Memory & Cognition
2007, 35 (5), 974-983

Phonology as the source of syllable frequency effects in visual word recognition: Evidence from French

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In order to investigate whether syllable frequency effects in visual word recognition can be attributed to phonologically or orthographically defined syllables, we designed one experiment that allowed six critical comparisons. Whereas only a weak effect was obtained when both orthographic and phonological syllable frequency were conjointly manipulated in Comparison 1, robust effects for phonological and null effects for orthographic syllable frequency were found in Comparisons 2 and 3. Comparisons 4 and 5 showed that the syllable frequency effect does not result from a confound with the frequency of letter or phoneme clusters at the beginning of words. The syllable frequency effect was shown to diminish with increasing word frequency in Comparison 6. These results suggest that visually presented polysyllabic words are parsed into phonologically defined syllables during visual word recognition. Materials and links may be accessed at www.psychonomic.org/archive.

The syllable has enjoyed a privileged status in many accounts of how humans recognize both spoken words (e.g., Cutler, Mehler, Norris, & Segui, 1986; Mehler, Dommergues, Frauenfelder, & Segui, 1981; Morais, Content, Cary, Mehler, & Segui, 1989) and printed words (Lima & Pollatsek, 1983; Millis, 1986; Prinzmetal, Treiman, & Rho, 1986; Spoehr & Smith, 1973; Taft & Forster, 1976; Tousman & Inhoff, 1992). Initial support for the hypothesized role of the syllable during visual word recognition was provided by Carreiras, Álvarez, and de Vega (1993), who found an effect of syllable frequency on lexical decision latencies to visually presented Spanish words. More precisely, lexical decision was sensitive to the frequency of the first syllable of disyllabic words, with longer latencies to words with high initial syllable frequency. Carreiras et al. interpreted the observed processing cost for words with high-frequency first syllables as the result of interference caused by the representations of other words sharing the same initial syllable (in analogy with accounts of the interfering effects of orthographic neighbors; Grainger, O'Regan, Jacobs, & Segui, 1989).

The inhibitory effect of syllable frequency in Spanish (Carreiras et al., 1993) has been replicated in a number of studies (e.g., Álvarez, Carreiras, & Taft, 2001; Perea & Carreiras, 1998) and has also been found in other languages: French (Mathey & Zagar, 2002), another Romance language, but also German (Conrad & Jacobs, 2004), a non-Romance language. This research has allowed several alternative explanations, not related to syllabic representations, to be discarded. The syllable frequency effect proved not to be confounded with orthographic neighborhood (Perea & Carreiras, 1998) or with morpheme frequency (Álvarez et al., 2001). Furthermore, syllable frequency effects have also been found in electrophysiological investigations measuring event-related potentials (Barber, Vergara, & Carreiras, 2004; Hutzler et al., 2004) and eye movements (Carreiras & Perea, 2004; Hutzler, Conrad, & Jacobs, 2005). Nevertheless, two outstanding questions remain concerning the interpretation of such syllable frequency effects. These questions are the focus of the present study.

First, all studies reporting an inhibitory effect of syllable frequency to date have confounded the influence of orthographically and phonologically defined syllables because, in many languages, including Spanish and German, it is not easy to disentangle the two. Spanish is almost perfectly consistent regarding the relation of spelling and sound. The graphemes V and B, as well as the graphemes Y and LL, which are pronounced in the same way, or the graphemes C and G, the pronunciation of which is deter-

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mined by the following vowel, are rare examples of inconsistency. Also, in German, an inconsistent transcription of graphemes into phonemes and of phonemes into graphemes is rather the exception than the rule. Inconsistency in German is related mainly to the issues of vowel length and terminal devoicing, but this inconsistency is typically resolved by the surrounding context, at least regarding the transcription of graphemes into phonemes. For example, a vowel sound in German words is short when followed by two consonants and long when followed by a single consonant or when the letter H is present between the vowel and subsequent consonants; the letter D is pronounced in a similar way as the letter T only when occurring in final position.

Theoretically, it is important to distinguish the influence of orthographically and phonologically defined syllables, since this will provide important constraints concerning the possible locus of this effect within a general architecture for word recognition. For example, Taft (1979) has proposed an account of visual word recognition in which orthographically defined syllables play a key role, whereas in Ferrand, Segui, and Grainger's (1996) model, it is phonologically defined syllables that have functional significance (see also Colé, Magnan, & Grainger, 1999).

Second, all studies to date reporting an inhibitory effect of syllable frequency have confounded syllable frequency with initial segment frequency (letter and/or phoneme clusters). Words with a higher first-syllable frequency will also tend to have higher initial letter and phoneme frequencies, independently of whether or not these initial letter or phoneme clusters form a syllable. Thus, what researchers have called a *syllable* frequency effect could, in fact, be an effect of initial cluster frequency (Schiller, 1998, 2000). Furthermore, the way cluster frequencies vary within and across syllable boundaries has also been proposed as a possible confounding variable (Seidenberg, 1987, 1989; but see also Rapp, 1992). Thus, for example, bigram frequency is typically greater within a given syllable than at the boundary of two syllables, creating what Seidenberg referred to as a "bigram trough." Carreiras et al. (1993) had tried to rule out an alternative explanation for their empirical effects by ensuring that the word stimuli they used did not show the bigram trough pattern. However, the confound with initial cluster frequency still remained, and no attempt has been made to remove this confound in prior experimentation.

In the present study, we used the French language in an attempt to answer these two key questions. French orthography has some inconsistency regarding its transcription of graphemes into phonemes—for example, the first syllable *de* is pronounced as /de/ in *dessin* (*drawing*) and as /d*/ in *dessous* (*beneath*)—but French can be considered highly inconsistent in the way phonemes can be represented by graphemes. Ziegler, Jacobs, and Stone (1996) presented a statistical analysis of the spelling-to-sound consistency for the bodies of monosyllabic French words, showing 12% inconsistency for the spelling-to-sound mapping and 79% inconsistency for the mapping of sound to spelling. As a consequence, the fact that a specific phonological syllable can be written in different ways is a common feature of the French language (an example in English would be the initial syllable /si/ in *ceiling* and *seaman*. Examples of French words sharing the same phonological syllable are *cigare*, *cyclone*, and *sirène*). Therefore, in French, it is possible to experimentally disentangle the frequencies of orthographically and phonologically defined syllables and also to distinguish syllable frequency from letter and phoneme cluster frequency. In the present study, we designed a single experiment that included all the appropriate comparisons to allow us to address these two key questions. We first attempted to replicate the general effect of syllable frequency in French. Then we examined the orthographic versus phonological nature of syllable frequency effects in two comparisons involving (1) the cumulated word frequency of first-syllable neighbors and (2) the number of higher frequency first-syllable neighbors. We examined the true syllabic nature of syllable frequency effects in two further comparisons involving (1) a control for initial cluster frequency while syllable frequency was varied and (2) a manipulation of initial cluster frequency while syllable frequency was controlled. Finally, the question of the mandatory character of syllabic processing was addressed in a comparison in which syllable frequency was manipulated within different ranges of word frequency.

GENERAL METHOD

Participants

Forty-one students from the University of Provence participated in the experiment. Their participation was rewarded with course credits. All were native speakers of French and had normal or corrected-to-normal vision.

Design and Stimuli

All of the words tested in this experiment were bisyllabic with initial CV syllables (except for some words in Comparison 2 that started with a different syllable structure), and all were carefully controlled for bigram frequency profile (the frequency of the bigram straddling the word's two syllables was always as least as high as the mean frequency of the other bigrams, so that none contained a bigram trough pattern at the syllable boundary). The LEXIQUE database (New, Pallier, Brysbaert, & Ferrand, 2004) for the French language includes about 40,000 bisyllabic words for which the phonological syllables, but not the orthographic syllables, are listed. Combining this database with an additional list giving orthographic syllables for French words,[1] we obtained 9,673 bisyllabic words for which both phonological and orthographic syllables were available. Applying the above-mentioned selection criteria (bigram troughs and syllabic structure) and considering only nouns and adjectives with a length of 4–8 letters and with a printed frequency of at least 0.5 per million occurrences (p.m.o.), the number of words that could possibly enter any experiment examining syllabic effects was reduced to 579. When we tried to experimentally disentangle several statistical measures that are highly correlated (e.g., phonological and orthographic syllable frequency and the frequencies of the first bigram and of the first two phonemes), it was impossible to find enough words that could serve as items in several completely independent experiments without any overlap of items between them. Therefore, instead of performing six different experiments with overlapping sets of stimuli, we decided to perform a single experiment containing the complete set of stimuli that would have been tested in the six different experiments, but without stimulus repetition. We then performed six different analyses on six distinct but overlapping subsets of stimuli drawn from the total set of stimuli that were tested. A total of 278 different words were tested in the experiment, and the total number of words involved in all six analyses was 490. Prior to the presentation of each of the six analyses (Comparisons 1–6), we will describe the stimulus characteristics relative to the particular subset of stimuli involved.

This experimental procedure has the following advantages. When the effects of closely related measures are compared, it may be of interest to directly compare the strength of the corresponding empirical effects. With the present experimental approach, these effect sizes are directly comparable, because they are based on the performance of the same group of participants. Furthermore, the greater number of words within one experimental session including several experimental comparisons will result in a more natural reading context. Nonwords were orthographically legal, pronounceable bisyllabic letter strings in French, and had at least one orthographic neighbor among existing French words. About 5% of the nonwords were pseudohomophones.

Apparatus and Procedure

The stimuli were presented in uppercase letters using Courier 24 point font on a 17-in. ProNitron color monitor (resolution, 1,024 × 768 pixels; 75 Hz) driven by an Umax Pulsar computer. Stimulus presentation and response recording was controlled by PsyScope software (Version 1.2.4 PPC; Cohen, MacWhinney, Flatt, & Provost, 1993). At the utilized viewing distance of 50 cm, the stimuli subtended a visual angle of approximately 1.7º. Each trial was initiated by a fixation point appearing at the center of the screen for 500 msec. The fixation point was then replaced by a blank screen (0 msec), followed by the word or nonword stimulus that remained visible until the participants pressed a button indicating their decision concerning the lexicality (*yes* button for a word or *no* button for a nonword) of the stimulus. The time between the onset of stimulus presentation and the response was measured as the dependent variable. There were also 10 initial training trials. The participants were tested individually in a quiet room. The stimulus list contained 278 words and 278 nonwords. The order of appearance of items was randomized for each participant.

COMPARISON 1
General Syllable Frequency

The first comparison was designed to verify that the inhibitory effect of syllable frequency is reliable in French. In prior reports of such an effect (Mathey & Zagar, 2002), number of higher frequency syllabic neighbors had been manipulated, rather than the traditional syllable frequency manipulation. Number of higher frequency syllabic neighbors had been proposed by Perea and Carreiras (1998) as the strongest predictor of inhibitory effects related to syllable frequency. Therefore, it might be the case that a standard manipulation of syllable frequency (e.g., Carreiras et al., 1993) would be less reliable in French.

Method

One hundred words were selected in order to manipulate the positional frequency (high vs. low) of the first syllable. Syllable frequency was computed as the cumulated word frequency (i.e., a token count) of all bisyllabic words sharing the initial syllable of the target word (see Conrad, Carreiras, & Jacobs, in press, for differential effects of type and token measures of syllable frequency in lexical decision). Syllable frequency was computed separately for both the orthographic and the phonological realizations of any given syllable. A word was considered of high syllable frequency when its syllable frequency was at least 600 per 1 million of occurrence (henceforth referred to as p.m.o.) in both the orthographic and the phonological syllable frequency count (e.g., the word *parrain* [*godfather*]), and of low syllable frequency with less than 200 p.m.o. in both counts (e.g., the word *neveu* [*nephew*]).[2] Words were matched across conditions for the following variables: word frequency, word length, length of the first syllable, orthographic and phonological neighborhood (density and number of higher frequency neighbors), and positional frequency of the second syllable (orthographic and phonological). All the words were of low word frequency (less than 10 p.m.o.). Characteristics for the words used in all the comparisons presented in this study, as well as the items used in each comparison and their corresponding mean response latencies and error rates, are available online at www.psychonomic.org/archive.

Results and Discussion

In this and the following analyses, mean correct response latencies and percentages of errors (see Table 1) were submitted to separate ANOVAs by participants and by items (F_1 and F_2, respectively). For all the comparisons reported in this study, response latencies differing by more than two standard deviations from the mean for each participant and experimental condition were excluded from the analyses. This led to the exclusion of 3.8% of the data in Comparison 1. Thirteen of the word stimuli in Comparison 1 had to be excluded from the analysis because their corresponding mean error rates were higher than 45% (the same exclusion criterion was applied in all the reported comparisons).

Analyses revealed an effect of syllable frequency on response latencies that was significant in the analysis over participants: Words were responded to 23 msec more slowly when their first syllable was of high frequency than when it was of low frequency, which was significant in the participant analysis [$F_1(1,40) = 7.96$, $p < .008$; $F_2(1,85) = 2.54$, $p > .1$]. Error rates also increased with syllable frequency—13.5% versus 11.8% for high syllable frequency versus low syllable frequency words—although this effect did not reach statistical significance [$F_1(1,40) = 3.72$, $p < .07$; $F_2(1,85) < 1$].

Comparison 1 established a standard syllable frequency effect in French that was somewhat weaker than the effect of higher frequency syllabic neighbors reported by Mathey and Zagar (2002) and less reliable than prior reports of syllable frequency effects in Spanish and German. However, our count of first-syllable frequency explicitly applied to both orthographic and phonological syllable frequency. These two frequencies converge automatically in a consistent orthography such as Spanish or German, but they differ to some degree in an orthography with inconsistent phoneme-to-grapheme mapping, such as French. The question of whether the standard effect of syllable frequency is mediated by orthographic and phonological syllable frequency in the same way is an open question of

Table 1
Mean Reaction Times (RTs, in Milliseconds; With Standard Deviations) and Percentages of Errors (%E) for the Words in Comparison 1

Syllable Frequency	RT *M*	RT *SD*	%E
High	754	139	13.5
Low	731	122	11.8

Note—Both orthographic and phonological syllable frequency were conjointly manipulated.

theoretical interest. On the hypothesis that orthographic and phonological syllables influence visual word recognition in different ways, the strength of the empirical effect in Comparison 1 might have suffered from the fact that orthographic and phonological syllable frequency were conjointly manipulated in this comparison. Comparison 2 was designed to examine the influence of phonological and orthographic syllable neighborhood separately.

COMPARISON 2
Orthographic Versus Phonological Syllables

Method

Comparison 2A. Sixty words were selected in order to manipulate the positional frequency (high vs. low) of the first syllable, realized as orthographic syllable frequency. Orthographic syllables were considered high frequency when they had a frequency of at least 530 p.m.o. and were considered low frequency when they had a frequency of less than 245 p.m.o. The frequency of the phonological first syllable was held constant across the two cells of the design. Example words are *canal* (*canal*) and *kayak* (*kayak*), which share their initial phonological syllable, but the orthographic syllable *ca* is of high frequency (573 p.m.o.), whereas *ka* is of low frequency (7 p.m.o.).

Comparison 2B. Sixty words were selected in order to manipulate the positional frequency (high vs. low) of the first syllable, realized as phonological syllable frequency. Ranges set for the manipulation of phonological syllable frequency were the same as those for orthographic syllable frequency in Comparison 2A. The frequency of the orthographic first syllable was held constant across the two cells of the design. Example words are *cigogne* (*swan*) and *tomate* (*tomato*), which have initial orthographic syllables of comparable frequency (173 vs. 177 p.m.o.) but differ in phonological syllable frequency, because the phonological syllable /si/ of *cigogne* increases much in frequency (653 p.m.o.) due to words like *sirop* (*syrup*), which share this phonological syllable, whereas the contribution of alternative orthographic realizations to the frequency of the phonological syllable /to/ of *tomate* (195 p.m.o.) is less important.

The words in both Comparisons 2A and 2B were equated on the same variables as were the words in Comparison 1 across the two cells of the factor syllable frequency. None of the words was of high printed frequency (100 or more p.m.o.).

Results and Discussion

Outlier rejection led to a loss of 5% of the data in each of Comparisons 2A and 2B. Three stimulus words in Comparison 2A and two words in Comparison 2B had to be excluded because of excessive error rates. Mean response latencies and error rates for the words in Comparisons 2A and 2B are shown in Table 2.

Comparison 2A. For orthographic syllable frequency, analyses revealed no effect on response latencies. Words were responded to 6 msec more slowly when their first syllable was of high orthographic frequency than when it was of low orthographic frequency, but this mean difference was far from significant ($p > .4$). No significant effect of orthographic syllable frequency on error rates was obtained either ($p > .1$).

Comparison 2B. For phonological syllable frequency, there was a significant effect of syllable frequency on response latencies: Words were responded to 42 msec more slowly when their first syllable was of high phonological frequency, as compared with low phonological syllable frequency [$F_1(1,40) = 14.69, p \leq .0004$; $F_2(1,56) = 5.29, p < .03$]. This inhibitory effect of phonological syllable frequency was also present in the error data, in which it reached statistical significance in the analysis over participants [$F_1(1,40) = 6.57, p < .02$; $F_2(1,56) = 1.31, p > .2$]. Words with high-frequency phonological first syllables provoked more errors than did words with low-frequency phonological syllables (11.2% vs. 7.9%, respectively).

Table 2
Mean Reaction Times (RTs, in Milliseconds; With Standard Deviations) and Percentages of Errors (%E) for the Words in Comparisons 2A and 2B

Syllable Frequency	RT *M*	RT *SD*	%E
	Comparison 2A		
Orthographic			
High	695	117	10.8
Low	689	107	9.0
	Comparison 2B		
Phonological			
High	712	131	11.2
Low	670	97	7.9

Comparison 2 showed a robust inhibitory effect of syllable frequency on response latencies only when phonological syllable frequency was manipulated, and not for orthographic syllable frequency. These results strongly suggested that phonologically defined syllables are the basis of syllable frequency effects.

Comparison 3 provided a further examination of orthographic versus phonological syllable frequency effects but, this time, defined in terms of the number of higher frequency syllabic neighbors. As was noted before, Perea and Carreiras (1998) found that number of higher frequency syllabic neighbors was a better predictor of response latencies than was the standard syllable frequency measure.

COMPARISON 3
Number of Higher Frequency Syllabic Neighbors

Method

Comparison 3A. Seventy-six words were selected in order to manipulate the number of higher frequency orthographic syllabic neighbors—high (>17) versus low (<15)—of the first syllable. The number of higher frequency phonological syllabic neighbors of the first syllable was held constant across the two cells of the design. For example, *famine* (*famine*) and *sauveur* (*savior*) have a comparable number of higher frequency phonological syllabic neighbors (18 vs. 19) but differ in the number of higher frequency orthographic syllabic neighbors (18 vs. 4), because of high-frequency words, such as *social* (*social*), that share the phonological, but not the orthographic, first syllable with *sauveur*.

Comparison 3B. Seventy-eight words were selected in order to manipulate the number of higher frequency phonological syllabic neighbors—high (>17) versus low (<15)—of the first syllable. The number of higher frequency orthographic syllabic neighbors of the first syllable was held constant across the two cells of the design. Example words are *ciseau* (*chisel*) and *dilemme* (*dilemma*), with 10 and 11 higher frequency orthographic syllabic neighbors, respectively. The phonological syllable /si/ is shared by many relatively high-frequency words with an orthographic syllable other than *ci*—for example, *silence* (*silence*)—which is not the case for the phonological syllable /di/. In consequence, there are 35 versus 12 higher frequency phonological syllabic neighbors for the words *ciseau* and *dilemme*.

The words in both Comparisons 3A and 3B were equated on the same variables as were the words in Comparison 1 across the two cells of the experimental factor. None of the words was of high word frequency (100 or more p.m.o.).

Results and Discussion

Outlier rejection led to a loss of 3.8% of the data in Comparison 3A and 3.4% in Comparison 3B. Eight stimulus words in Comparison 3A had to be excluded because of excessive error rates. The same was the case for 10 words in Comparison 3B. Mean response latencies and error rates for the words in Comparisons 3A and 3B are shown in Table 3.

Comparison 3A. Mean response latencies did not differ for words with many or few higher frequency orthographic syllabic neighbors. Error rates slightly increased with increases in the number of higher frequency orthographic syllabic neighbors (14.1% vs. 12.2%), but this difference was not statistically significant [$F_1(1,40) = 3.41, p < .08$; $F_2(1,66) < 1$].

Comparison 3B. Analyses revealed a significant inhibitory effect on response latencies: Responses were 32 msec slower to words with many than to those with few higher frequency phonological syllabic neighbors [$F_1(1,40) = 12.73, p < .002$; $F_2(1,66) = 4.69, p < .04$]. There was also an inhibitory effect, significant in the analysis over participants, in the error data [14.2% vs. 9.5% errors for words with many vs. few higher frequency phonological syllabic neighbors; $F_1(1,40) = 15.68, p < .0003$; $F_2(1,66) = 3.16, p < .09$].

The differential effects of orthographic and phonological syllable frequency found in Comparison 2 were even more clear-cut in Comparison 3. In the response latencies, there was an inhibitory effect of the number of higher frequency phonological syllabic neighbors but no hint of an effect for the number of higher frequency orthographic syllabic neighbors. Thus, again we have clear evidence that it is phonologically defined syllables that are driving syllable frequency effects in visual word recognition (for the effects of phonological syllable frequency in speech production, see Cholin, Levelt, & Schiller, 2006).

Table 3
Mean Reaction Times (RTs, in Milliseconds; With Standard Deviations) and Percentages of Errors (%E) for the Words in Comparisons 3A and 3B

Number of Higher Frequency Syllabic Neighbors	RT *M*	RT *SD*	%E
Comparison 3A			
Orthographic			
High	743	131	14.1
Low	744	143	12.2
Comparison 3B			
Phonological			
High	747	136	14.2
Low	715	135	9.5

However, as was noted in the introduction, there is one remaining issue that must be addressed before one can safely interpret syllable frequency effects as evidence for syllabic processing. Words that have a high first-syllable frequency also have high initial letter/phoneme cluster frequencies. Comparison 4 was designed to examine the effects of phonological syllable frequency while controlling for initial letter cluster frequency.

COMPARISON 4
Effects of Phonological Syllable Frequency With Letter Cluster Frequency Controlled For

Method

Seventy words were selected in order to manipulate the phonological frequency (high vs. low) of the first syllable. Phonological syllables were considered high frequency when they had a frequency of at least 570 p.m.o. and were considered low frequency when they had a frequency of less than 45 p.m.o. The following frequency measures were held constant across the two cells of the experimental design: the frequencies of the first bigram, the first trigram, the first quadrigram, and the letter cluster representing the first syllable. The frequencies of these letter clusters were computed in a way similar to that described for syllable frequency in order to ensure that the numerical correlations of these alternative variables with the syllable frequency measures used in this study were as close as possible, which should guarantee that these alternative variables in this comparison are controlled validly. The frequency of the first bigram was computed as the cumulated frequency of all bisyllabic words sharing this bigram in the initial position. This was done independently of whether this first bigram was the word's first syllable or not. The same procedure was applied to compute the frequency of a word's initial three or four letters (the first trigram or quadrigram). Similarly, the frequency of the letters representing the initial syllable was computed as follows: the cumulated frequency of all bisyllabic words starting with these letters, regardless of whether they represent the first syllable or not. Given that the initial syllables of the words used in the experiment differed in orthographic length, this last variable might be an important one to control for, because it reflects the pure orthographic nonsyllabic frequency of the first syllable in a more flexible way than does initial bigram or trigram frequency.

The words were also equated on the same variables as the words in Comparison 1 across the two cells of the experimental factor. None of the words was of high word frequency (100 or more p.m.o.). Example words are *cigogne* (*swan*) with a high phonological syllable frequency (653 p.m.o.) and *piscine* (*swimming pool*) with a low (160 p.m.o.) phonological syllable frequency. For these two words, there is no relevant difference for the frequencies of the letter cluster forming the initial syllable, the first bigram in this case (277 vs. 284 p.m.o.). This is because of the inconsistent phonological first syllable /si/ of *cigogne*, but also because of the fact that for 40% of bisyllabic words starting with the bigram *pi*, this bigram is not the first syllable—for example, *pincée* (*pinch*). In contrast, *ci* is the initial syllable of 76% of bisyllabic words starting with the bigram *ci*.

Results and Discussion

Outlier rejection led to a loss of 4.7% of the data in Comparison 4. Five stimulus words in Comparison 4 had to be excluded because of excessive error rates. Mean response latencies and error rates for the words in Comparison 4 are shown in Table 4.

Words with a high-frequency phonological syllable were responded to 56 msec more slowly [$F_1(1,40) = 48.313, p \leq .0001$; $F_2(1,63) = 11.87, p < .002$] and less

Table 4
Mean Reaction Times (RTs, in Milliseconds; With Standard Deviations) and Percentages of Errors (%E) for the Words in Comparison 4

Phonological Syllable Frequency	RT *M*	RT *SD*	%E
High	723	118	12.4
Low	667	95	8.6

Note—Letter cluster frequencies were controlled for.

accurately [$F_1(1,40) = 14.81, p < .0004$; $F_2(1,63) = 2.03$, $p > .1$] than words with a low-frequency phonological syllable (12.4% vs. 8.6% errors). The effect on error rates was significant in the analysis over participants.

Comparison 4 shows that even if syllable frequency correlates systematically with the frequency of the letter cluster forming the orthographic syllable, the effect of syllable frequency in lexical decision proved to be independent of the frequencies of any letter cluster at the beginning of a word. Therefore, what had already been suggested by Comparisons 2 and 3 could again be confirmed: The syllable frequency effect in lexical decision seems to have its base in phonological processing, in which phonological syllables are used as sublexical units mediating the segmentation of polysyllabic words.

However, given that it is phonological, and not orthographic, syllables that are driving the syllable frequency effects obtained in the present study, it could well be argued that it is initial phoneme cluster frequency, and not bigram or trigram frequency, that is the potential confounding variable. Comparison 5 was therefore designed to test for the effects of initial phoneme frequency while controlling for the frequency of the first phonological syllable.

COMPARISON 5
Effects of Phoneme Cluster Frequency With Syllable Frequency Held Constant

Method

Forty-six words were selected in order to manipulate the frequency of the first two phonemes (high vs. low). Initial biphone frequency was computed in the same way as the frequency of the first bigram in Comparison 4. Initial biphones were considered high frequency when they had a frequency of at least 325 and were considered low frequency when they had a frequency of less than 245 p.m.o. The frequency of the first syllable was held constant across the two cells of the experimental design. Example words are *garant* (*guarantor*) and *rivage* (*coastline*), which differ in initial biphone frequency (424 vs. 224 p.m.o.) but do not differ considerably in initial phonological syllable frequency (193 vs. 202 p.m.o.), because the first two phonemes of *garant* more often form the beginning of other bisyllabic words without forming their initial syllable—for example, *gardien* (*guard*)—than is the case for the first two phonemes of the word *rivage*. Words were equated on syllable frequency according to all of the following realizations of syllable frequency: orthographic and phonological first-syllable frequency and number of higher frequency syllabic neighbors of both the orthographic and the phonological syllables. The words were also equated on the same variables as were the words in Comparison 1 across the two cells of the experimental factor. None of the words was of high word frequency (100 or more p.m.o.).

Results and Discussion

Outlier rejection led to a loss of 4.5% of the data. Three stimulus words in Comparison 5 had to be excluded because of excessive error rates. Mean response latencies and error rates for the words in Comparison 5 are shown in Table 5.

Responses were 13 msec faster to words with high-frequency initial biphones. This difference was not statistically significant ($p > .4$). No effect was obtained for the error data ($F < 1$).

Comparison 5 showed that initial biphone frequency did not significantly affect lexical decision latencies when initial syllable frequency was controlled. Therefore, we have successfully excluded the role of both initial orthographic and phonological cluster frequency as potential sources of syllable frequency effects.

The conjoined output of Comparisons 1–5 indicated that syllables are functional units during visual word recognition and that syllabic processing is phonological in nature. However, it remains to be seen whether or not this type of phonological processing based on the syllabic structure of polysyllabic words is an obligatory feature of silent reading, occurring independently of word frequency. Previous studies have reported an interaction between the effects of word frequency and syllable frequency, with syllable frequency effects being stronger for low-frequency words (for error rates in Experiment 1 and for response latencies for lexical decision in Experiment 3 in Perea & Carreiras, 1998; for both dependent variables, Conrad & Jacobs, 2004). Comparison 6 was therefore designed to test whether the syllable frequency effect is modulated by word frequency.

COMPARISON 6
Effects of Phonological Syllable Frequency As a Function of Word Frequency

Method

Ninety-six words were selected according to the orthogonal manipulation of the factors word frequency and initial phonological syllable frequency. A word was considered low frequency when it had a frequency of less than 4 p.m.o. Words with a frequency between 5 and 100 p.m.o. were placed in the high-frequency category. The ranges of initial syllable frequency were above 570 p.m.o. for high syllable frequency words and below 225 p.m.o. for low syllable frequency words. *Salive* (*saliva*) and *museau* (*muzzle*) are examples for high-frequency words with high and low syllable frequency, respectively. *Microbe* (*germ*) and *tisane* (*herb tea*) are examples for this syllable frequency manipulation within low-frequency words. Across the four cells of the experimental design, the following variables were held constant: word length, length of the initial syllable,

Table 5
Mean Reaction Times (RTs, in Milliseconds; With Standard Deviations) and Percentages of Errors (%E) for the Words in Comparison 5

Frequency of the First Biphone	RT *M*	RT *SD*	%E
High	712	100	13.5
Low	725	135	13.0

orthographic and phonological neighborhood (density and number of higher frequency neighbors), and positional frequency of the second syllable (orthographic and phonological). All the words started with a CV syllable.

Results and Discussion

Outlier rejection led to a loss of 4.8% of the data. Mean response latencies and error rates for the words in Comparison 6 are shown in Table 6. Analyses revealed a significant effect of word frequency, with high-frequency words being responded to 83 msec more quickly than low-frequency words [$F_1(1,40) = 73.99$, $p \leq .0001$; $F_2(1,92) = 52.60$, $p \leq .0001$]. Error rates also decreased with increases in word frequency [14.4% errors occurred for low-frequency words vs. 5.0% for high-frequency words; $F_1(1,40) = 55.26$, $p \leq .0001$; $F_2(1,92) = 33.74$, $p \leq .0001$]. A significant inhibitory effect was obtained for the factor of syllable frequency. Responses were 35 msec slower to words starting with a high-frequency syllable than to those with low-frequency initial syllables [$F_1(1,40) = 15.54$, $p \leq .0003$; $F_2(1,92) = 10.67$, $p < .002$]. More errors (11.2% vs. 8.1%) were provoked by high syllable frequency than by low syllable frequency words; the effect was significant in the participant analysis [$F_1(1,40) = 9.97$, $p < .004$; $F_2(1,92) = 3.67$, $p < .06$]. There was a significant interaction between the two factors of word frequency and syllable frequency in the analyses for both response latencies and error rates. The syllable frequency effect on response latencies was stronger for low-frequency words than for high-frequency words [63 vs. 7 msec; $F_1(1,40) = 19.43$, $p \leq .0001$; $F_2(1,92) = 6.57$, $p < .02$]. Syllable frequency led to increased error rates only for low-frequency words [$F_1(1,40) = 21.05$, $p \leq .0001$; $F_2(1,92) = 5.84$, $p < .02$].

The results of Comparison 6 show that the syllable frequency effect interacts with word frequency and is robust only in low-frequency words. This fits with the results of previous studies (Conrad & Jacobs, 2004; Perea & Carreiras, 1998) showing a greater sensitivity to syllabic processing as word frequency diminished.

GENERAL DISCUSSION

The results of the present study provide an innovative perspective on the role of syllables in visual word recognition and, more generally, on the role of phonology in reading. Our study was based on a finding known as the syllable frequency effect, a phenomenon that has been replicated in several studies now in both Spanish and German (Álvarez et al., 2001; Carreiras et al., 1993; Conrad & Jacobs, 2004; Conrad, Stenneken, & Jacobs, 2006; Perea & Carreiras, 1998). It refers to the finding that polysyllabic words that have an initial syllable that is shared by many other polysyllabic words (i.e., a high-frequency syllable) are harder to recognize than are polysyllabic words that have initial syllables of low frequency. Comparison 1 of the present study showed that syllable frequency effects in French are also apparent when this standard manipulation of syllable frequency is applied (the only previous study of syllable frequency effects in French had used a higher frequency syllabic neighbor manipulation; Mathey & Zagar, 2002). Having established a basic syllable frequency effect in French, analogous to the effects previously reported for Spanish and German, Comparisons 2–5 were designed to examine two outstanding issues concerning such effects: (1) Are they driven by orthographically defined or phonologically defined syllables? (2) Are they true syllabic effects and not simply the result of correlated changes in initial cluster (orthographic or phonological) frequency?

Comparison 2 demonstrated a robust inhibitory effect for phonological syllable frequency in contrast with a null effect (a small trend toward inhibition) on response latencies for orthographic syllable frequency. Comparison 3 confirmed this pattern with a manipulation of the number of higher frequency syllabic neighbors. Again, syllable frequency affected response latencies only when the syllable was defined phonologically, and not when it was defined orthographically. Comparisons 4 and 5 allowed us to rule out the possibility that syllable frequency effects are, in fact, effects of initial letter or phoneme cluster frequency and have nothing to do with syllables. Comparison 4 showed a robust effect of syllable frequency when the frequency of word-initial letter clusters (bigrams and trigrams) was held constant. Comparison 5 showed that the frequency of a word's two initial phonemes (biphone frequency), a variable that is strongly correlated with phonological syllable frequency especially for CV syllables, did not produce a significant effect on response latencies when syllable frequency was controlled for. Finally, Comparison 6 showed that syllable frequency effects were robust only in low-frequency words. Therefore, the results of the present study suggest that syllable frequency effects indeed reflect processing of syllable-sized units during visual word recognition and also suggest that these syllable-sized units are defined phonologically. The influence of such syllabically structured phonological processing is most evident during the recognition of low-frequency words.

A recent masked priming study by Álvarez, Carreiras, and Perea (2004) also has provided evidence that syllable effects in visual word recognition are phonological, rather than orthographic, effects. Primes that shared their initial syllable with target words facilitated target word recognition even when the syllable had a different orthographic realization (e.g., the pronunciation of the Spanish orthographic syllables BI and VI is the same). Thus, the effects of syllabic manipulations with polysyllabic words add to the already vast literature showing phonological

Table 6
Mean Reaction Times (RTs, in Milliseconds; With Standard Deviations) and Percentages of Errors (%E) for the Words in Comparison 6

	Word Frequency					
	High			Low		
	RT			RT		
Syllable Frequency	*M*	*SD*	%E	*M*	*SD*	%E
High	670	124	4.6	782	163	17.9
Low	663	104	5.4	719	125	10.9

influences on visual word recognition (e.g., Ferrand & Grainger, 1992, 1994; Frost, 1998; Grainger & Ferrand, 1994; Lukatela, Eaton, Lee, Carello, & Turvey, 2002; Lukatela, Frost, & Turvey, 1998; Lukatela & Turvey, 1994; Perfetti & Bell, 1991; Pollatsek, Lesch, Morris, & Rayner, 1992; Van Orden, 1987; Van Orden, Johnston, & Hale, 1988). These phonological influences can be accommodated by a model in which sublexical orthographic representations (i.e., letters and graphemes) are immediately converted into sublexical phonological representations (i.e., phonemes) during the processing of a printed word (Ferrand et al., 1996; Grainger & Ferrand, 1994; Jacobs, Rey, Ziegler, & Grainger, 1998).

What the present results tell us is that this process of sublexical conversion from orthography to phonology also involves syllable-sized representations. The conversion of graphemes into phonological syllable representations could easily be achieved for most polysyllabic words in a language such as French, where inconsistency in the mapping of graphemes into phonemes is rather the exception than the rule (see Ziegler et al., 1996) and where syllabic boundaries are clearly defined (see Ferrand et al., 1996; Kaye & Lowenstamm, 1984; for syllabification algorithms in French, see Dell, 1995; Laporte, 1993). Thus, on presentation of a printed word, a sublexical orthographic code generates activation in the appropriate set of phoneme representations that then converge on syllabic representations. These syllable-sized units receive bottom-up input only via phoneme representations and are, therefore, phonologically defined syllables. The syllable representations then control activation at the level of whole-word orthographic and phonological representations. On presentation of a polysyllabic word, all whole-word representations that are connected with the first syllable of the target word will, therefore, receive activation from that syllable representation and will compete with the target word for recognition. This is how inhibitory effects of syllable frequency arise.

In Comparison 6 in the present study, we examined whether or not syllable frequency effects are influenced by word frequency. The results showed that the effect of phonological syllable frequency diminished with increasing word frequency. This finding fits with our phonological interpretation of syllable frequency effects. In models of visual word recognition that postulate a direct orthographic route to meaning and an indirect phonological route (e.g., Ferrand et al., 1996; Grainger & Ferrand, 1994; Jacobs et al., 1998), it is clear that phonological influences depend on speed of processing in the direct route. Orthographic processing may be too fast in high-frequency words for the sublexical computation of phonology (including phonological syllables) to significantly influence a lexical decision response based on activity in whole-word representations (Grainger & Jacobs, 1996).

Finally, to end on a methodological note, in the present study, a relatively large set of preplanned orthogonal contrasts was tested in a single experiment. This has the advantage of allowing comparisons of different experimental manipulations on the basis of data obtained from the same set of participants in the same testing conditions. It also has the advantage of examining effects involving quite small numbers of stimuli (due to the massive constraints on stimulus selection) embedded in a larger, more heterogeneous stimulus set. Given the evidence for effects of list composition on performance in standard word recognition tasks (e.g., Gordon, 1983; Lupker, Brown, & Colombo, 1997; Perea, Carreiras, & Grainger, 2004), large heterogeneous lists of stimuli have the advantage of reducing effects that are uniquely due to the repetition of stimuli from a particular experimental condition (via trial-to-trial adjustments in response criteria; Perea et al., 2004). It is obvious that "normal" extralaboratory reading rarely involves the successive presentation of stimuli fulfilling the highly specific stimulus selection criteria that we typically apply in laboratory experiments.

In conclusion, the present study provides further support in favor of a model of visual word recognition in which the rapid sublexical computation of phonology from orthography involves phonologically defined syllable-sized representations. These syllabic representations control activation at the level of whole-word representations, so that high-frequency initial syllables activate many such whole-word representations, which then compete with the target word for identification.

AUTHOR NOTE

This research was supported by a grant of the Deutsche Forschungsgemeinschaft to A.M.J., Freie Universität Berlin (Ja 823/3-1/Jacobs, "Zur Rolle phonologischer Prozesse beim Lesen komplexer Wörter. Ein sprachvergleichender Ansatz"). The authors are grateful to Albrecht Inhoff and two anonymous reviewers for their helpful comments on a previous version of the manuscript. Correspondence concerning this article should be addressed to M. Conrad, Department of General Psychology, Freie Universität Berlin, Habelschwerdter Allee 45, 14195 Berlin, Germany (e-mail: markus_conrad@gmx.de).

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NOTES

1. We are grateful to Ronald Peereman, Université de Bourgogne, for providing this database.

2. All the example words for the different comparisons in this study were taken from the stimulus material of the corresponding comparison.

ARCHIVED MATERIALS

The following materials and links may be accessed through the Psychonomic Society's Norms, Stimuli, and Data Archive, www.psychonomic.org/archive. To access these files or links, search the archive for this article using the journal name (*Memory & Cognition*), the first author's name (Conrad), and the publication year (2007).

FILE: conrad-M&C-2007.zip

DESCRIPTION: The compressed archive file contains one file:

conrad2007EtAlapp.rtf, containing tables with item characteristics for words used in Comparisons 1–6 as well as items used in each comparison and their corresponding mean response latencies and error rates. The file is in Rich Text Format.

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(Manuscript received December 15, 2005;
revision accepted for publication May 19, 2006.)