Phonological typicality influences on-line sentence comprehension

Thomas A. Farmer*, Morten H. Christiansen*†, and Padraic Monaghan‡

*Department of Psychology, Cornell University, Uris Hall, Ithaca, NY 14853; and ‡Department of Psychology, University of York, York YO10 5DD, United Kingdom

Since Saussure, the relationship between the sound and the meaning of words has been regarded as largely arbitrary. Here, however, we show that a probabilistic relationship exists between the sound of a word and its lexical category. Corpus analyses of nouns and verbs indicate that the phonological properties of the individual words in these two lexical categories form relatively separate and coherent clusters, with some nouns sounding more typical of the noun category than others and likewise for verbs. Additional analyses reveal that the phonological properties of nouns and verbs affect lexical access, and we also demonstrate the influence of such properties during the on-line processing of both simple unambiguous and syntactically ambiguous sentences. Thus, although the sound of a word may not provide cues to its specific meaning, phonological typicality, the degree to which the sound properties of an individual word are typical of other words in its lexical category, affects both word- and sentence-level language processing. The findings are consistent with a perspective on language comprehension in which sensitivity to multiple syntactic constraints in adulthood emerges as a product of language-development processes that are driven by the integration of multiple cues to linguistic structure, including phonological typicality.

T he principle of "the arbitrariness of the sign" (1) has been a cornerstone of the study of language for more than a century and is often highlighted as one of its central design features (2). Except in rare cases of onomatopoeia and sound symbolism, words are considered to be arbitrary symbols that do not resemble what they stand for. Indeed, even prototypical onomatopoeia, such as animal sounds, appear highly idiosyncratic when compared cross-linguistically (3). For example, the words for the noises that pigs make differ dramatically across languages, from "buubuu" in Japanese and "ut-it" in Vietnamese to "øf" in Danish, "rok-rok" in Croatian, and "oink-oink" in English. It is therefore not surprising that most modern frameworks for understanding language assume that there is little, if any, relationship between the sound of a word and how it is used (e.g., refs. 3–5). In this article, however, we demonstrate that there is a systematic relationship between the sound of a word and its lexical category and that this relationship affects language processing.

Previous research on language development has suggested that the relationship between a word's phonology and how it is used is not entirely arbitrary. For example, several phonological properties, including lexical stress (6), number of phonemes (7), and vowel duration (8), differ between function words (determiners, prepositions, etc.) and content words (nouns, verbs, adjectives, and adverbs), and newborn infants appear to be able to use such cues to differentiate these two major syntactically motivated categories of words (9). Nouns and verbs also differ in terms of their phonological properties, and this difference may be important for early acquisition of syntax (10, 11). Corpus-based analyses of child-directed speech indicate that nouns can be differentiated from verbs in terms of differences in phonological cues such as syllabic complexity, lexical stress position, and number of syllables (7, 11, 12). Sensitivity to these cues begins early; e.g., 4-day-old infants can detect differences in syllable number among isolated words (13), and, by age 3, children can use differences in number of syllables to guide their interpretation of novel words (14). Moreover, phonological cues have also been shown to improve the learning of artificial languages by both children (15) and adults (11). Together, these studies indicate that nouns are distinct from verbs in terms of their phonological properties and that children are not only sensitive to such cues but also appear to use them to facilitate learning.

Given the potential importance of phonological cues for syntactic development, we predicted that they would continue to play a role in adulthood as constraints on syntactic processing. Indirect support for this prediction comes from sentence-production studies in which adults show sensitivity to phonological cues that may distinguish nouns from verbs. Adults are more likely to use a nonsense word as a noun when it is multisyllabic (16) or has stress on the first syllable (17). Here, we investigate the degree to which sensitivity to phonological cues extends to the on-line processing of sentences, focusing on the two major lexical categories of nouns and verbs.

If the phonological properties of nouns differ systematically from those of verbs, then nouns should form coherent clusters in phonological space in which nouns tend to be closer to one another than to verbs and vice versa for verbs. We quantify the phonological clustering of nouns and verbs by measuring the distance between words within and across lexical categories. This corpus analysis shows that there exist coherent probabilistic constraints between a word's phonological form and its lexical category. Analyses of lexical naming latencies in experiment 1 indicate that these constraints influence lexical processing, with nouns and verbs that are typical of their lexical category being accessed faster. Experiments 2 and 3 demonstrate a similar effect of phonological typicality, the degree to which the phonology of a given word is typical of other words in its lexical category, when nouns and verbs are processed in the context of simple unambiguous sentences. Finally, experiment 4 shows that phonological typicality directly affects on-line comprehension of sentences containing syntactic ambiguities arising from the presence of noun/verb (N/V) homonyms.

Measuring Phonological Typicality

To determine the extent to which the phonological properties of words cluster together coherently within lexical categories, we extracted all of the 3,158 monosyllabic nouns and verbs that were classified unambiguously according to lexical category in the CELEX database (18). We represented each word in terms of three phoneme slots for onset, two slots for nucleus, and three slots for the coda, with phonemes represented in terms of eleven phonemic features (adapted from ref. 19). For each pair of words, the phonemes were shuffled between each phoneme slot within the onset, nucleus, or coda positions to minimize the Euclidean distance between the words. Thus, when "kelp" is compared with "street," the alignment would be /.k . ɛ . lp . / and /stɹ ii . t . / (where
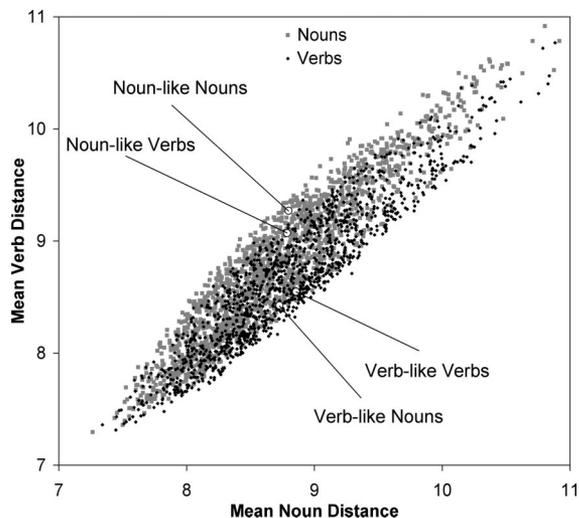
PSYCHOLOGY

Fig. 1. The 3,158 words from the corpus analyses in experiment 1, plotted as a function of their mean Euclidian distance in phonological feature space to all nouns (x axis) and all verbs (y axis). Nouns (gray squares) tend to cluster in the upper left and the verbs (black diamonds) in the lower right. The points labeled Noun-like Nouns and Verb-like Nouns indicate the center of the phonologically typical and atypical nouns, respectively, used in experiment 2. Similarly, the points Verb-like Verbs and Noun-like Verbs denote the center of the typical and atypical verbs used in experiment 3.

"." denotes an empty slot), because the distance between/k/and/ t/was smaller than between/k/and/s/or/k/and/ɹ/, and the distance between/t/and/p/was the smallest for the coda. However, when kelp is compared with "goat," its alignment changes to /k . . ɛ . lp ./to minimize its distance to/g . . aʊ . t ./. We then computed the Euclidean distance between the target word and each of the nouns to measure the mean noun distance and between the target word and each of the verbs to measure the mean verb distance. For example, for the noun/mɑ ː bəl/, the mean distance to all nouns was 8.93, whereas the distance to all verbs was 9.49, indicating that "marble" is closer in terms of its phonology to nouns than to verbs.

Each of the 1,742 nouns and 1,416 verbs in the analysis are plotted in Fig. 1 as a function of their mean distance to all nouns and all verbs. Although there is considerable variation within each lexical category, separate clustering of nouns (upper left) and verbs (lower right) are visible in phonological space. There is, however, also a large overlap between nouns and verbs within the space, indicating that some nouns are closer overall to verbs than they are to other nouns, and, similarly, some verbs are closer to nouns than they are to other verbs. The points labeled Noun-like Nouns and Verb-like Nouns denote words that are phonologically typical and atypical, respectively, of nouns. These points show the centers of the words used in experiment 2. Similarly, the points Verb-like Verbs and Noun-like Verbs indicate, respectively, the centers of the phonologically typical and atypical words used in experiment 3.

To test the significance of the noun and verb clusters, we performed Monte Carlo analyses in which the category labels were randomly assigned to the 3,158 words, and the same distance measures were computed. Over both nouns and verbs, words were significantly closer to other words of their own category ($P < 0.001$). This effect was also found when nouns and verbs were considered separately. Nouns were significantly closer to other nouns than would be expected by chance ($P < 0.001$), and verbs were significantly closer to other verbs than would be expected by chance ($P < 0.004$). These results confirm that the noun and verb clusters, discernable in Fig. 1, are phonologically coherent and differ significantly from one another.

Table 1. Regression results for experiment 1

Steps	β-Weight	t value	R^2
NOUNS			
Step 1			0.296
Onset-phoneme			
Step 2			0.474
Log-frequency	−0.193	−3.237***	
Length	−0.216	−4.327***	
Neighborhood size	0.050	1.007	
Familiarity	−0.154	−2.555*	
Imageability	−0.095	−2.248*	
Step 3			0.482
Noun distance	0.101	2.346*	
Step 3			0.485
Noun distance	−0.007	−0.090	
Verb distance	0.121	1.540	
VERBS			
Step 1			0.556
Onset-phoneme			
Step 2			0.654
Log-frequency	0.344	1.853	
Length	0.125	1.081	
Neighborhood size	0.300	2.277*	
Familiarity	−0.530	−2.883**	
Imageability	0.108	1.132	
Step 3			0.697
Noun distance	0.265	2.683**	
Step 3			0.742
Noun distance	−0.465	−2.967**	
Verb distance	0.646	4.090***	

*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

The analyses so far have involved measures of global similarity, where the phonological coherence was quantified in terms of the mean distance of a word to the remaining 3,157 nouns and verbs. We performed additional analyses to test whether coherence can also be observed locally for each individual word by testing whether the nearest neighbor to each word was of the same lexical category. For example, for "marble," the nearest neighbor in phonological space was the noun "barbel," at a distance of 2.65. When locating the word with the smallest Euclidian distance to the target word, 65.3% of the nouns had other nouns as nearest neighbors, and 64.7% of the verbs had verbs as nearest neighbors. A Monte Carlo analysis demonstrated that these results were highly significant: for nouns and verbs combined, for nouns only, and also for verbs only, P values < 0.001.

These coherence analyses confirmed that nouns are closer to one another than they are to verbs in terms of their phonology and, similarly, that verbs are closer to one another than they are to nouns. These findings motivate the hypothesis that a word's phonological typicality can influence how readily it is accessed.

Experiment 1

Naming Latency Analysis. To test our hypothesis that phonological typicality should influence the processing of single words, we reanalyzed an existing database of lexical naming latencies (20). We repeated the hierarchical regression analysis from the original study on the unambiguous nouns and verbs in the data set to test the extent to which phonological typicality could account for variance after other variables had been entered into the analysis. Nouns and verbs were analyzed separately.

Results and Discussion. The results for nouns are shown at the top of Table 1. The onset-phoneme coding accounted for similar variance to that found in the original analysis (20) for both nouns and verbs. For nouns, log-frequency, neighborhood size, familiarity, and imageability were significant predictors of response times (RTs). For the final step, distance to nouns was a significant

predictor for nouns, indicating that nouns closer to other nouns were responded to more quickly than those distant from other nouns. When both distance to nouns and distance to verbs were entered at the final step, neither was a significant predictor.

The results for verbs are shown at the bottom of Table 1. For verbs, length and familiarity were significant predictors. For the final step, distance to verbs was a significant predictor, indicating that verbs phonologically similar to other verbs were responded to more quickly than verbs distant from other verbs. When both distance to nouns and distance to verbs were entered, both were significant predictors. Verbs that are closer to verbs and more distant from nouns were responded to most quickly.

The results from experiment 1 indicate that the typicality of a word's phonological representation influences how fast it is read aloud. This suggests that adults are sensitive to the systematic relationship between the phonology of a word and its lexical category when reading words in isolation. In experiments 2 and 3, we test the prediction that the phonological typicality of nouns and verbs should also influence on-line processing of words in sentences.

Experiment 2

Noun Study. Experiment 2 aimed to determine whether phonological typicality would influence RTs on nouns occurring in an unambiguous syntactic structure in which a noun would be strongly expected. To produce a single measure of phonological typicality for both nouns and verbs, we subtracted the distance from a given word to all verbs from the distance from that word to all nouns. Negative values indicate that the word is closer to nouns and, thus, has a noun-like phonology, whereas positive values indicate that the word has a verb-like phonology because it is closer to verbs. For example, /mɑːbəl/has a phonological typicality of $8.93 - 9.49 = -0.56$, indicating that "marble" has a noun-like phonology. Based on the results of experiment 1, we predicted that noun-like nouns would be read more quickly than verb-like nouns.

We identified 10 verbs that exhibit a strong structural bias to be followed by a noun phrase (NP). Ten sentence frames were then constructed from the NP-biased verbs ("saved," in example 1). All words through the second determiner "the" were held constant across both sentences in each frame.

(1a) The curious young boy saved the marble that he found on the playground.
(1b) The curious young boy saved the insect that he found in his backyard.

Two sentence versions were constructed from each frame. One version included an NP with a noun-like noun ("marble," 1a). The other version contained a verb-like noun ("insect," 1b). The sentences were presented to participants using a self-paced reading task in which the RT for each word was recorded.

Results and Discussion. RTs on each target word were length-adjusted to eliminate differences between conditions due to character-length (21). First, using the raw RTs on all words in both the experimental and filler items, we computed a regression equation predicting each participant's overall RT per word from the number of characters in each word. The equation was used to generate an expected RT on each word, given its length. Expected RTs on each word were then subtracted from the observed RTs and the resulting adjusted RTs used for all analyses.

Comprehension-question accuracy was high: 98.2% for noun-like target noun sentences vs. 97.3% for verb-like target noun sentences. However, as illustrated in Fig. 2 (left panel), the noun-like nouns were processed significantly faster than the verb-like nouns, $t(21) =$
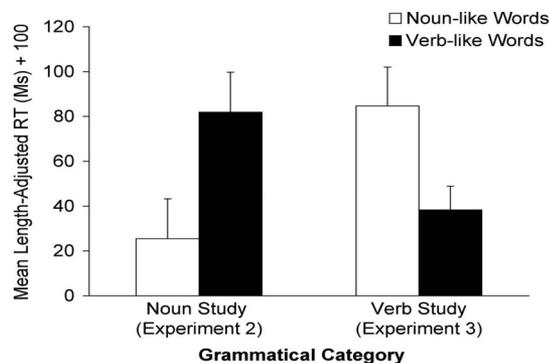

Fig. 2. Mean RTs (and standard errors) for the phonologically typical and atypical conditions in experiments 2 and 3. After length-adjustment, a constant of 100 was added to make the figure easier to interpret.

$2.84, P = 0.01.$[§] Given that it has been suggested that differences in the number of syllables may affect whether a word is more likely to be perceived as a noun or a verb, with multiple syllables being indicative of a noun (16), we conducted a second RT analysis in which we factored out syllable number using the same regression-based length-adjustment procedure as before, and observed a commensurate significant difference, $t(21) = 3.71, P = 0.001$. The faster responses for noun-like compared with verb-like nouns indicate that adults are sensitive to the typical phonological properties of words in the lexical category of nouns. Next, we investigate whether a similar sensitivity can be found for verbs.

Experiment 3

Verb Study. Experiment 3 was designed to determine whether the effect of phonological typicality on processing unambiguous sentences would extend to verbs. We predicted that verb-like verbs would be read faster than noun-like verbs.

We identified 10 verbs exhibiting a strong tendency to take an infinitival complement (inf-comp) structure (e.g., "...tried to..."). Ten sentence frames were then constructed from the chosen frame verbs ("tried," in example 2). Two versions of each frame were constructed in which all words up through the infinitival "to" marker were held constant across both sentences in each frame.

(2a) The young girl had tried to amuse herself while waiting for her mother by working on a crossword puzzle.
(2b) The young girl had tried to ignore the boy that kept on pulling her hair during recess.

One version included an inf-comp structure with a verb-like target verb ("amuse," 2a). The other version included an inf-comp with a noun-like target verb ("ignore," 2b).

Results and Discussion. Again, comprehension accuracy was high: 98.2% correct for verb-like verb sentences vs. 95.5% correct for noun-like verb sentences. As illustrated in Fig. 2 (right panel), however, the verb-like verbs were processed significantly faster than the noun-like verbs, $t(21) = 3.15, P = 0.005$. The syllable length-adjusted RT analyses also yielded a significant difference, $t(21) = 2.86, P = 0.009$. These results indicate that participants were sensitive to the phonological typicality of verbs. Participants took longer to read the verbs that were more typical of nouns in terms of their phonology.

One possible concern with experiments 2 and 3 is that orthographic regularities, instead of phonological typicality, could be the cause of the observed difference in RTs. To address this concern,

---

[§]The combination of the tightly controlled stimuli in experiments 2–4, and their counterbalancing across conditions, makes item analyses inappropriate (47).
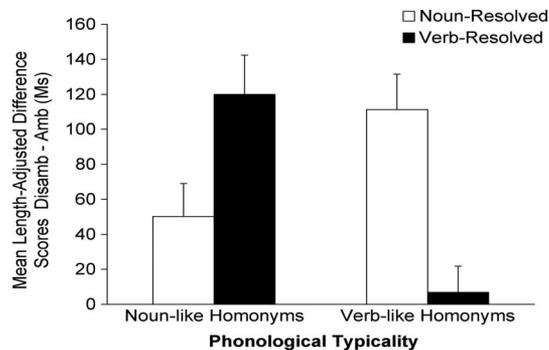
Fig. 3. Mean difference (disambiguation minus point of ambiguity) scores (and standard errors) for each of the four possible conditions in experiment 4. Rising bars indicate that RTs increased from the point of ambiguity to disambiguation.

we created a measure of orthographic typicality that directly parallels phonological typicality using Coltheart's N (22) by subtracting the number of verbs that can be found by changing one letter in the target word from the number of nouns generated by the same process of single-letter modification. This measure of orthographic typicality was then used to predict RTs on each target word in a regression equation. We found that orthographic typicality did not predict length-adjusted RTs on the target words for experiments 2 and 3, $t(19) = 1.02$, $P = 0.323$ and $t(19) = 0.70$, $P = 0.496$, respectively. To further address concerns about orthographic typicality, we controlled for it *a priori* in experiment 4.

The results of experiments 2 and 3 showed that, when a word's phonological typicality is incongruent with the expected lexical category of that word, on-line processing is, at least momentarily, impeded. This effect is robust for both nouns and verbs, demonstrating on-line effects of phonological typicality on unambiguous sentences. To determine whether the systematic phonological regularities of nouns and verbs also affect sentence interpretation, experiment 4 investigates whether phonological typicality can influence on-line parsing preferences during the processing of syntactically ambiguous sentences.

Experiment 4

Homonym Study. We investigated the influence of phonological typicality on the processing of syntactic ambiguities arising from the lexical category ambiguity associated with N/V homonyms. A classic example of this type of ambiguity can be seen in the sentence fragment "I know that the desert trains. . ." (23, 24), in which the lexical ambiguity of the homonym "trains" introduces a syntactic ambiguity with respect to the continuation of the sentence. A noun reading would lead to the expectation of an upcoming verb (as in, ". . . could resupply the camps") and a verb reading would result in the expectation of some type of complement (as in, ". . . soldiers to be tough"). We hypothesized that the phonological typicality of the N/V homonym would have an on-line influence on whether participants would expect a verb or complement continuation of the sentence. Specifically, we predicted that noun-like N/V homonyms would cause participants to experience processing difficulties when the sentence was resolved with a verb interpretation of the N/V homonym, and vice versa for verb-like N/V homonyms.

Twenty sentence frames incorporating a syntactic ambiguity arising from a N/V homonym were constructed consistent with the previous example.

(3a) Chris and Ben are glad that the bird perches seem easy to install.

(3b) Chris and Ben are glad that the bird perches comfortably in the cage.

(4a) The teacher told the principal that the student needs were not being met.

(4b) The teacher told the principal that the student needs to be more focused.

Ten sentence frames contained a noun-like N/V homonym, such as "perches" in 3a and b, and 10 contained a verb-like N/V homonym, such as "needs" in 4a and b. Two different versions of each sentence frame were constructed; one contained a noun resolution of the syntactic ambiguity, as in sentences 3a and 4a, whereas the other contained a verb resolution of the ambiguity, as in 3b and 4b. Across all 40 sentences, the N/V homonym occupied the ninth word position, followed by four words.

Results and Discussion. Participants encountered a syntactic ambiguity upon reading the N/V homonym, which could be parsed as a noun that is modified by the preceding word to form a noun compound, or which could be interpreted as a verb. All sentences were disambiguated by the word after the N/V homonym (the 10th word). However, given some concern about the actual disambiguation point,¶ we also included the 11th word. Accordingly, two segments were created, the point of ambiguity (word 9), and the point of disambiguation (words 10 and 11 averaged together).

A 2 (noun-like vs. verb-like N/V homonym) × 2 (noun vs. verb resolution) × 2 (ambiguity vs. disambiguation) repeated-measures ANOVA yielded a statistically reliable three-way interaction, $F(1, 39) = 19.79$, $P < 0.0005$, mean square error (MSE) = 7,667.22. This three-way interaction was also significant in the syllable length-adjusted analysis, $F(1, 39) = 17.31$, $P < 0.0005$, MSE = 6,988.21. Fig. 3 illustrates the mean of the difference scores between the point of disambiguation and point of ambiguity (disambiguation minus ambiguity) for each of the four possible conditions. In all conditions, RTs increased from the point of ambiguity to the point of disambiguation. However, for sentences containing noun-like N/V homonyms, RTs increased significantly more for the verb-resolved than for the noun-resolved sentences, $t(39) = 2.50$, $P = 0.017$. Similarly, for sentences containing verb-like N/V homonyms, RTs increased significantly more from ambiguity to disambiguation for the noun-resolved sentences than they did for the verb-resolved sentences, $t(39) = 4.17$, $P < 0.0005$.

The RT interaction demonstrates that phonological typicality can bias readers to entertain one interpretation of the ambiguity over the other. The effect of phonological typicality on processing is further illustrated, off-line, by the pattern of comprehension accuracy rates. For the noun-like N/V homonym sentences, accuracy rates were 99.5% correct on the noun-resolved sentences and 95% on the verb-resolved sentences. For the verb-like N/V homonym sentences, accuracy rates were 94.5% correct on the verb-resolved sentences and 91.5% on the noun-resolved sentences. Notably, participants were significantly more accurate on conditions where a match existed between the phonological typicality of the N/V homonym and the resolution of the sentence ($M = 9.7$ correct, SD = 0.52) than on sentences containing a mismatch ($M = 9.33$, SD = 0.92), $t(39) = 2.49$, $P = 0.017$.

In summary, not only does phonological typicality appear to bias the on-line interpretation of a syntactically ambiguous sentence, as demonstrated by the RT data, but it also influences, off-line, whether or not people eventually comprehend the sentence correctly.

General Discussion

Although it has long been known that both phonological information (25) and grapheme–phoneme correspondence (26) can affect reading performance, the studies presented here demonstrate that the relationship between phonology and lexical categories can directly affect on-line language processing. Previous studies have

---

¶In a few cases, there is a small chance that the second noun in the noun compound (e.g., needs, as in, "the student needs") could be considered a modifier for an upcoming head noun. However, plural nouns are rarely modifiers in English (24) (see also ref. 48).

indicated that adults are sensitive to gross-level phonological properties, such as stress (17) and syllable length (16), when producing sentences using nonsense words. In contrast, our results reveal that the more subtle phonological properties that comprise phonological typicality relative to lexical categories have an effect on both lexical and sentential processing. The corpus analysis revealed a systematic relationship between the sound of a word and whether it is used as a noun or a verb. The subsequent four experiments demonstrated that adults are sensitive to such phonological typicality both when reading isolated words aloud and when comprehending ambiguous and unambiguous sentences. Thus, contrary to what would be expected, given the Saussurean principle of the "arbitrariness of the sign" (1) our results show that the sound of a word does provide an indication of what it refers to; specifically, whether it refers to a noun or a verb.

Analyses of languages, such as Dutch, French, Japanese, Mandarin, and Turkish (refs. 7, 12, and 27, and see ref. 10 for a review) suggest that phonological cues to lexical categories are not unique to English but may be a universal property of language. Additionally, more fine-grained phonologically based subdivisions of words within lexical categories may also be found in the form of sound symbolism (see ref. 28 for a review). For example, "gl-" in English tends to occur in words relating to sound and vision: glimmer, glitter, gleam, glow, glint, etc; and people are sensitive to these sound-meaning relations as evidenced by priming experiments (29). Although it is often assumed that the presence of sound symbolism would require that words with similar referents have the same phonological form across different languages (1, 3), we suggest that systematic relationships between sound and word use are more likely to be specific to individual languages. Indeed, phonological cues to lexical categories vary considerably across languages (27), and we would expect more fine-grained cues to show similar cross-language variation, although some overlap may be expected because of historical relationships between languages. Each language is hypothesized to have its own constellation of phonological cues relevant for distinguishing between lexical categories and perhaps some subdivisions within these. What is important is that the cues form a reasonably coherent system within a language. However, computational simulations involving artificial neural-network models learning mappings between pseudophonological word forms and pseudomeanings have suggested that a considerable degree of arbitrariness in the form–meaning mappings is likely to remain important for language learning (30). Crucially, these simulations indicate that, from a computational perspective, a language is most easily learned if it coheres with phonological typicality in relation to lexical categories but maintains, as much as possible, arbitrary form–meaning relations.

An important implication of our results is that nonsyntactic information, even in the form of phonological cues, can exert an early influence on sentence comprehension. Further investigations will be needed to establish the exact time course within which phonological typicality may be influencing the comprehension process. However, an early effect of phonological typicality appears likely, given the growing number of event-related brain-potential studies indicating that the language system generates fast, probabilistic expectations for various characteristics of upcoming words, including their specific lexical category (31) and onset phoneme (32). Moreover, not only does phonology facilitate the integration of word meaning with sentential context in silent reading independent of orthography (33), but also, in the form of prosody, has an immediate influence on syntactic interpretation (34), even when words are presented visually (35) similar to experiments 2–4.

More broadly, our results are consistent with a view of language comprehension in which the use of multiple constraints in adult sentence processing emerges as the product of a developmental process driven by the integration of multiple cues (36–38). Because language comprehension is a complex task that involves constructing an incremental interpretation of a rapid sequence of incoming words before they fade from immediate memory, the adult comprehension system has been developed to exploit multiple sources of information to facilitate the task (39, 40). Many factors, including referential context (41), lexically based verb biases (42), and prosody (43), appear to constrain how an incoming string of words is processed. Sensitivity to each of these constraints emerges gradually, following different time scales, during language development because of relative differences in saliency and reliability. Owing to the higher reliability of lexicosyntactic contingencies, sensitivity to local word-specific cues such as phonological typicality are likely to appear earlier in children's language comprehension than the ability to use more complex cues deriving from global information sources, such as referential context and prosody. We suggest that the effects of phonological typicality observed here in adult sentence processing are due to the role of phonology in the early development of lexical representations. Thus, the importance of phonological cues in language acquisition can be observed in adulthood as the influence of phonological typicality on sentence comprehension.

Methods

Naming Latency Data in Experiment 1. In the original study (20), several variables were found to account for portions of the variance in naming RTs (20, 44), including features relating to the phonemic properties of the onset (e.g., dental, palatal, and fricative), log-frequency, orthographic neighborhood size, and length. At the first step in our regression analyses, we entered the 13 onset-phoneme properties (20). At the second step, we entered log-frequency, orthographic neighborhood, length, imageability, and familiarity. At the third step, for the noun analysis, we entered distance from each word to all other nouns, for the verb analysis we entered distance from each word to all other verbs, and for both sets of words, we entered both distance to nouns and distance to verbs simultaneously. There were 370 nouns and 70 verbs in the analyses.

Participants in Experiments 2–4. Three separate groups of native English-speaking Cornell undergraduates participated for $5 or course credit: 22 in experiment 2, 22 in experiment 3, and 40 in experiment 4.

Materials. All experimental items along with the means and standard deviations for all control *t* tests reported below are found in *Supporting Information*, which is published on the PNAS web site.

Experiment 2. We selected the verb frames for the noun study from a prior norming study (45). The mean percentage of NP completions for the verbs selected for this study was 87.7% (SD = 6.8%), indicating an overwhelming structural bias to take an NP.

We controlled for several potential confounds: No significant differences between the noun-like vs. verb-like target nouns existed on CELEX-based frequency, $t(18) = 0.26$, $P = 0.801$; orthographic length, $t(18) = 0.95$, $P = 0.355$; number of phonemes, $t(18) = 1.62$, $P = 0.123$; or number of phonological neighbors, $t(18) = 1.42$, $P = 0.172$. There were also no differences between noun-like and verb-like noun sentences in the web-based occurrence of the word triples (trigrams) involving the frame verb, "the," and the target noun (e.g., "saved the marble" vs. "saved the insect"), $t(18) = 0.14$, $P = 0.888$. We used Google-based frequencies because the occurrence of specific triples of words is quite rare even in relatively large corpora. Although web-based word-cooccurrence frequencies incorporate a certain amount of noise, the resulting frequencies are not only highly correlated with corpus-based frequencies (when available), but provide even better correlations with human plausibility judgments than do corpus-based frequencies (46).

To ensure that the sentences containing noun-like target nouns were not significantly more plausible than the sentences containing verb-like target nouns, we conducted a norming study. Twenty separate native English-speaking Cornell undergraduates rated sentences for plausibility on a seven-point Likert-type scale (7 = very plausible). The items, along with 20 unrelated fillers, were

counterbalanced across two lists. There were no significant differences in overall plausibility ratings, $t(18) = 0.14$, $P = 0.890$.

The 20 experimental sentences were counterbalanced across two different presentation lists in such a way that each list contained five noun-like noun sentences and five verb-like noun sentences but only one version of each of the 10 frames. Each list also contained 50 unrelated filler items and eight practice items.

Experiment 3. For the verb study, four verbs were selected from prior norming data (45), for which >80% of participants followed the verb with an inf-comp when asked to use the verb in a sentence. The other six verbs were selected from a norming study in which we presented 15 separate native English speakers from Cornell University with a sentence completion task containing 13 sentence stems that ended with the verb of interest (e.g., "The employees were expected. . . "). Two of the verbs selected for the study elicited 100% inf-comp completion, and the other four elicited 95% inf-comp completion.

There were no significant differences between the verb-like and noun-like verbs on CELEX-based overall frequency, $t(18) = 0.01$, $P = 0.990$; number of nearest phonological neighbors, $t(18) = 1.14$, $P = 0.269$; orthographic length, $t(18) = 0.91$, $P = 0.375$; the number of phonemes, $t(18) = 1.24$, $P = 0.230$; or their occurrence in trigrams consisting of the frame verb, "to," and the target verb (e.g., "tried to amuse" vs. "tried to ignore"), $t(18) = 0.96$, $P = 0.348$. Additionally, 20 separate Cornell undergraduates participated in a plausibility norming study using the same method as in experiment 2. There were no significant differences in plausibility between the sentences containing verb-like and noun-like verbs, $t(18) = 0.75$, $P = 0.462$. The materials were counterbalanced and presented as described in experiment 2.

Experiment 4. Because the homonym study involved a syntactic manipulation, we controlled for stimulus-specific factors that may influence syntactic processing. There was no significant difference for the noun-like N/V homonyms in the frequency of usage as a noun vs. as a verb, $t(9) = 0.17$, $P = 0.87$, nor was there a difference for the verb-like N/V homonyms, $t(9) = 1.54$, $P = 0.15$. Additionally, we used web-based frequency counts to ensure that the trigrams involving the potential noun compound and the disambiguating word (e.g., "bird perches seem" vs. "bird perches comfortably") were not more frequent for noun resolutions than for verb resolutions in both noun-like, $t(18) = 0.90$, $P = 0.381$, and verb-like, $t(18) = 1.01$, $P = 0.328$, homonym sentences. Likewise, the trigrams involving the ambiguous homonym and the two following disambiguating words (e.g., "perches seem easy" vs.

"perches comfortably in") were not more frequent for either resolution in the noun-like, $t(18) = 1.00$, $P = 0.333$, or verb-like, $t(18) = 1.00$, $P = 0.331$, homonym items. We additionally controlled for orthographic typicality to ensure that it did not differ from chance for the noun-like, $t(9) = 0.80$, $P = 0.496$, or the verb-like N/V, $t(9) = 1.41$, $P = 0.191$, homonyms.

To ensure that noun compounds sounded equally plausible when involving either noun-like or verb-like homonyms (48), we presented 20 separate Cornell students with the 20 noun compounds used in this study, along with 30 filler items. They were asked to indicate, on a seven-point Likert-type scale, how likely the compound was to be a noun compound. The noun-like N/V homonym compounds were not rated differently than the verb-like N/V homonym compounds, $t(19) = 1.07$, $P = 0.297$. Finally, we presented 20 separate Cornell undergraduates with one of two counterbalanced lists containing half of the noun-like and half of the verb-like N/V homonym items, in their complete form, intermixed with 16 filler items, and asked them to rate the overall plausibility of each sentence on a seven-point Likert-type scale. We found no significant difference in overall plausibility ratings between the noun and verb resolutions for the noun-like N/V homonym items, $t(18) = 1.41$, $P = 0.175$, and none between the noun and verb resolutions for the verb-like N/V homonym items, $t(18) = 0.53$, $P = 0.605$.

The 40 sentences were counterbalanced across two different presentation lists such that each participant saw five sentences in each possible condition but only one version of each of the 20 sentence frames. The items were presented along with 30 unrelated filler items and eight practice items.

Procedure for experiments 2–4. Participants were randomly assigned to one of the two presentation lists. All sentences were randomly presented in a noncumulative, word-by-word moving-window format. After a brief tutorial, participants were instructed to press the "GO" key to begin the task. The entire test item appeared on the center (left-justified) of the screen in such a way that dashes preserved the spatial layout of the sentence, but masked the actual characters of each word. As the participant pressed the "GO" key, the word that was just read disappeared and the next one appeared. RTs (in milliseconds) were recorded for each word. After each sentence, participants responded to a Yes/No comprehension question, after which the next item appeared.

1. de Saussure, F. (1916) *Cours de Linguistique Generale* (Paycot, Paris).
2. Hockett, C.-F. (1960) *Sci. Am.* **203 (3),** 89–96.
3. Pinker, S. (1999) *Words and Rules* (Harper, New York).
4. Jackendoff, R. (2002) *Foundations of Language* (Oxford Univ. Press, New York).
5. Goldberg, A. (2006) *Constructions at Work* (Oxford Univ. Press, New York).
6. Gleitman, L. & Wanner, E. (1982) in *Language Acquisition: The State of the Art*, eds. Wanner, E. & Gleitman, L. (Cambridge Univ. Press, Cambridge, U.K.), pp. 3–48.
7. Morgan, J.-L., Shi, R. & Allopenna, P. (1996) in *Signal to Syntax*, eds. Morgan, J.-L. & Demuth, K. (Erlbaum, Mahwah, NJ), pp. 263–283.
8. Swanson, L., Leonard, L. & Gandour, J. (1992) *J. Psycholinguist. Res.* **35,** 617–625.
9. Shi, R., Werker, J.-F. & Morgan, J.-L. (1999) *Cognition* **72,** B11–B21.
10. Kelly, M. (1992) *Psychol. Rev.* **99,** 349–364.
11. Monaghan, P., Chater, N. & Christiansen, M.-H. (2005) *Cognition* **96,** 143–182.
12. Durieux, G. & Gillis, S. (2001) in *Approaches to Bootstrapping*, eds. Weissenborn, J. & Höhle, B. (Benjamins, Amsterdam), pp. 189–229.
13. Bijeljac, R., Bertoncini, J. & Mehler, J. (1993) *Dev. Psychol.* **2,** 711–721.
14. Cassidy, K.-W. & Kelly, M.-H. (2001) *Psychol. Bull. Rev.* **8,** 519–523.
15. Brooks, P.-J., Braine, M.-D., Catalano, L., Brody, R.-E. & Sudhalter, V. (1993) *J. Mem. Lang.* **32,** 76–95.
16. Cassidy, K.-W. & Kelly, M.-H. (1991) *J. Mem. Lang.* **30,** 348–369.
17. Kelly, M.-H. (1988) *J. Mem. Lang.* **27,** 343–358.
18. Baayen, R., Piepenbrock, R. & Gulikers, L. (1995) *The CELEX Lexical Database* (Linguistic Data Consortium, Philadelphia).
19. Harm, M.-W. & Seidenberg, M.-S. (1999) *Psychol. Rev.* **106,** 491–528.
20. Spieler, D.-H. & Balota, D.-A. (1997) *Psychol. Sci.* **8,** 411–416.
21. Ferreira, F. & Clifton, C. (1986) *J. Mem. Lang.* **25,** 348–368.
22. Coltheart, M., Davelaar, E., Jonasson, J.-T. & Bresner, D. (1977) in *Attention and Performance*, ed. Dornic, S. (Erlbaum, Hillside, NJ), Vol. VI, pp. 535–555.
23. Frazier, L. & Rayner, K. (1987) *J. Mem. Lang.* **26,** 505–526.
24. MacDonald, M.-C. (1993) *J. Mem. Lang.* **32,** 692–715.
25. Huey, E.-B. (1908) *The Psychology and Pedagogy of Reading* (Macmillan, New York).
26. Gibson, E.-J., Pick, A., Osser, H. & Hammond, M. (1962) *Am. J. Psychol.* **75,** 554–570.
27. Onnis, L. & Christiansen, M.-H. (2005) in *Proceedings of the 27th Annual Cognitive Sciences Society Conference* (Erlbaum, Mahwah, NJ), pp. 1678–1683.
28. Nuckolls, J.-B. (1999) *Annu. Rev. Anthropol.* **28,** 225–252.
29. Bergen, B.-K. (2004) *Language* **80,** 290–311.
30. Gasser, M. (2004) in *Proceedings of the 26th Annual Cognitive Sciences Society Conference* (Erlbaum, Mahwah, NJ), pp. 434–439.
31. Hinojosa, J.-A., Moreno, E.-M., Casado, P., Muñoz, F. & Pozo, M.-A. (2005) *Neurosci. Lett.* **378,** 34–39.
32. DeLong, K.-A., Urbach, T.-P. & Kutas, M. (2005) *Nat. Neurosci.* **8,** 1117–1121.
33. Newman, R.-L. & Connolly, J.-F. (2004) *Cogn. Brain Res.* **21,** 94–105.
34. Steinhauer, K., Alter, K. & Friederici, A.-D. (1999) *Nat. Neurosci.* **2,** 191–196.
35. Steinhauer, K. & Friederici, A.-D. (2001) *J. Psycholinguist. Res.* **30,** 267–295.
36. Bates, E. & MacWhinney, B. (1987) in *Mechanisms of Language Acquisition*, ed. MacWhinney, B. (Erlbaum, Hillsdale, NJ), pp. 157–193.
37. Seidenberg, M. & MacDonald, M. (1999) *Cogn. Sci.* **23,** 569–588.
38. Snedeker, J. & Trueswell, J.-C. (2004) *Cogn. Psychol.* **49,** 238–299.
39. Tanenhaus, M.-K. & Trueswell, J.-C. (1995) in *Speech, Language, and Communication*, eds. Miller, J.-L. & Eimas, P.-D. (Academic, San Diego), pp. 217–262.
40. MacDonald, M.-C., Pearlmutter, N.-J. & Seidenberg, M.-S. (1994) *Psychol. Rev.* **101,** 676–703.
41. Altmann, G.-T. & Steedman, M.-J. (1988) *Cognition* **30,** 191–238.
42. Trueswell, J.-C., Tanenhaus, M.-K. & Kello, C. (1993) *J. Exp. Psychol. Learn. Mem. Cogn.* **19,** 528–553.
43. Snedeker, J. & Trueswell, J.-C. (2003) *J. Mem. Lang.* **48,** 103–130.
44. Balota, D.-A., Cortese, M.-J., Sergent-Marshall, S., Spieler, D.-H. & Yap, M.-J. (2004) *J. Exp. Psychol. Gen.* **133,** 283–316.
45. Connine, C., Ferreira, F., Jones, C., Clifton, C. & Frazier, L. (1984) *J. Psycholinguist. Res.* **13,** 307–319.
46. Keller, F. & Lapata, M. (2003) *Comput. Linguist.* **29,** 459–484.
47. Raaijmakers, J., Schrijnemakers, J. & Gremmen, F. (1999) *J. Mem. Lang.* **41,** 416–426.
48. Haskell, T.-R., MacDonald, M.-C. & Seidenberg, M.-S. (2003) *Cogn. Psychol.* **47,** 119–163.