects of phonotactic probability provide insights about the role of phonological representations in language processing (Vitevitch & Luce, 1999). *Neighborhood density* refers to the number of words that sound similar to a given word. Behavioral effects of

neighborhood density are presumed to reveal the influence of lexical representations on language processing (Vitevitch & Luce, 1999). Findings from past studies are summarized in Table 1.

Although there are no published studies documenting the effects of phonotactic probability and neighborhood density on word learning by adults, there are numerous studies documenting the effect of each of these variables on recognition, production, and memory (see Table 1). In terms of phonotactic probability, adults recognize and name high-probability sound sequences more rapidly and accurately than low-probability sound sequences (e.g., Frisch, Large, & Pisoni, 2000; Luce & Large, 2001; Vitevitch, Armbruster, & Chu, 2004; Vitevitch & Luce, 1998, 1999). In addition, adults recall high-probability nonwords more accurately than low-probability nonwords (Thorn & Frankish, 2005, but see Roodenrys & Hinton, 2002, who failed to find an effect of phonotactic probability). Taken together, phonological processing appears to entail a high-probability advantage in recognition, production, and memory by adults.

Turning to neighborhood density, adults recognize high-density words more slowly and less accurately than low-density words (e.g., Luce & Large, 2001; Luce & Pisoni, 1998; Vitevitch, 2002b; Vitevitch & Luce, 1998, 1999). In contrast, adults produce high-density words more rapidly and accurately than low-density words (Vitevitch, 1997, 2002a), and recall high-density nonwords more accurately than low-density nonwords in serial recall tasks (Roodenrys & Hinton, 2002). Thus, lexical processing appears to lead to a high-density disadvantage in recognition but a high-density advantage in production and memory.

Although no published study has examined the effect of phonotactic probability and neighborhood density on word learning by adults, there are several studies of the effect of phonotactic probability and neighborhood density on child word learning. These child studies are relevant to adult word learning because children show similar effects of phonotactic probability and neighborhood density on spoken language processing (see Table 1). In terms of phonotactic

probability, children repeat high-probability nonwords more accurately than low-probability nonwords (e.g., Beckman & Edwards, 2000; Edwards, Beckman, & Munson, 2004; Gathercole, Frankish, Pickering, & Peaker, 1999; Munson, 2001; Munson, Edwards, & Beckman, 2005; Munson, Kurtz, & Windsor, 2005; Munson, Swenson, & Manthei, 2005). Thus, the available evidence suggests that phonological processing in children entails a high-probability advantage similar to adults. Turning to neighborhood density, children recognize and repeat high-density real words more slowly and less accurately than low-density real words (e.g., Garlock, Walley, & Metsala, 2001; Metsala, 1997; Munson, Swenson et al., 2005). In addition, children name high-density real words more accurately than low-density real words (German & Newman, 2004; but see Newman & German, 2002; Newman & German, 2005). This suggests that lexical processing in children entails a high-density disadvantage in recognition and a high-density advantage in production. This pattern of child findings is similar to that of adults.

The parallels between the adult and child recognition, production, and memory findings suggest that similarities also may be found between adult and child word learning. Word learning by typically developing preschool children appears to be influenced by phonotactic probability and/or neighborhood density (Storkel, 2001, 2003, 2004a; Storkel & Maekawa, 2005; Storkel & Rogers, 2000). In a series of studies, children were exposed to nonwords that were high probability/high density (e.g., /pin/) and those that were low probability/low density (e.g., /mɔɪd/) in a story context. Learning of the nonwords was examined in a receptive picture-pointing task and/or a picture-naming task. Results showed that children learned high-probability/high-density nonwords more rapidly than low-probability/low-density nonwords across a variety of word types (i.e., nouns, verbs, and homonyms, Storkel, 2001; Storkel, 2003, 2004a; Storkel & Maekawa, 2005; Storkel & Rogers, 2000).

These child results establish a high phonotactic probability/high neighborhood density advantage in word learning by typically developing children; however, it is unclear whether this advantage is attributable to phonological or lexical processing because the stimuli were correlated in phonotactic probability and neighborhood density. Although this correlation is consistent with the structure of English (Storkel, 2004b; Vitevitch, Luce, Pisoni, & Auer, 1999), it makes it difficult to assess the independent and interactive influence of phonological and lexical processing on word learning. In addition, no information is available to suggest what aspects of the word learning process, namely triggering learning, formation of an initial representation, or integration with existing representations, are affected by phonological or lexical representations.

The goal of the present study was to disentangle the influence of phonological and lexical representations on adult word learning by examining learning of nonwords orthogonally varying in phonotactic probability and neighborhood density. The effect of these two variables on overall word learning will aid in determining whether phonological representations, lexical representations, neither, or both influence word learning by adults. A further question addressed by the current study is which word learning processes (i.e., triggering learning, formation of an initial representation, integration with existing representations) are affected by phonological or lexical representations. This issue was explored by examining the effect of phonotactic probability and neighborhood density on partially correct versus completely correct responses. We assume that a partially correct response will index an early stage of word learning, providing information about the factors that affect triggering of learning and creation of an initial representation. In contrast, completely correct responses will index a later stage of word learning, providing information about the factors that affect integration of the new representation

with existing representations. Thus, analysis of these two types of responses will allow exploration of the specific variables that affect learning at each stage.

Method

Participants

Thirty two native English-speaking adults (M age = 20 years, SD = 3 years, range 18-36 years) from the University of Kansas student community participated. All subjects reported no history of speech, hearing, or learning disorder and received partial course credit in exchange for participation.

Materials

Phonotactic probability. The nonwords to be learned differed on two independent variables, phonotactic probability and neighborhood density. Phonotactic probability was computed using a 20,000 word electronic dictionary (*Webster's Seventh Collegiate Dictionary*, 1967) containing phonemic transcriptions of American English. Two measures of phonotactic probability were computed: positional segment frequency and biphone frequency. *Positional segment frequency* is the frequency that a given sound occurs in a given word position, where position is defined from the left edge of the word (i.e., first sound, second sound, etc.). To compute this, the sum of the log frequencies of all the words in the dictionary containing a particular sound in a particular position of a word was divided by the sum of the log frequencies of all the words in the dictionary containing any sound in the same word position (Storkel, 2004b). *Biphone frequency* is the likelihood that two adjacent sounds co-occur in a given word position (i.e., first + second sounds, second + third sounds, etc.). This is calculated by taking the sum of the log frequencies of all the words containing a particular biphone in a particular word position and dividing this sum by the sum of the log frequencies of all the words containing any phoneme in the same word position (Storkel, 2004b).

Positional segment frequency and biphone frequency were computed for all legal consonant-vowel-consonant (CVC) patterns in American English. Each CVC was then categorized as high or low using a median split. Values above the median were classified as high, and values at or below the median were classified as low. When the classification by positional segment frequency disagreed with that of biphone frequency, the CVC was eliminated from the potential stimulus pool.

Neighborhood density. Neighborhood density was computed by counting the number of words in the dictionary that differed from the target by a one phoneme addition, deletion, or substitution. As with phonotactic probability, density was computed for all legal CVCs, and each CVC was categorized as high or low based on a median split.

Sixteen nonwords were chosen with four nonwords in each of the following conditions: (a) high probability/high density, (b) high probability/low density, (c) low probability/high density, and (d) low probability/low density. Means and standard deviations for positional segment frequency, biphone frequency, and neighborhood density for each condition are shown in Table 2. The specific nonwords selected are shown in Table 3.

Novel objects. The selected nonwords were paired with pictures of novel objects that adults were not able to name with one word. These novel objects were previously used in studies of preschool children (Storkel, 2004a). Semantic category was matched across the four phonotactic probability/neighborhood density conditions. The pairing of nonwords with objects was counterbalanced across participants. Table 3 provides a description of the novel objects.

Story exposure. The 16 nonword-object pairs were divided into two sets of 8 with phonotactic probability/neighborhood density condition and semantic category balanced across sets. Each set of nonword-object pairs was embedded in one of two stories, with the order of

presentation of the two stories being counterbalanced across participants. Each story consisted of three distinct episodes.

Each episode in the two stories contained a set of six visual scenes and a corresponding auditory narrative. The scenes and narrative frame were used in previous studies of child word learning (Storkel, 2004a). The appendix provides an example of the visual scenes and narrative for story episode 1. The first visual scene and narrative provided an introduction to the two main characters and a central activity (e.g., selecting objects to take to another location). The four intermediate visual scenes and corresponding narrative provided exposure to the nonword-object pairs, with semantically related objects being presented simultaneously. In these four visual scenes, the two main characters were presented interacting with the novel objects. The accompanying auditory narrative presented the corresponding nonword embedded in a sentence. The sixth and final scene and narrative provided the conclusion of the activity. Across episodes, the main characters remained the same but the central activity (e.g., selecting objects vs. hiding objects) changed. In addition, the number of exposures to the nonword-object pairs varied across episodes: episode 1 provided one exposure to each nonword-object pair, whereas episodes 2 and 3 provided three exposures to each pair. Thus, the cumulative number of exposures following each episode was 1 (episode 1), 4 (episode 2), and 7 (episode 3).

Visual scenes were digitized and edited. The auditory narrative was recorded in a sound proof booth, digitized, and edited. The speaking rate, measured in syllables per second, was similar across the phonotactic probability/neighborhood density conditions, all $F(1, 56) < 1.0$, $p > .70$. In addition, under the same listening conditions as the subjects, two naive listeners transcribed the nonwords as intended, demonstrating appropriate quality of the audio recordings.

Measure of learning. A picture-naming task was used to assess learning of the nonword-object pairs. In this task, a picture of one of the novel objects appeared on the computer screen

and the participant attempted to produce the corresponding nonword. This task was given four times per story: before the story to obtain a baseline and following each of the three episodes. The responses were phonetically transcribed and scored. A response was scored as partially correct if two of the three phonemes were produced in the correct word position. A partially correct response was thought to result from an emerging or partial representation of the new word. A response was scored as completely correct if all three phonemes were produced correctly in the correct order. A completely correct response was thought to reflect a complete and accurate representation of the new word. These two types of responses were combined in one analysis to afford comparison to past child word learning studies (Storkel, 2001, 2003, 2004a; Storkel & Maekawa, 2005; Storkel & Rogers, 2000). In addition, each type of response was analyzed independently to examine the effect of phonotactic probability and neighborhood density on partial (i.e., early-stage word learning) versus complete representations (i.e., late-stage word learning).

Consonant-to-consonant transcription reliability and scoring reliability were computed for 22% of the participants. Inter-judge transcription reliability was 99% ($SD = 1\%$, range 96% to 100%). Inter-judge scoring reliability was 99% ($SD = 1\%$, range 97% to 100%).

Procedure

Each participant was seated in front of a computer that presented auditory stimuli over headphones (i.e., Sennheiser HMD280-13). Participant responses were recorded using a head-mounted microphone (i.e., Sennheiser HMD280-13) and a digital tape recorder (i.e., Tascam DA40). Presentation of the auditory and visual stimuli was controlled by the computer using DirectRT software (Jarvis, 2002).

The study required one 45-minute session. The session started with the baseline naming task for the first story. The eight objects for the first story were randomly presented on the

computer screen, and participants were instructed to guess the name of each object. Responses were audio recorded. Next, the first episode of the first story was presented. The introductory and concluding scene for each story episode were always presented first and last, respectively. The intermediate four scenes that provided exposure to the nonword-object pairs were presented in random order as determined by the DirectRT software. Although the presentation order was random, the coherence of the story was preserved because each scene related to an overall routine (e.g., selecting objects to take to another location), and each scene made no reference to the other scenes. Refer to the appendix for details of the first story episode. Then, the picture-naming task was re-administered with instructions for the participant to attempt to remember the names of the objects introduced in the story. The second and third episodes of the first story and corresponding naming tasks followed in the same manner. A break occurred after the first story, and then the second story was completed following the same procedure.

Results

Partially correct and completely correct responses

The first analysis examined the effect of phonotactic probability and neighborhood density on both partially correct (i.e., 2 of 3 phonemes) and completely correct (i.e., 3 of 3 phonemes) responses combined for comparison to previous studies. The dependent variable was the proportion correct (i.e., 2-3 of 3 phonemes) in the naming task for each phonotactic probability/neighborhood density condition (i.e., high probability/high density, high probability/low density, low probability/high density, and low probability/low density) at each exposure (i.e., 1, 4, and 7). These data were submitted to a 2 (phonotactic probability) x 2 (neighborhood density) x 3 (cumulative exposure) repeated measures ANOVA.

The main effects of phonotactic probability and neighborhood density were significant, $F(1, 31) = 6.07, p < .05, \eta_p^2 = .164$ for phonotactic probability and $F(1, 31) = 11.71, p < .01, \eta_p^2 =$

.274 for neighborhood density. The effect of exposure also was significant, $F(2, 62) = 131.80$, $p < .001$, $\eta_p^2 = .810$. There were no significant interactions of phonotactic probability and neighborhood density $F(1, 31) = 0.18$, $p > 0.65$, $\eta_p^2 = 0.006$, phonotactic probability and exposure $F(2, 62) = 1.98$, $p > 0.10$, $\eta_p^2 = 0.060$, neighborhood density and exposure $F(2, 62) = 0.28$, $p > 0.70$, $\eta_p^2 = 0.009$, or neighborhood density and phonotactic probability and exposure $F(2, 62) = 1.61$, $p > 0.20$, $\eta_p^2 = 0.049$.

Considering phonotactic probability first, adults learned a lower proportion of high-probability nonwords ($M = 0.42$, $SD = 0.36$, $SEM = 0.06$) than low-probability nonwords ($M = 0.47$, $SD = 0.35$, $SEM = 0.06$). Figure 1 shows the naming responses to high- and low-probability nonwords at each exposure for high-density (top panel) and low-density (bottom panel) nonwords. As can be seen from this figure and the lack of any significant interactions, this high-probability disadvantage was relatively consistent across exposures and neighborhood density, although the size of the disadvantage did show some variability. This high-probability disadvantage was counter to past findings from child word learning studies (Storkel, 2001, 2003, 2004a; Storkel & Maekawa, 2005; Storkel & Rogers, 2000).

Turning now to neighborhood density, adults learned a higher proportion of high-density nonwords ($M = 0.48$, $SD = 0.35$, $SEM = 0.06$) than low-density nonwords ($M = 0.41$, $SD = 0.35$, $SEM = 0.06$). Figure 2 shows the naming responses to high- and low-density nonwords at each exposure for high-probability (top panel) and low-probability (bottom panel) nonwords. As with phonotactic probability, the high-density advantage was relatively consistent across exposures and phonotactic probability. This high-density advantage was consistent with past word learning studies (Storkel, 2001, 2003, 2004a; Storkel & Maekawa, 2005; Storkel & Rogers, 2000).

Finally, accuracy increased with the number of exposures as is typical in learning tasks. Specifically, lowest accuracy was observed following 1 exposure ($M = 0.18$, $SD = 0.21$, $SEM =$

0.04), intermediate accuracy following 4 exposures ($M = 0.49$, $SD = 0.32$, $SEM = 0.06$), and highest accuracy following 7 exposures ($M = 0.68$, $SD = 0.32$, $SEM = 0.06$). Planned comparisons showed that accuracy at each increasing exposure level was significantly higher than the previous level, all F s (1, 31) > 74, all p s < 0.001, all $\eta_p^2 > 0.70$.

Partially correct responses

The second analysis examined the effect of phonotactic probability and neighborhood density on partially correct responses to determine whether each variable had a similar effect on early word learning. The dependent variable was the proportion of partially correct responses (i.e., 2 of 3 phonemes) in the naming task for each phonotactic probability/neighborhood density condition (i.e., high probability/high density, high probability/low density, low probability/high density, and low probability/low density) at each exposure (i.e., 1, 4, and 7). These data were submitted to a 2 (phonotactic probability) x 2 (neighborhood density) x 3 (cumulative exposure) repeated measures ANOVA.

The main effect of phonotactic probability was significant, $F(1, 31) = 6.37$, $p < .05$, $\eta_p^2 = .170$. The main effect of neighborhood density was not significant, $F(1, 31) = 1.14$, $p > 0.25$, $\eta_p^2 = 0.036$. The main effect of exposure was significant, $F(2, 62) = 13.23$, $p < .001$, $\eta_p^2 = .299$.

There were no significant interactions of phonotactic probability and neighborhood density $F(1, 31) = 2.21$, $p > 0.10$, $\eta_p^2 = 0.067$, phonotactic probability and exposure $F(2, 62) = 1.09$, $p > 0.30$, $\eta_p^2 = 0.034$, neighborhood density and exposure $F(2, 62) = 1.50$, $p > 0.20$, $\eta_p^2 = 0.046$, or neighborhood density and phonotactic probability and exposure $F(2, 62) = 1.08$, $p > 0.30$, $\eta_p^2 = 0.034$.

In terms of phonotactic probability, adults formed fewer partial representations for high-probability nonwords ($M = 0.10$, $SD = 0.15$, $SEM = 0.03$) than low-probability nonwords ($M = 0.14$, $SD = 0.18$, $SEM = 0.03$). Figure 3 shows the partially correct responses to high- and low-

probability nonwords at each exposure for high-density (top panel) and low-density (bottom panel) nonwords. In this figure, there is a clear high-probability disadvantage for high-density nonwords. Despite the lack of a significant interaction, the effect of phonotactic probability for low-density nonwords is reduced relative to the effect for high-density nonwords. The significant main effect of phonotactic probability on partially correct responses suggests that phonotactic probability may play a role in the earliest stages of word learning.

In terms of neighborhood density, adults formed partial representations relatively equivalently for high-density ($M = 0.13$, $SD = 0.18$, $SEM = 0.03$) and low-density nonwords ($M = 0.11$, $SD = 0.15$, $SEM = 0.03$). Figure 4 shows the partially correct responses to high- and low-density nonwords at each exposure for high-probability (top panel) and low-probability (bottom panel) nonwords. The effect of neighborhood density did not show a clear pattern, suggesting that neighborhood density may be less critical in the earliest stages of word learning.

Finally, partially correct responses increased from 1 exposure ($M = 0.06$, $SD = 0.13$, $SEM = 0.02$) to 4 exposures ($M = 0.16$, $SD = 0.18$, $SEM = 0.03$) and then leveled off at 7 exposures ($M = 0.13$, $SD = 0.18$, $SEM = 0.03$). Planned comparisons showed that the difference between 1 and 4 exposures was significant, $F(1, 31) = 30.83$, $p < 0.001$, $\eta_p^2 = 0.499$; whereas the difference between 4 and 7 exposures was not significant, $F(1, 31) = 1.28$, $p > 0.25$, $\eta_p^2 = 0.040$.

Completely correct responses

The final analysis examined the effect of phonotactic probability and neighborhood density on completely correct responses to determine whether each variable had a similar effect on late word learning. The dependent variable was the proportion of completely correct responses (i.e., 3 of 3 phonemes) in the naming task for each phonotactic probability/neighborhood density condition (i.e., high probability/high density, high probability/low density, low probability/high density, and low probability/low density) at each

exposure (i.e., 1, 4, and 7). These data were submitted to a 2 (phonotactic probability) x 2 (neighborhood density) x 3 (cumulative exposure) repeated measures ANOVA.

The main effect of phonotactic probability was not significant, $F(1, 31) = 0.64, p > .40, \eta_p^2 = .020$. In contrast, the main effect of neighborhood density was significant, $F(1, 31) = 6.23, p < 0.05, \eta_p^2 = 0.167$, as was the main effect of exposure, $F(2, 62) = 88.88, p < .001, \eta_p^2 = .741$. One of the interactions approached significance, namely the interaction of phonotactic probability and neighborhood density $F(1, 31) = 3.35, p = 0.08, \eta_p^2 = 0.098$. In contrast, there were no significant interactions of phonotactic probability and exposure $F(2, 62) = 0.28, p > 0.75, \eta_p^2 = 0.009$, neighborhood density and exposure $F(2, 62) = 1.79, p > 0.15, \eta_p^2 = 0.055$, or neighborhood density and phonotactic probability and exposure $F(2, 62) = 0.26, p > 0.75, \eta_p^2 = 0.008$.

In terms of phonotactic probability, adults formed an equivalent number of complete representations for high-probability ($M = 0.32, SD = 0.31, SEM = 0.05$) and low-probability nonwords ($M = 0.34, SD = 0.33, SEM = 0.06$). Figure 5 shows the completely correct responses to high- and low-probability nonwords at each exposure for high-density (top panel) and low-density (bottom panel) nonwords. In this figure, there is no apparent effect of phonotactic probability for high-density or low-density nonwords. The lack of a significant main effect of phonotactic probability suggests that phonological representations may play a lesser role, if any, in later stages of word learning.

In terms of neighborhood density, adults formed more complete representations for high-density nonwords ($M = 0.36, SD = 0.33, SEM = 0.06$) than low-density nonwords ($M = 0.30, SD = 0.31, SEM = 0.05$). Figure 6 shows the completely correct responses to high- and low-density nonwords at each exposure for high-probability (top panel) and low-probability (bottom panel) nonwords. There is a high-density advantage for high-probability nonwords, $F(1, 31) = 8.94, p <$

0.01, $\eta_p^2 = 0.224$. In contrast, there is no apparent effect of neighborhood density for low-probability nonwords, $F(1, 31) = 0.42$, $p > 0.50$, $\eta_p^2 = 0.013$. Thus, the near significant interaction of phonotactic probability and neighborhood density may be attributable to this asymmetry in the high-density advantage across high-probability versus low-probability nonwords, although this effect warrants replication. The significant main effect of neighborhood density suggests that this variable may play a critical role in later stages of word learning.

Finally, completely correct responses increased from 1 exposure ($M = 0.12$, $SD = 0.17$, $SEM = 0.03$) to 4 exposures ($M = 0.32$, $SD = 0.27$, $SEM = 0.05$) and from 4 exposures to 7 exposures ($M = 0.54$, $SD = 0.34$, $SEM = 0.06$). Planned comparisons showed that accuracy at each increasing exposure level was significantly higher than the previous level, all $F_s(1, 31) > 54$, all $p_s < 0.001$, all $\eta_p^2 > 0.60$.

Discussion

The goals of this study were to examine the role of phonological and lexical representations in adult word learning and to attempt to determine which aspects of word learning are influenced by each type of representation. The results for the combined analysis of partially correct and completely correct responses showed a high phonotactic probability disadvantage and a high neighborhood density advantage, indicating that both phonological and lexical representations influence word learning in a unique way. Moreover, each representation appeared to influence a different aspect of word learning as revealed through the separate analysis of partially correct and completely correct responses. Specifically, only phonotactic probability influenced partially correct responses. In contrast, only neighborhood density influenced completely correct responses. This pattern suggests that phonological representations may play a role in processes associated with early word learning, whereas lexical representations may play a role in processes associated with later word learning.

Locus of the phonotactic probability effect

As shown in Table 4, past studies of adults and children generally have shown a high-probability advantage in recognition, production, and serial recall. Thus, our finding of a high-probability disadvantage in word learning is particularly striking because, to our knowledge, this is the first report of a high-probability disadvantage in normal language processing. Given this difference between past studies of recognition, production, and serial recall and this study, the high-probability disadvantage in word learning is not likely attributable to recognition, production, or working memory influences on word learning, although this was not directly tested. Instead, this high-probability disadvantage may be specific to word learning, and therefore it is likely attributable to a process that primarily occurs when learning new words.

One process that is unique to word learning is the triggering of the formation of a new representation in long-term memory. That is, when listening to speech, presentation of a novel word may not be highlighted in any way (e.g., "Here's a word you probably don't know"). Thus, the listener must have some way of determining which words are known, thereby accessing existing stored representations, and which words are new, thereby initiating learning through the creation of new representations. If such a process did not exist, then listeners would be forced to process all incoming words as either known or new. In fact, several types of computational models include some type of process to trigger new learning to allow for differential processing of known versus new words. For example, adaptive resonance theory (ART) relies on a mismatch between input from the environment and stored representations in long-term memory to identify novel events and to trigger the creation of a new representation in long-term memory for that event (e.g., Carpenter & Grossberg, 1987).

We hypothesize that phonotactic probability may influence triggering of word learning. In particular, high-probability novel words will be more "wordlike" than low-probability novel

words (e.g., Frisch et al., 2000; Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997). In this way, high-probability novel words may be deceptively similar to many other known sound sequences in the language, whereas low-probability novel words will stand apart from other sound sequences as unique. Based on this deceptive wordlikeness, learning may not be triggered upon first exposure to a high-probability sound pattern but may be immediately triggered upon first exposure to a low-probability sound pattern. Thus, learning a high-probability sound sequence may require more exposures than learning a low-probability sound sequence because there is a lag between first exposure and the creation of a new representation. Consistent with this hypothesis, Gaskell and Dumay (2003) provide evidence that novel words can activate the representation of phonologically similar real words, rather than triggering the formation of a new representation. The current results extend these findings by suggesting an asymmetry between high- and low-probability novel words, with high-probability novel words being more likely to activate real words and low-probability novel words being more likely to trigger new learning.

Locus of the neighborhood density effect

As previously described (see Table 4), neighborhood density appears to lead to a high-density disadvantage in recognition but a high-density advantage in production and serial recall (Roodenrys & Hinton, 2002; Vitevitch, 2002a). Thus, the high-density advantage observed in adult word learning is consistent with the findings from production and serial recall. Therefore, it is possible that the observed high-density advantage in word learning is attributable to production or working memory processes rather than a process specific to word learning. For example, neighborhood density may have influenced production of the nonwords at test, rather than the word learning process itself. This seems unlikely because past word learning studies show similar effects of correlated phonotactic probability and neighborhood density on receptive and expressive measures of learning (Storkel, 2001; Storkel & Maekawa, 2005). In addition, the

high-density advantage was observed primarily for completely correct responses rather than for partially correct responses. If the effect were attributable to production, then the effect should have been observed for both types of responses.

Alternatively, neighborhood density may influence the ability to hold a novel sound sequence in working memory by determining the number of words from long-term memory that are activated during learning (Roodenrys & Hinton, 2002). That is, high-density nonwords will activate more neighbors in long term memory than low-density nonwords, strengthening the memory trace of high-density nonwords in working memory. A stronger memory trace in working memory may facilitate the creation of an accurate and detailed representation for high-density over low-density novel words. In this way, neighborhood density may influence the initial creation of a lexical representation of a novel word. However, if this were the case, we would expect to observe an effect of neighborhood density on early word learning rather than on later word learning. This prediction is counter to the observed results.

A final possibility is that the effect of neighborhood density on word learning may be specific to the integration that occurs during later word learning. Once a new lexical representation has been created, neighborhood density may influence the integration of the new representation with existing representations, and this may have consequences for stabilizing the new representation. Specifically, during integration with existing representations, the lexical representation of a high-density novel word will form connections with many other existing lexical representations. Upon subsequent encounters with the novel word, the new lexical representation will be activated, and this in turn will activate other lexical representations. These lexical representations will activate phonological representations, which in turn will spread activation back to the corresponding lexical representations. This interactive process will strengthen the connections between the new lexical representation and phonological

representations increasing the likelihood that the representation and links will stabilize with fewer exposures. This same process will occur for a low-density novel word but the amount of activation will be reduced because fewer lexical representations will be activated. As a result, more exposures to the novel word will be required for the new representation to stabilize.

The above hypotheses are somewhat speculative for several reasons. First, a non-production task was not used as a measure of word learning. Thus, it is difficult to differentiate language production effects at test from word learning effects. Second, working memory was not directly examined to afford comparison to the word learning data. A study of this type would allow direct testing of the hypothesis that the influence of neighborhood density on word learning is mediated by working memory. Third, the formation of connections between new representations and existing representations was not explicitly tested, as was done in Gaskell and Dumay (2003). Examination of connections would provide a direct test of the hypothesis that the formation of these connections facilitates word learning. In addition, it would allow for an even stronger test of the hypothesis that neighborhood density influences later stages of word learning. Specifically, it is possible that neighborhood density influences earlier stages of word learning but that this was not detected in the current study because only target appropriate connections between representations were considered. That is, neighborhood density calculations were based on the target, even when partially correct responses were examined. It is possible that new partial representations do form connections to existing representations immediately and that this provides a benefit to word learning. However, the connections formed would likely be based on both the correct as well as the inaccurate or underspecified information in the partial representation, leading to both target-appropriate as well as target-inappropriate connections. An attempt to examine the specific connections being formed would provide evidence to support or refute this hypothesis. Finally, like Gaskell and Dumay (2003), we indexed early versus late

word learning via a performance measure (i.e., partially correct vs. completely correct responses), albeit a different performance measure (i.e., type of response vs. different tasks). A performance measure was selected over a time based measure (e.g., number of exposures) because of the between participant variability at each exposure. Given this variability, it was assumed that examining word learning at a given exposure would not guarantee that each individual subject was in the same stage of word learning. Additional research is needed to identify the measure that best indexes early versus later word learning. In undertaking this research, it will be important to consider a variety of both time and performance measures.

Comparison to past adult word learning studies

In terms of comparison to the previous study of Gaskell and Dumay (2003), it is important to note that we hypothesized that integration of new representations with old representations may have occurred during the course of this study. This claim is somewhat at odds with findings from Gaskell and Dumay, where integration only occurred after a delay of several days. We did not specifically test for integration of new and old representations, thus our hypotheses are tentative. However, it is possible that integration did occur because of several differences between the methods in the current study and those of Gaskell and Dumay. In particular, the current study paired nonwords with novel objects, whereas Gaskell and Dumay presented nonwords without any referents. The current study presented the nonwords in the meaningful context of a story, whereas Gaskell and Dumay presented nonwords in a decontextualized phoneme monitoring task. The current study presented a smaller number of shorter nonwords in a set as compared to Gaskell and Dumay. These differences may have facilitated word learning in the current study leading to faster creation and integration of representations of novel words. Future work systematically varying exposure conditions may aid

in identifying the factors that influence the integration of new representations with existing representations during word learning.

Conclusions

Investigation of the influence of phonotactic probability on adult word learning yielded a high-probability disadvantage that may be accounted for by assuming that phonological representations influence novelty detection thereby triggering new learning. In contrast, the effect of neighborhood density on adult word learning entailed a high-density advantage that appeared consistent with the hypothesis that lexical representations influence word learning directly by affecting stabilization of the new representation, although alternative hypotheses related to language production and working memory could not be completely ruled out. Current models of word learning do not appear to account fully for these findings because they are either too narrow, accounting for a set of specific effects (e.g., Samuelson, 2002), or too broad, lacking specificity in word learning mechanisms (e.g., Gupta & MacWhinney, 1997; Plunkett, Sinha, Moller, & Strandsby, 1992). The current findings indicate a need to consider the factors that influence the triggering of new learning as well as the integration of new representations.

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Appendix. Sample story episode.

Episode 1	Story 1		Story 2	
	Scene	Narrative	Scene	Narrative
Scene 1	<i>Girl monster character sitting on floor next to couch crying. Boy monster character standing next to couch.</i>	Mom and dad were at work. Big Brother had to take care of Little Sister. Little Sister was crying. “I’ll take you to the park if you stop crying,” said Big Brother.	<i>Girl crocodile character talking and boy crocodile character listening.</i>	Mary and Joe crocodile had to go to school. Today was a big day. It was show and tell day. Mary and Joe were looking for things to bring.
Scene 2	<i>Boy character dancing with red candy + 1 chute in thought cloud. Girl character dancing with blue candy + 2 chutes in thought cloud.</i>	“We can go to the candy machines at the park,” said Big Brother. “My favorite is the /faʊg/.” Little Sister said, “My favorite is the /pim/.	<i>Girl character dancing with yellow candy + 1 chute in thought cloud. Boy character dancing with green candy + 1 chute in thought cloud.</i>	“We can stop at the candy machines on the way to school,” said Mary. “My favorite is the /jeɪm/.” Joe said, “My favorite is the /han/.
Scene 3	<i>Boy character standing and holding punch toy. Girl character sitting and holding cork gun.</i>	“Can we bring some toys?” asked Little Sister. “Yes,” said Big Brother. “I’m bringing my /nɛp/.” Little Sister said, “I’m bringing	<i>Girl character standing and holding punch arrow. Boy character standing and holding marshmallow sprayer.</i>	“Can we bring some toys?” asked Joe. “Yes,” said Mary. “I’m bringing my /joun/.” Joe said, “I’m bringing my /feɪg/.”

		my /jʌd/.”		
Scene 4	<i>Boy character standing blowing on orange trumpet with bell pointing down. Girl character in profile blowing on yellow hand-held tuba.</i>	“We can play music at the park,” said Big Brother. “I’m taking my /jɪb/.” Little Sister said, “I’m taking my /hɪf/.”	<i>Girl character in profile blowing on red saxophone pointing down. Boy character in profile blowing blue oboe pointing up.</i>	“We can play music at show and tell,” said Mary. “I’m taking my /mɛk/.” Joe said, “I’m taking my /wʌf/.”
Scene 5	<i>Boy character walking green gerbil with antenna on a leash. Girl character carrying purple mouse-bat.</i>	“What about the pets?” asked Little Sister. “We’ll take them with us,” said Big Brother. “I’ll get /pɑɪb/.” Little Sister said, “I’ll get /wæd/.”	<i>Girl character holding yellow frog bat. Boy character walking orange elephant-mouse on leash.</i>	“Can we bring our pets?” asked Joe. “Sure,” said Mary. “I’ll get /mʌg/.” Joe said, “I’ll get /nɑʊt/.”
Scene 6	<i>Boy and girl character running down a sidewalk with arms in the air.</i>	“Let’s go!” said Big Brother. “Yea!” said Little Sister. They ran all the way to the park. What will they do at the park?	<i>Boy and girl character seated in a car with father character driving.</i>	“Let’s go!” said Mary. “Yea!” said Joe. They climbed in the car to go to school. What will the other kinds think of their stuff?

Note. There were three additional alternative versions of this story episode to achieve counterbalancing in pairing nonwords with referents across participants. In addition, the order of presentation of scenes 2-5 was randomized across participants.

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Table 1

Summary of past research on phonotactic probability and neighborhood density effects

	Recognition	Production	Memory	Word Learning
Adults	High-probability advantage	High-probability advantage	High-probability advantage	
	High-density disadvantage	High-density advantage	High-density advantage	
Children		High-probability advantage ¹	High-probability advantage ¹	High-probability/ High-density
	High-density disadvantage	High-density advantage		advantage ²

¹ Results based on nonword repetition tasks which contain elements of production and memory

² Phonotactic probability effects have not been differentiated from neighborhood density effects

Table 2

Phonological and Lexical Characteristics of the Stimuli

		High phonotactic probability		Low phonotactic probability	
		High density	Low density	High density	Low density
Positional segment frequency					
	<i>M</i>	0.16	0.15	0.09	0.09
	<i>(SD)</i>	(0.02)	(0.03)	(0.01)	(0.01)
Biphone frequency					
	<i>M</i>	0.0056	0.0066	0.0017	0.0010
	<i>(SD)</i>	(0.0050)	(0.0061)	(0.0007)	(0.0003)
Neighborhood density					
	<i>M</i>	14	5	14	5
	<i>(SD)</i>	(2)	(1)	(2)	(1)

Table 3

Form and Referent Characteristics of the Stimuli

High phonotactic probability		Low phonotactic probability		Category	Referent 1	Referent 2	Referent 3	Referent 4
High density	Low density	High density	Low density					
pim	han	jeim	faug	Candy Machine	Red candy + 1 chute (created)	Blue candy + 2 chutes (created)	Yellow candy + 1 chute (created)	Green candy + 1 chute (created)
joun	nep	ferg	jʌd	Toy	Punch toy (Geisel & Geisel, 1958)	Cork gun (Geisel & Geisel, 1958)	Punch arrow (Geisel & Geisel, 1958)	Marshmallow sprayer (Geisel & Geisel, 1958)
mɛk	jɪb	hɪf	waf	Horn	Orange trumpet bell pointing down (Geisel & Geisel, 1954)	Yellow hand-held tuba (Geisel & Geisel, 1954)	Red saxophone pointing down (Geisel & Geisel, 1954)	Blue oboe pointing upward (Geisel & Geisel, 1954)
wæd	paɪb	naʊt	mʊg	Pet	Green gerbil + antenna (DeBrunhoff, 1981)	Purple mouse-bat (Mayer, 1992)	Yellow frog-bat (Mayer, 1992)	Orange elephant mouse (Mayer, 1992)

Note. Pairing of nonwords to referents was counterbalanced across participants.

Table 4

Integration of current results with those of past research on phonotactic probability and neighborhood density effects

	Recognition	Production	Memory	Word Learning
Adults	High-probability advantage	High-probability advantage	High-probability advantage	High-probability disadvantage
	High-density disadvantage	High-density advantage	High-density advantage	High-density advantage
Children		High-probability advantage ¹	High-probability advantage ¹	High-probability/ High-density
	High-density disadvantage	High-density advantage		advantage ²

¹ Results based on nonword repetition tasks which contain elements of production and memory

² Phonotactic probability effects have not been differentiated from neighborhood density effects

Figure Captions

Figure 1. Proportion of correct responses (partial + complete) by cumulative exposure for high phonotactic probability (triangles, squares) versus low phonotactic probability (circles, diamonds) for high-density (top panel) and low-density nonwords (bottom panel). Note that these are the same data as in figure 2 but re-arranged to afford easier comparison between high versus low phonotactic probability.

Figure 2. Proportion of correct responses (partial + complete) by cumulative exposure for high density (diamonds, squares) versus low density (circles, triangles) for high-probability (top panel) and low-probability nonwords (bottom panel). Note that these are the same data as in figure 1 but re-arranged to afford easier comparison of high versus low density.

Figure 3. Proportion of partially correct responses (i.e., 2 of 3 phonemes correct) by cumulative exposure for high phonotactic probability (triangles, squares) versus low phonotactic probability (circles, diamonds) for high-density (top panel) and low-density nonwords (bottom panel). Note that these are the same data as in figure 4 but re-arranged to afford easier comparison between high versus low phonotactic probability.

Figure 4. Proportion of partially correct responses (i.e., 2 of 3 phonemes correct) by cumulative exposure for high density (diamonds, squares) versus low density (circles, triangles) for high-probability (top panel) and low-probability nonwords (bottom panel). Note that these are the same data as in figure 3 but re-arranged to afford easier comparison of high versus low density.

Figure 5. Proportion of completely correct responses (i.e., 3 of 3 phonemes correct) by cumulative exposure for high phonotactic probability (triangles, squares) versus low phonotactic probability (circles, diamonds) for high-density (top panel) and low-density nonwords (bottom

panel). Note that these are the same data as in figure 6 but re-arranged to afford easier comparison between high versus low phonotactic probability.

Figure 6. Proportion of completely correct responses (i.e., 3 of 3 phonemes correct) by cumulative exposure for high density (diamonds, squares) versus low density (circles, triangles) for high-probability (top panel) and low-probability nonwords (bottom panel). Note that these are the same data as in figure 5 but re-arranged to afford easier comparison of high versus low density.











