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Attentional allocation to syllabic boundaries in English first-syllable stress words

Athanassios Protopapas, Steven A. Finney, and Peter D. Eimas

Department of Cognitive & Linguistic Sciences

Brown University, Providence, RI 02912

Correspondence address:

ILSP, Artemidos 6 & Epidavrou

GR-151 25 Maroussi, Greece

Tel: +30 210 6875409, Fax: +30 210 6854270

e-mail: protopap@ilsp.gr

Abstract

Recent work using an attentional allocation paradigm with a phoneme monitoring task has shown that syllabic boundaries preceding stressed syllables are automatically available during online processing of spoken English (Finney et al., 1996). The present research expands on these findings to show that syllabic boundaries preceding unstressed syllables are also available, suggesting that the lack of syllabic effects in earlier syllabic word-fragment monitoring studies (e.g., Cutler et al., 1986) may be due to an interaction of the experimental design and the ambisyllabicity of the materials used. In addition, an experiment using second-syllable stress words to induce expectations about syllabification in first-syllable stress words with the same syllabic structure showed a strong syllabic effect, suggesting that the prelexical syllabic representations used by English listeners are not necessarily contingent on stress. We tentatively argue for a speech perception theory in which syllabic frames organize incoming phonetic features into abstract syllabic units.

Attentional allocation to syllabic boundaries in English first-syllable stress words

The role of the syllable in language structure and processing has been a topic of extensive research and debate over the past two decades in both cognitive psychology and linguistics. In linguistics, much of contemporary phonology revolves around the concept of the syllable and its precise role in language organization (Goldsmith, 1990; Kenstowicz, 1994). Phonological theory has made use of the syllable as a suprasegmental structure that allows for a clear account of phenomena such as stress assignment (e.g., Pulgram, 1970; Anderson & Jones, 1974) and has argued that the syllable is a ubiquitous unit of phonological organization subject to universal as well as language-specific constraints on permissible structures. Constraints on phonetic organization (phonotactics) are based on syllabic structure. The syllable would thus seem to be indispensable in the explanation of phonological regularities.

Psychological evidence for the syllable comes from a number of different domains. Massaro (1972) argued that the duration of a hypothesized auditory perceptual window corresponded to the length of syllables in speech, consistent with the view that syllable-sized chunks are the perceptual units of speech. Psychological evidence that phonotactic information is used in lexical segmentation (e.g., McQueen & Cox, 1995) can be taken as indirect evidence for a role of syllabic representations in perception, to the extent that such phonotactic constraints are defined over syllabic structure. Moreover, perceptual phase transitions in syllabic organization have been observed as a function of linear articulatory changes (Tuller & Kelso, 1991). In addition, studies of speech production have suggested that articulatory motor plans are best understood as organized around syllable-sized units, as evidenced by within- vs. between-syllable coarticulation (Fujimura and Lovins, 1978; but see also Gay, 1978, and Lisker, 1978), mispronunciation patterns (Stemberger, 1983), and by the difficulty in switching between syllabic ‘‘frames’’ (Sevald, Dell, & Cole, 1995). If syllable-based motor procedures form the acoustic patterns of language (on which both initial language learning and mature language perception are necessarily based) it would be surprising if mental representations of syllabic structure derived from this exposure were not applied to speech perception.

Overall, a number of articulatory, phonological, and learning considerations have led to the conclusion that syllabic representations are part of a person’s knowledge of language. More direct evidence for a role of the syllable in speech perception was provided by Mehler, Dommergues, and Frauenfelder (1981), who found evidence for syllabic segmentation using the word-fragment monitoring paradigm (reviewed in Frauenfelder & Kearns, 1996) with syllable-size (i.e., the fragments) targets in French. This effect has been replicated in a number of other languages (for review, see Allopenna, 1995; Eimas, 1997). However, the view of the syllable as a possible universal segmentation unit (Mehler et al., 1981) has been questioned in light of reports of failure to obtain syllabic effects in the fragment monitoring paradigm with British English (Cutler et al., 1986). It was argued that certain characteristics of English (in particular, the ambiguity resulting from ambisyllabicity, discussed below) cause syllabification to be unclear and thus make syllabic segmentation an inefficient strategy for English.

More recent findings, however, indicate that even in the ‘‘unclearly syllabified’’ English language there may be an important role for syllables in perception, although the data are sometimes compatible with alternative hypotheses. Notably, studies that have failed to obtain syllabic effects in English have used first-syllable stress stimuli (e.g., Cutler et al., 1986). In contrast, using the fragment monitoring paradigm, Allopenna (1995, Experiment 4) obtained a syllabic effect with second-syllable stress words but not with first-syllable stress words. Likewise, using the attentional allocation paradigm of Pallier, Sebastián-Gallés, Felguera, Christophe, and Mehler (1993, described below), Finney et al. (1996) found evidence for the use of syllabic information in the online processing of second-syllable stress words words (Experiments 1--4) but no such effect with first-syllable stress words (Experiment 5). More recently, Pitt, Smith, and Klein (1998) also used the attentional allocation paradigm (termed ‘‘structural induction’’) and obtained syllabic effects using stimulus lists containing a mix of first- and second-syllable stress words.

Thus, the mixed results for English can be interpreted in at least two ways. One possibility is that syllabic structure *per se* plays no role in the perception of English; rather, stress-sensitive segmentation of speech (cf. the proposal of Cutler & Norris, 1988, for segmentation only before strong syllables) has led to what appear to be ‘‘syllabic’’ effects for syllable boundaries that precede stressed syllables. Cutler (1997) has expressed this view most strongly, stating that ‘‘phoneme detection attention cannot be allocated to the internal syllable boundary in an initially stressed word’’ (p. 840) and that ‘‘syllabic segmentation in a stress language is simply inefficient, and not worth undertaking ...[T]he evidence to date does not seem to warrant a change in this verdict'' (p. 841). Alternatively, the syllable may play a more general role in the perception of English, but its effects are obscured by an interaction between possibly ambiguous syllable boundaries (arising from ambisyllabicity) with the experimental paradigms used. Elaboration of this requires a more precise understanding of the relation between ambisyllabicity and stress. In the present manuscript we demonstrate that, in contrast to Cutler's assertion, prelexical syllabic representations are automatically available in online speech processing regardless of the type of syllables in the speech stream (e.g., stressed or unstressed, strong or weak).

The issue of ambisyllabicity has occupied a central position in discussions of English syllabic structure (e.g., Kahn, 1980; Selkirk, 1982) and in the design of experiments addressing the role of syllabic units in perception (e.g., Allopenna, 1995; Bradley, Sánchez-Casas, & García-Albea, 1993; Cutler et al., 1986). Ambisyllabicity refers to a certain ambiguity in the syllabic membership of segments such as the /l/ in ``balance.'' Such ambiguity could be conceptualized as one phonological segment's membership in two syllables simultaneously (Kahn, 1980) or as a difference between ``canonical'' and ``surface'' syllabification (Selkirk, 1982), in which the former adheres to universal principles and the latter to the phonotactics of the language. For purposes of speech processing theories, one point of view is that an ambisyllabic segment can be considered as belonging to two syllables simultaneously or, as in Selkirk's view, to only one at a time, though the membership may change at different stages. Alternatively, it might be that an ambisyllabic segment is simply unspecified or ‘‘ambiguous’’ with respect to syllabification. Ambisyllabic segments may thus have important consequences for experimental designs and processing accounts because a segment clearly participating in two syllables will behave as both onset and coda whereas an ambiguously syllabified segment might not exhibit any syllable-related properties.

In the treatment of these phenomena, issues of stress become crucial. An intervocalic consonant preceding a stressed syllable nucleus is taken as unambiguously belonging to that stressed syllable (‘‘be.lieve"), whereas matters can be more complicated at the end of a stressed syllable. Specifically, the medial consonant in first-syllable stress words with short (lax) vowels (e.g., the /l/ in ‘‘balance’’ and the /b/ in ‘‘fabric’’) is ambisyllabic, due to the phonological constraint that stressed syllables with a short vowel must have a closing consonant.[1] However, a stressed syllable with a long (tense) vowel (e.g., /sei/ in ‘‘sacred’’) does not require consonantal closure, and a following consonant will thus typically belong to the following syllable (‘‘sa.cred’’).

In addition to phonological considerations, experimental evidence for the membership of medial consonants in the two adjoining syllables has also been provided. The studies of Treiman and Danis (1988) and Treiman and Zukowski (1990), using metalinguistic tasks, have indicated a role of stress in syllabification, in that stressed syllables ‘‘attract’’ consonants. More recently, Pitt et al. (1998) provided further (and arguably on-line) evidence for such consonantal dual membership using a task similar to that of Pallier et al. (1993) and Finney et al. (1996). The possible role of stress, however, was not addressed in their study.

Consider now the relevance of these issues of stress and ambisyllabicity to existing experimental work on the role of syllable in perception. When the fragment monitoring paradigm has been used for English (Allopenna, 1995; Bradley et al., 1993; Cutler et al., 1986; Kearns, 1994), the words used have predominantly borne first syllable stress and have contained a short vowel in their first (and target) syllable (e.g., ‘‘balance,’’ contrasting with ‘‘balcony’’). The ambisyllabicity of the third segment in words like ‘‘balance’’ makes it hard to precisely identify the cause for the lack of clear syllabic effects. Although one interpretation is that the ambisyllabicity of /l/ in ‘‘balance’’ leads to the syllable boundary being unclear, an alternative interpretation is that both ‘‘balance’’ and ‘‘balcony’’ begin with the syllable /bæl/ and there is thus no difference between conditions to produce a syllabic effect. In fact, the overall CVC target advantage found by Bradley et al. (1993), Allopenna (1995), and others in fragment monitoring tasks with first syllable stress words is fully consistent with this interpretation, since all of the words could be viewed as starting with CVC syllables.

Issues of syllabic structure related to ambisyllabicity and stress are also important for interpreting the results with the attentional phoneme monitoring task. Pallier (1994) reported the absence of a syllabic effect with first syllable stress words with short vowels in English. As noted, Finney et al. (1996) found evidence for a syllabic effect when second-syllable stress words were used, but no such effect was found with first-syllable stress words in their Experiment 5. However, the words used in Finney et al. (1996) were evenly split between those that contained short (lax) vowels in their first syllable (i.e., words in which the critical third phoneme is ambisyllabic), and words with long vowels (arguably clearly syllabified). This mix means that there was not a consistent distinction in syllabic structure between the classes of words used.

In summary, syllabic effects have been demonstrated in English with second-syllable stress words (and mixed-stress lists by Pitt et al., 1998) but not with first-syllable stress words. However, it is not yet clear whether the demonstrated difference between first- and second-syllable stress words is due to the stress of the second syllable, or to the effects of ambisyllabicity. In the present article we engage in a more specific investigation of first-syllable stress words, and on the perceptual consequences of ambisyllabicity. The crucial extension is the use of first syllable stress words containing a long vowel in their first syllable; such words arguably have a clear syllable boundary. As in Finney et al. (1996), we used the attentional allocation paradigm of Pallier et al. (1993), as it has proved to be reliable in producing robust syllabic effects without the possible confound of making syllable-level representations explicitly salient to the participants.

The experimental method of the present experiments has been described in detail elsewhere (Pallier et al., 1993; Finney et al., 1996). The underlying rationale is that target phonemes in a phoneme monitoring task should be detected faster when they occur in an expected position, and slower in an unexpected position. If the stimuli are designed such that ‘‘expected position’’ is defined *only* on the basis of syllable structure (with other factors controlled), then facilitated performance in the task will be evidence for the availability of syllabic structure information.

Thus, the following experiments involve phoneme-monitoring with words in which the target phoneme occurs more frequently on a given side of a syllabic boundary.

As an example, consider two words such as ‘‘sector’’ and ‘‘sacred,’’ syllabified /sɛk.tɚ/ and /seɪ.krəd/.[2] The target phoneme /k/ is the third segment in both cases; it occurs in the coda of the CVC.CV__ word ‘‘sector’’ (henceforth a ‘‘coda-type’’ word), but in the onset of the CV.CCV__ word ‘‘sacred’’ (henceforth ‘‘onset-type’’). Lists of such items can be constructed differing in syllabic structure, as determined by the legality of the medial consonant cluster in syllable-initial position, e.g., /kr/ is legal syllable-initially whereas /kt/ is not. If syllabic boundaries are automatically determined in online speech perception and if this information is available for a phoneme monitoring task, then embedding these two target words in a list comprising mostly onset-type items should induce an expectation about the likely position of target phonemes that will result in faster identification of the /k/ in ‘‘sacred’’ than in ‘‘sector’’ and, conversely, if the same two words are embedded in a list of coda-type items, then the /k/ in ‘‘sector’’ will be identified faster. With sets of onset-type and coda-type targets, a statistical interaction results between ‘‘induction type’’ (i.e., the predominant structure in the expectation-inducing word list) and ‘‘target type’’ (i.e., the syllabic structure of the actual target words). A particularly elegant aspect of this design is that response times to the same phonemes in the same items are compared across conditions, and thus any observed effects are attributable solely to the differences between the induction sets and not confounded with any segmental or item-specific properties.

Experiment 1

If ambiguity in syllabification and not stress *per se* is the primary determinant of syllabic effects then we would expect to find syllabic effects using first-syllable stress words with long vowels in their first syllable (i.e., onset-type targets such as ‘‘sacred’’, which are unambiguously syllabified: /seɪ.krɨd/), as such syllables do not require (or, when followed by another syllable, even typically allow) a closing consonant. If, on the other hand, syllabification is only performed before stressed syllables, then first-syllable stress words with unstressed second syllables would not show syllabic effects. The goal of Experiment 1 was to test this prediction by using words with long vowels in their first syllable.

Method

Stimuli. Two lists of CVCCV__ words that were stressed on their first syllable were constructed: One list consisted of *onset-type* words (CV.CCV__) with the medial consonant cluster between the first and the second syllable being a legal syllabic onset (e.g., ‘‘sacred’’). The other list consisted of *coda-type* (CVC.CV__) words with the medial consonant cluster being an illegal syllabic onset (e.g., ‘‘sector’’). The onset and coda terminology derives from the syllabic position of the third segment (/k/), which belongs to the onset of the second syllable in ‘‘sacred’’ but to the coda of the first syllable in ‘‘sector.’’ The vowel of the first syllable was long (tense) in the onset-type words and short (lax) in the coda-type words.[3]

From each list, 16 words with a /b/, /p/, /g/, or /k/ in the third position were designated as *target* items, 16 words were designated *distractor* items, and 50 were *inductor* items. (A full list of the words used is provided in the Appendix.) All words were spoken, in random order, by a male native speaker of American English, recorded onto digital audio tape (DAT), low-pass filtered at 9.8 kHz, and transferred onto a Gateway 2000 PC using 20 kHz sampling rate and 12-bit linear quantization.

The third phoneme of each of the target and inductor items (e.g., /k/ in ''sacred'' and ''sector'') was the target phoneme associated with that item for the phoneme monitoring task. The burst onset of the (stop consonant) target phoneme in each target item was marked in the corresponding audio file using a waveform editor. In cases with no discernible burst the midpoint of the intervocalic silent segment was marked. This mark served to measure the beginning of the response time (RT) to the target phoneme. For each distractor item, a phoneme not occurring in it was selected as the target phoneme (e.g., /r/ in ''weekly'' and ''jetsam'').

Two experimental lists were constructed. Each contained all 32 target and 32 distractor items plus the fifty inductor items of either onset or coda type, for a total of 114 items in each experimental list. Thus, in each list, 82 of the items (72%) were of the predominant syllabic structure (onset-type or coda-type) . The list with the onset-type inductor items (with target phonemes in the onset of their second syllable) was used for the *onset induction condition* and the list with the coda-type items (with target phonemes in the coda of their first syllable) was used for the *coda induction condition.* The order of the items within each list was semi-random, but the same for all participants, under the following constraints (following Pallier et al., 1993): no target item occurred in the first eight trials, and each target item was immediately preceded by at least one inductor trial.

Procedure. Participants were tested one at a time, seated in front of a monitor screen and a response box with two buttons, one labeled ‘‘Y’’ (at the participant’s preferred hand side) and the other ‘‘N.’’ Each trial was initiated with the 500 ms visual display of a capital letter symbolizing the target phoneme for the trial. Orthography was specifically dissociated from the task through explicit instructions to ‘‘think of the sound usually represented by the letter’’ and using examples such as ‘‘‘K’ as in ‘wreckage’ and ‘vector’ and ‘F’ as in ‘telephone’.’’ A 500 ms silent interval followed the target presentation, and a word was then played over the headphones at approximately 78 dB SPL. The participants were instructed to respond as fast as possible, by pressing Y(es) if the target ‘‘sound’’ occurred in the word or N(o) if it did not. The next trial followed 2.5 s after the participant’s response, with a 4-s response collection time window. Response times (RTs) were automatically recorded, measured from the digitally placed marks at the targets, described above, to the time of the button push.

Participants. Forty six members of the Brown University community, all native speakers of American English, were recruited through postings at University bulletin boards and were paid for their participation in this experiment. In this and the next experiment participants were recruited until there were twenty in each induction condition who made less than 15% errors on targets and distractors combined (less than 10 incorrect responses in 64 trials) and whose mean response time to target items did not exceed 1000 ms. Each person participated in only one experiment.

Results and Discussion

Data from 6 participants who violated the above criteria were discarded. Of the data from the remaining forty participants (twenty in each induction condition) incorrect responses (4.14%) and response times more than 2.58 standard deviations from the participant mean (2.19%) were not considered in the analyses of variance. Table 1 shows the mean response times and corresponding standard deviations as well as the error rates for each combination of induction condition and target type.

Insert Table 1 about here

Two-way analyses of variance (2 induction conditions $\times$ 2 target types) were performed separately with participants and with items as the random factor (reported throughout as F_1 and F_2, respectively). In this and all following analyses, results are considered statistically significant if both participants and items analyses yielded a p value of 0.05 or less.

In the error analysis there were no statistically significant effects (for both main effects, F_1 and $F_2 < 1$; for the interaction, $F_1(1,38)=2.54$, $p=0.120$ and $F_2(1,30)=1.789$, $p=0.191$). In the response time (RT) analysis, the 81 ms main effect of induction condition was significant by items only ($F_1(1,38)<1$; $F_2(1,30)=32.47$, $p<0.0005$), whereas the 14 ms main effect of target type was not significant in either analysis (F_1, $F_2 < 1$). The 62 ms interaction[4] between induction condition and target type, however, was significant both by participants and by items ($F_1(1,38)=4.74$, $p=0.036$; $F_2(1,30)=4.17$, $p=0.050$), in agreement with a syllabic hypothesis.

Because of the importance of this result and the relative weakness of the syllabic effect compared to those reported in Finney et al. (1996), we repeated this experiment with twenty new participants, and with a slightly altered stimulus set (5 coda-type items with deviant RT difference between the induction conditions were replaced by new words of similar structure; see list in Appendix). The findings confirmed those of Experiment 1: The RT interaction (105 ms) between induction type and target type was again significant ($F_1(1,18)=5.42$, $p=0.032$; $F_2(1,30)=7.04$, $p=0.013$). We are therefore confident in the reliability of this syllabic effect.

In addition, we verified the lack of a syllabic effect for first-syllable stress words with short vowels in their first syllable by replacing all onset-type words (targets, inductors, and distractors) with short-vowel words (such as ‘‘fabric’’ and ‘‘macro’’) and testing forty new participants. As expected based on Finney et al. and the preceding discussion on ambisyllabicity, the RT interaction (30 ms) between induction type and target type was not significant ($F_1(1,38)=1.53$, $p=0.22$; $F_2(1,30)=5.51$, $p=0.026$).

However, it remains to address the confound of syllabic structure with vowel type that was unavoidable in the present materials before being confident in the existence of syllabic segmentation in first syllable stress words. One possible test would be using nonword stimuli because nonwords can be matched on arbitrary criteria and they have already been used successfully with the present experimental methodology (Experiment 4 of Finney et al., 1996). For the present purposes one could create phonetically matched onset-type and coda-type first-syllable stress peudowords with a long vowel in their first syllable, such as, for example, /heɪkrəd/ (substituting /h/ for /s/ in ‘‘sacred’’) and /heɪktɚ/ (borrowing the second syllable from ‘‘sector’’). Unfortunately, there are structural constraints that restrict nonword formation of the desired form. Specifically, such long-vowel coda-type pseudowords violate a generalization of English phonology that forbids long vowels in closed nonfinal syllables (Myers, 1987, see footnote 3). The near-absence of such words in the English lexicon (and thus in listeners’ experience of the language) may lead to difficulty in processing the pseudowords of this structure, inasmuch as participants may have an expectation that no long-vowel initial syllable would have a coda. Indeed, this may well be the case in that a pilot experiment designed to test this possibility failed to produce an effect of either syllabic structure or vowel type. Therefore, in Experiment 2 we opted for removing the confound by matching the inductor items among the induction conditions instead. In addition, the test for syllabic structure induction was made more stringent by using inductor items mismatched in stress with the target items.

Experiment 2

In Experiment 1, as well as those in Finney et al. (1996), inductors and targets were always matched in stress. It is of additional interest to models of speech processing to determine whether the syllabic representation used is directly dependent on stress, or is of a more general or abstract form. That is, are syllables containing stressed and unstressed vowels of the same syllabic structure, that is to say, represented in the same manner? The interaction of syllabification with stress (e.g., in the phenomenon of ambisyllabicity) suggests that perhaps they are not. In addition, if the syllabic representations involved in online speech processing are formed at an early (''low'') level, stressed vowels may be represented in distinct groups from unstressed vowels on the basis of acoustic/phonetic differences associated with stress. To address this question, Experiment 2 used second-syllable stress inductors and first-syllable stress target words. If a significant syllabic interaction is obtained in spite of the different stress patterns, this would be consistent with the view that the syllabic representations that are activated are stress-independent and removed from immediate acoustic/phonetic representations.

Consider, for example, the second-syllable stress words ''sublime'' and ''subdue,'' (syllabified /sə.blaɪm/ and /səb.du/, respectively), where the target /b/ unambiguously occurs in a syllabic onset in ''sublime'' and in a syllabic coda in ''subdue.'' If an expectation of this syllabic position for the target is formed during repeated presentation of items of one of these structures, it should be possible to observe differential effects in response times to target phonemes in unambiguously syllabified first-syllable stress words such as ''sacred'' and ''sector,'' in each of which the target phoneme /k/ also occurs in an unambiguous syllabic position: in the onset of the second syllable in ''sacred'' (matching the position of /b/ in ''sublime'') and in the coda of the first syllable in ''sector'' (likewise matching the position of /b/ in ''subdue'').

Furthermore, and of critical importance to the interpretation of

Experiment 1, if the inductors do not consistently match the targets of their corresponding syllabic structure in vowel type then the confound between syllabic structure and vowel type is removed. That is, if the syllabic effect occurs with mismatched vowels then it cannot be a vowel-derived effect. Therefore, if a significant syllabic effect is found it would invalidate the interpretation that the confound of vowel type and not syllabic structure led to the significant RT interaction in Experiment 1.

In the present experiment we used the second-syllable stress inductor words of onset and coda type, taken from Experiment 1 of Finney et al. (1996), and the first-syllable stress target words from Experiment 1 above. If the syllabic position (regardless of stress) of the target phonemes in the inductors is the main factor driving syllabic effects, we would expect to observe an interaction between target type and inductor type similar to that in Experiment 1 and in the experiments of Finney et al. (1996), in spite of the mismatch in stress position.

Method

Stimuli. The (second-syllable stress) inductor words and half the distractor words from Experiment 1 of Finney et al. (1996) replaced the inductors and corresponding distractors of Experiment 1. All but five of the target words and all remaining distractor words were unchanged. Target phonemes occurred in the third serial position within each target item. The full list of second-syllable stress inductor and distractor items can be found in the Appendix.

Participants and Procedure. Forty six new participants were recruited from the same population and were paid for their participation. The procedure was the same as in Experiment 1.

Results and Discussion

Data from 6 participants who violated the performance criteria given in Experiment 1 were discarded. Of the data from the remaining forty participants (twenty in each induction condition) incorrect responses (6.09%) and response times more than 2.58 standard deviations from the participant mean (2.75%) were not considered in the analyses of variance. Table 2 shows the mean response times and corresponding standard deviations as well as the error rates for each combination of induction condition and target type.

Insert Table 2 about here

Two-way analyses of variance (2 induction conditions $\times$ 2 target types) were conducted separately on the error rate and the response time data. In the error analysis there was a significant main effect of induction condition ($F_1(1,38)=7.73$, $p=0.008$; $F_2(1,30)=9.02$, $p=0.005$) but no main effect of target type (F_1 and $F_2 < 1$). The interaction of the two factors approached significance in the expected direction ($F_1(1,38)=4.01$, $p=0.052$; $F_2(1,30)=2.95$, $p=0.096$). In the RT analysis there was no significant main effect of induction condition or target type (F_1, $F_2 < 1$), but there was a highly significant 68 ms interaction of the two factors ($F_1(1,38)=9.56$, $p=0.004$; $F_2(1,30)=11.39$, $p=0.002$).

The results of this experiment support the syllabic hypothesis, given that a reliable effect was obtained in spite of the stress mismatch between inductors and targets. This finding indicates that the syllabic representation derived in the course of online speech processing is not itself characterized or identified by stress, but is of a somewhat more abstract form; this topic is considered further in the following discussion. Importantly, there was no confound of vowel type with syllabic structure in this experiment when the same target items were used as in Experiment 1. The observed statistical interaction between target type and induction can thus be taken as support for the interpetation that it was syllabic structure and not vowel type that caused the significant effect obtained in Experiment 1.

General Discussion

In the preceding experiments, we have obtained evidence that syllabic boundaries and knowledge of the components of syllables are automatically available during online speech processing, corroborating the claims made by Finney et al. (1996) and Allopenna (1995), and in agreement with more recent findings by Pitt et al. (1998). Importantly, in our experiments all target items were stressed on their initial syllable, in contrast to those used by Pitt et al. (1998). Thus, this is the first clear-cut demonstration that first-syllable stress words are syllabified online as are second-syllable stress words. Our findings stand in stark contrast to the assertion of Cutler (1997) that ‘‘phoneme detection attention cannot be allocated to the internal syllable boundary in an initially stressed word’’ and therefore it is our impression that a change of verdict is now empirically warranted. The findings are also consistent with the hypothesis that differences in syllabification are conditioned by stress only indirectly, i.e., via syllable availability constraints leading to ambisyllabicity.

In Experiment 1 we used long-vowel onset-type words, which begin with an unambiguous CV syllable (such as ‘‘sacred,’’ syllabified /seɪ.krɨd/), and contrasted those with short-vowel coda-type words (e.g., ‘‘sector,’’ syllabified /sɛk.tɚ/). In agreement with the hypothesis of online syllabic representations, we obtained a reliable syllabic interaction. In Experiment 2 we demonstrated that syllabic representations are not critically dependent on stress. We obtained a significant syllabic effect using second-syllable stress inductor words and the first-syllable stress target words of Experiment 1. Moreover, because in Experiment 2 the inductor items no longer matched consistently the corresponding target items in vowel type (long vs. short), as they did in Experiment 1, it was concluded that the significant interaction obtained in Experiment 1 was due to syllable structure rather than to a confound of vowel type.

On the nature of syllabic representations

The exact processes and representations involved in the observed syllabic effects remain to be determined. One possibility is that the effects are due to consequences of particular phonetic feature patterns that result from surface similarities between utterances previously encountered. Donselaar and Stoutjesdijk (1994) claimed that ‘‘syllabic’’ findings using the fragment monitoring paradigm of Mehler et al. (1981) could be explained as resulting from such superficial phonetic matching because of coarticulatory differences between open and closed syllables. It is necessarily true that syllabic representations must derive, at least initially and to some extent in the mature speaker, from acoustic/phonetic representations of the speech input. It is also true that the design of most fragment monitoring experiments covary syllable-related coarticulation with syllabic structure and thus non-structural phonetic matches could affect their results (given the task of matching a given syllable-like target to subsequent speech input). In our experiments, however, in which response times are measured to the same phonemes in the same words (but in different induction conditions), such criticisms do not apply. Instead, it appears that our findings are due to structural properties of speech best described on a syllabic level that is determined at least in part by somewhat abstract phonetic information. In agreement with this interpretation, Pitt et al. (1998, Experiment 3) also provided direct evidence to the effect that ‘‘low-level’’ acoustic/phonetic match alone cannot account for the robust syllabic findings using this paradigm.

As noted in the introduction, the articulatory regularity in speech production which supports the existence of syllabic structure would be expected to result in a mirroring regularity on the perceptual side, that is, in perceptual representation of syllabic structure of a phonetic nature. This representation encodes the structural regularities of a language’s syllables and may be actively involved in imposing language-specific organization on the (often poorly heard) speech stream. That is, consistent with the current phonological notion of the syllable as a ‘‘licensing structure’’ (Goldsmith, 1990, p. 104), we view the syllabic level of representation in speech perception as a set of ‘‘frames’’ or ''templates'' that may only admit certain combinations of phonetic features (which do not violate the language-specific syllabic constraints) and thereby aid in the clarification of the incoming phonetic input by filling in missing information while filtering out or modifying extraneous information (cf. Pallier, 1994, p. 149).

In this context, the recent study of Dupoux, Kakehi, Hirose, Pallier, and Mehler (1999) is illuminating: They found that Japanese, but not French, listeners, tended to perceive an illusory epenthetic vowel inside consonant clusters that were illegal by Japanese phonotactics, thus misperceiving the acoustic stream according to canonical native syllabification. Regardless of the precise form a syllabic constraint might take, it is clear that syllabic structure must be taken into account in theoretical treatments of speech perception. The epenthetic vowel effect appeared with nonword stimuli, as have syllabic effects using the attentional allocation paradigm. Therefore the processing level on which such a constraint might operate must be below the lexical level. It is likely, however, that lexical knowledge modulates syllabic effects. For example, in Spanish, a strongly syllable-timed language, the fragment monitoring paradigm has produced syllabic effects for words only when RTs are long (Sebastián-Gallés, Dupoux, Seguí, & Mehler, 1992) and neither an expected RT effect nor an event related potential (ERP) effect for nonwords (Vigil-Colet, Pérez-Ollé, & García-Albea, 1998).

In addition, as mentioned in the discussion of Experiment 1, a syllabification which does not occur in the lexicon failed to lead to reliable syllabic effects. This finding suggests that the nature of the hypothesized syllabic representation is a direct result of learning the structure of a language through lexical acquisition. In the words of Kessler and Treiman (1997) with respect to subsyllabic structural asymmetries, the learning implied here may be consist in ‘‘adaptations to preexisting patterns in the vocabulary, patterns that may have their origin in the physical facts of articulation and acoustics’’ (p. 309). From a developmental point of view, such a statistical generalization process might resemble the one demonstrated by Saffran, Aslin, and Newport (1996), who showed that infants rapidly learn to respond to frequently co-occurring patterns in the acoustic stream and treat such patterns as units. A further process is necessary to produce the more abstract representation of syllable which is consistent with the lexicon yet still fundamentally specified on a phonetic level.

Lexical access and metrical segmentation

The finding that syllabification occurs automatically during online speech processing has important implications for models of lexical access in that syllabic boundaries can be used as potential word boundaries to initiate lexical searches. It has long been postulated that some process of prelexical segmentation makes likely points in the speech stream available to the lexical processor for matching against the stored lexicon. Cutler and Norris (1988) proposed that syllabic boundaries preceding strong syllables (i.e., syllables containing a full, as opposed to reduced, vowel) may provide ‘‘the most efficient starting points for lexical access attempts.’’ Evidence for such a segmentation strategy was initially obtained using a word-spotting paradigm, in which participants were found to identify words (such as ‘‘mint’’) in spoken contexts when they were followed by a short-vowel syllable (such as [mɪntəf]) faster than when they continued with a long-vowel syllable (such as [mɪnteɪf]). Cutler and Norris (1988) argued that the source of this effect was that the strong vowel in the syllable following the word to be identified triggered segmentation of the utterance at a point before the offset of the target word (i.e., before the /t/), thus delaying its identification. McQueen, Norris, and Cutler (1994) and Norris, McQueen, and Cutler (1995) have since elaborated these claims and supported them with further experiments and modeling.

How do our findings bear on the claims of the MSS? Because the design of our experiments included a stress factor but did not distinguish between strong and weak following (second) syllables, only a *post-hoc* comparison is possible. In Experiment 2, in which all inductor words were stressed on their second syllable and all target words were stressed on their first syllable, we may examine the induced syllabic effect separately for the target items with a strong second syllable, such as ''migraine'' (termed *SS*, for strong-strong) and for the target items with a weak second syllable, such as ''sacred'' (termed *SW*, for strong-weak).

To this end, we performed two additional ANOVAs on the data of Experiment 2, using only a subset of the items in each. One RT analysis only included the 11 SS items and the interaction between induction condition and target type was significant ($F_1(1,38)=31.61$, $p<0.0005$; $F_2(1,9)=13.65$, $p=0.005$). An analysis including only the 21 SW items, however, failed to produce a significant interaction ($F_1(1,38)=1.18$, $p=0.284$; $F_2(1,19)=2.60$, $p=0.123$). The corresponding analysis of the Experiment 1 data (which is less clean because inductor items also vary in the strong/weak vowel dimension) resulted in a similar pattern of findings: An RT analysis for the 11 SS items produced a marginally significant interaction effect (F_1(1,38)=3.84, p=0.057; F_2(1,9)=4.04, p=0.075), whereas in the analysis of the data from the 21 SW items the interaction was not significant (F_1(1,38)=1.74, p=0.196; F_2(1,19)=1.36, p=0.252). Given the statistically significant interaction in Experiment 1 with all items combined, it appears that error variance may have been too great to allow sufficient power for such segregated analyses.

Thus, in order to increase the power of this *post-hoc* test, we combined the data from both experiments for the 26 common items (9 SS and 17 SW), thus reducing item variance by averaging over more subjects, and analyzed by syllable strength introducing ''experiment'' as an additional within-item factor. This analysis produced a significant interaction both for SS items (F_1(1,76)=19.30, $p<0.0005$; F_2(1,7)=19.16, p=0.003) and for SW items (F_1(1,76)=12.314, p=0.001; F_2(1,15)=25.86, $p<0.0005$). In addition, the three-way interaction between second syllable strength, induction condition, and target type was not significant in either experiment or in the combined analysis. However, the power for detecting a significant three-way interaction was very low and it is still possible, especially in view of the separate analyses for each experiment, that the critical interaction (of induction condition by target type) does in fact differ between SS and SW items.

In conclusion, it appears that syllabic segmentation occurs at syllable boundaries preceding either strong or weak syllables. Even though there is some indication that segmentation at strong syllable onset boundaries is more robust, in agreement with the MSS, the MSS would not predict the evidenced syllabification preceding weak syllables. Moreover, the MSS still needs elaboration in terms of the precise processes involved, specified in terms of acoustic features in the speech stream and mental representations (possibly including syllabic representations that permit ambisyllabic segments). For example, once a triggering strong vowel is located (presumably by acoustic analysis), how is the actual word segmentation point, i.e., the syllable onset, identified? Our studies on the role of the syllable suggest that a representational level organized around the syllable is present in prelexical processing even in English, a stress-timed language commonly thought to involve no prelexical perceptual syllabic representations. Such a representation, while itself not necessarily directly involved in lexical segmentation, may serve to illuminate certain missing critical elements of segmentation-specific language-dependent strategies such as the MSS.

Possible sources for the observed differences in segmentation preceding strong vs. weak syllables might be the relative acoustic clarity (greater amplitude and duration; Lieberman, 1960) and intelligibility of stressed (hence unreduced) vowels (McAllister, 1991), their higher informational content (perhaps because of greater vowel differentiation; Altman & Carter, 1989), and the higher frequency with which they are found at the initial syllables of content words (Cutler & Carter, 1987). Any or all of these factors may combine to produce an observable difference in the nature of the initial activation between classes of lexical instances differing in their initial syllable (viz. strong vs. weak).

It is possible that listeners use a kind of Metrical Segmentation Strategy, be it acoustically or statistically motivated, in addition to the general syllabic segmentationroutine. Evidence for one strategy being more prominent than the other would depend on such factors as those noted above as well as task demands. For example, in the case where syllabic boundaries are preceded by stressed syllables with unreduced vowels, the MSS would be fully operative in addition to the general routine. Therefore evidence for prelexical syllabic processing would be highly robust, as in the present studies. In contrast, when the second syllable is unstressed and the vowel reduced, the syllabic boundary preceding this syllable would be less well indicated and less robustly evidenced. In that case, the Metrical Segmentation Strategy would not be operative and stimulus factors would limit the effectiveness of a general syllabic segmental strategy.

In sum, the present studies, in conjunction with those of Finney et al. (1996) and Pitt et al. (1998), serve to inform investigations of prelexical processing by establishing that syllabic boundaries are automatically available including boundaries preceding both stressed and unstressed syllables. The allocation of attention to syllabic boundaries has been shown to operate without regard to two variables known to strongly affect syllabification, namely, lexical stress and vowel quality. The results are consistent with a universal role for abstract syllabic structure in perception.

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Appendix

Stimulus Lists

In all of the stimulus lists, the letter(s) corresponding to the phoneme which is the target for monitoring is capitalized within the word; targets for distractors are listed in parentheses following the word.

Experiment 1

Onset-type targets: hyBrid, coBra, viBraphone, caBling, cyPress, duPlex, biPlane, rePlay, miGraine, miGrant, reGress, vaGrancy, cyClist, saCred, miCron, seCret.

Onset-type distractors: cyclase (B), vibrate (K), rubric (M), libra (F), sucrose (D), weekly (R), secrecy (P), cyclamate (B), microfilm (P), seagrass (T), hydrant (S), patron (G), hatred (P), retread (G), toaster (N), yeasty (K).

Onset-type inductors: hyDrate, viBrant, paTriarch, miCrobe, luBricate, tiGress, duPlicate, reFresh, heBrew, riPely, cuProus, biGram, feeBly, seaPlane, miGrate, neuTral, nuTrient, hyBridize, feBrile, niTrogen, liBrary, hyDrogen, highBrow, diGraph, keyStone, cyClone, vaGrant, waiTress, niTric, fiBrous, reFlex, nuCleus, miCroscope, cyClotron, cyClic, luCrative, doBro, maTrix, coaSter, hayStack, cheaPly, maCron, luBricant, nuClear, zeBra, miCrophone, shaPely, paTriot, deePly, rePrint.

Coda-type targets: seCtor, caPtain, coGnitive, suBject, faCtion, ruPture, huBcap, giBson, taCtile, piGment, doGma, gyPsy, baPtize, doCtor, suBterfuge, maGnet.

(In the replication mentioned in the discussion of Experiment 1, the

coda-type targets listed in Experiment 2 below were used instead.)

Coda-type distractors: magnum (B), tactics (N), hobnob (G), capsicum (L), sultan (K), mandate (P), jetsam (R), tamper (S), journal (T), morbid (K), lecture (P), halter (G), victor (M), signature (D), sigmoid (B), tipsy (K).

Coda-type inductors: maGma, keRnel, caNdid, boxer (K), moLten, liTmus, seCtion, fiLter, suBsidy, gyPsum, leNtil, seGmenT, diCtate, jaRgon, fiGment, seNtence, nePtune, tuRbine, peCtine, diGnity, pyGmy, caPsize, syMbol, siGma, siGnal, kiDney, chuTney, hyPnotize, siGnet, buMper, veCtor, voDka, maRgin, faCtor, vuLgar, raNdom, kiDnap, liGnite, haPtic, phaNtom, naPkin, suBset, raPtur, rhaPsody, puNdit, jiTney, ruGby, raMpant, poMpous, teMper.

Experiment 2

Onset-type targets as in Experiment 1.

Onset-type distractors: (*second syllable stress*) distort (B), distinct (P), distiller (B), reprieve (N), bedraggled (S), betrayal (G), nutritious (P), patrician (K), repress (F); (*first syllable stress*) vibrate (L), libra (K), sucrose (D), hydrant (G), hatred (M), retread (G), toaster (P), cyclase (N).

Onset-type inductors: deBrief, liBretto, viBrato, noBlesse, douBloon, luBricious, suPreme, caPrice, dePletion, rePly, dePraved, diPloma, dePlore, reProve, beGrudge, deGrade, deGree, diGression, miGration, reGroup, poGrom, seCretion, deCrease, deCline, reCruitment, reClaim, reDress, hyDraulic, beTray, beTrothed, reTreat, nuTrition, neuTrino, reStore, reSponse, diScuss, diSpute, diSperse, deSpise, caScade, reSpect, moSquito, geStation, reFrain, deFlate, deFraud, beFriend, nePHritis, deFlect, diFfract.

Coda-type targets: haCKney, caPtain, coGnitive, suBject, faCtion, ruPture, huBcap, hoBnail, leCture, piGment, doGma, caPture, baPtize, diCtion, suBterfuge, maGnet.

Coda-type inductors: suBmit, suBserve, suBtend, suBvert, suBside, suBject, sePtette, haPhazard, sePtillion, rhaPsodic, maGnesia, doGmatic, teCtonic, fiCtitious, suCceed, faCtitious, suCcess, daCtylic, maLformed, maLfunction, daLmation, paRtition, foRbid, peRfume, peRmit, feRment, peRcent, geRmane, foRsake, caRtoon, peRform, miSgive, diSjoint, diSrupt, miSvalue, miStake, coMbust, syMphonic, coMpound, syMbolic, coMbine, shaMpoo, laMpoon, coNvict, caNteen, coNsume, syNthetic, faNtastic, coNjoin, coNduct.

Coda-type distractors: (*second syllable stress*) concoct (P), cantata (R), cosmetic (L), fortell (K), sulfuric (G), harpoon (G), bamboo (R); (*first syllable stress*) hobnob (K), magnum (B), tactics (M), sultan (G), mandate (S), capsicum (R), tamper (S), halter (P).

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Footnotes

[1]Stressed syllables in English are obligatorily ‘‘heavy.’’ A common conceptualization of heavy syllables is a multi-segment rime, which can be realized either with a coda (of one or more consonants) following a short vowel or with a long (tense) vowel, which may occupy two slots in the syllabic frame (Clements & Keyser, 1983). In the cases of stressed open syllables with a short vowel (such as /fæ/ in ‘‘fabric’’) the consonant (/b/) following the short vowel (/æ/) attaches itself to the stressed syllable and forms its coda in order to complete a well-formed (i.e., heavy) syllable (/fæb/).

[2] Syllabifications in this article were initially based on the intuition of the authors and other native informators and verified with the help of a dictionary (Webster’s II New Riverside University Dictionary, 1984). Segments are claimed to be ambisyllabic in agreement with Anderson and Jones (1974) and Kahn (1980), and consistent with the findings of Treiman and Zukowski (1990, Experiment 5).

[3] Unfortunately, although there are many long-vowel onset-type words such as ‘‘sacred,’’ there are very few long-vowel coda-type words in English (‘‘beatnik’’ is a rare exception) and most of them are multimorphemic. Therefore, it was not possible to design an experiment with the items of the two types differing in syllabification only and not in vowel type as well. In Experiment 1 we chose to use long-vowel onset-type words (e.g., ‘‘sacred’’) and short-vowel coda-type words (e.g., ‘‘sector’’), all of which have an unambiguous syllabic structure. If induction effects are obtained, however, this may be due to the confound of vowel type with syllable, and would necessitate a control experiment for

this possibility, as exemplified by Experiment 2.

[4]The size of an interaction effect is computed as the difference of the differences between cells and is thus unaffected by main effects (so no baseline condition is necessary to argue for a syllabic effect; cf. Protopapas, Finney, & Eimas, 1999). In this case, (701-589)-(656-606)=62.

Table 1

Mean Response Times (SDs) in Milliseconds and Error Rates in Percent as a Function of Induction Condition and Target Type in Experiment 1.

	Target Type	
Induction Condition	Onset	Coda
Onset	656 (277)	701 (290)
	3.8	4.4
Coda	606 (305)	589 (277)
	5.3	3.1

Table 2

Mean Response Times (SDs) in Milliseconds and Error Rates in Percent as a Function of Induction Condition and Target Type in Experiment 2.

	Target Type	
Induction Condition	Onset	Coda
Onset	457 (96)	491 (108)
	6.6	10.0
Coda	484 (152)	450 (170)
	4.7	3.1