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Vowel Aperture and Syllable Segmentation in French

Jeremy Goslin\textsuperscript{1}, Ulrich H. Frauenfelder\textsuperscript{2}

\textsuperscript{1} School of Psychology, University of Plymouth, UK
\textsuperscript{2} Laboratoire de psycholinguistique expérimentale, Université de Genève, Switzerland

Abstract

The theories of Pulgram (1970) suggest that if the vowel of a French syllable is open then it will induce syllable segmentation responses that result in the syllable being closed, and vice versa. After the empirical verification that our target French-speaking population was capable of distinguishing between mid-vowel aperture, we examined the relationship between vowel and syllable aperture in two segmentation experiments. Initial findings from a metalinguistic repetition task supported the hypothesis, revealing significant segmentation differences due to vowel aperture across a range of bi-syllabic stimuli. These findings were also supported in an additional online experiment, in which a fragment detection task revealed a syllabic cross-over interaction due to vowel aperture. Evidence from these experiments suggest that multiple, independent cues are used in French syllable segmentation, including vowel aperture.

Key words

aperture
segmentation
syllabification
syllable
vowel

1 Vowel aperture and syllable segmentation in French

A perennial problem in the study of speech perception and word recognition is that of segmentation. How is the continuous speech signal mapped onto the mental lexicon, is segmentation involved, and if so, what is the segment? The popularity of one favored segmentation unit, the syllable, has enjoyed mixed fortunes over the past few decades, peaking with the study of Mehler, Dommergues, Frauenfelder, and Segui in 1981. In this study a sequence monitoring task revealed that the detection latencies of word fragments were faster when they matched the syllabic structure of matching carriers. The resulting cross-over interaction, known as the syllable effect, provided new and convincing evidence for the role of the syllable in pre-lexical segmentation and classification.

However, follow-up studies revealed that the syllable effect was language specific and could not be replicated with native English speakers when presented with either French or English stimuli (Cutler, Mehler, Norris, & Segui, 1986). This failure was attributed to...
the use of language-specific processing, with French speakers using the syllable because of the clear boundaries found in French, unlike English. The waters were muddied still further when studies of Spanish and Catalan, both having clear syllabic structure, found syllable effects only in certain restricted conditions (Sebastián-Gallés, Dupoux, Segui, & Mehler, 1992). These results supported a dual coding mechanism proposed by Dupoux (1993), in which listeners are capable of responding using either syllabic or sub-syllabic representations. Recently the significance of the original syllable effect in French was challenged in a study by Content, Meunier, Kearns, and Frauenefelder (2001). In this study the fragment detection task was repeated with an extended range of target/carrier pairs, using fricative and stop pivotal consonants in addition to the liquid pivotal consonants used in the original study. They found that the syllable effect interaction could only be replicated with the type of stimuli used in the original study. With these findings it was concluded that the narrow conditions required to reproduce syllable effect were not consistent with a syllabic pre-lexical classification unit.

As can be seen at the current time the role of the syllable, even in French, remains a matter of considerable debate. Another aspect of the syllable which is of considerable conjecture, and is a key component in its projected role in speech perception, is its definition. One of the prerequisites for the perceptual role of the syllable is that it should possess a clear and unambiguous structure with well-defined segmentation behavior. In our previous study of syllabification in French (Goslin & Frauenfelder, 2001) we compared empirical segmentation behavior with the predictions of a wide range of syllable segmentation models. Some of these models are based upon analyses of phonotactic regularities, using principles of syllabic legality (e.g., Hooper, 1972; Kahn, 1976; Pulgram, 1970; Vennemann, 1988), others upon the sonority scale (e.g., Clements, 1990; de Saussure, 1916). While there are considerable philosophical and practical differences among syllabification theories and the various instantiated segmentation models, they all share a fundamental tenet, that syllabification decisions are based upon intervocalic consonantal structure. Although the optimum segmentation model, that of Laporte (1993), was found to predict the preferential segmentation responses of our participants, it was unable to account for all of the variability found in segmentation responses (between 5–37% of responses, dependent upon the consonant cluster). Therefore it would appear that phonological information on the intervocalic consonant cluster/singleton is insufficient for the prediction of a substantial proportion of segmentation responses. Is it possible that participants were deriving syllabification cues from another source of information, the only universal feature of all syllables, the nucleus?

In studies of English phonology it has long been suggested that the distribution of long and short vowels is related to syllable structure (e.g., Barnwell, 1970; Church, 1983; Pulgram, 1970; Umeda, 1975) with short, also known as lax, vowels only to be found in closed syllables. For example this would predict different segmentation for the word “recall” depending on the length of the first vowel, segmented as “rec. all” when produced with the short vowel [e] and “re.call” with the long vowel [i].

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1 Laporte (1993) favored minimal legal syllable onsets with OBLI (OBstruent-LIquid) clusters treated as indivisible units.

2 Syllable aperture relates to the presence or absence of a syllable coda. Open syllables have no coda, while closed syllables have one or more segments in their coda.
Empirical evidence was found to support the theoretical relationship between vowel length and syllable aperture (the opposition between open and closed syllables) in a psycholinguistic study of the syllabification of intervocalic consonants (Treiman & Danis, 1988). In this study, oral syllable reversal and written tasks were used to elicit syllable boundary decisions for bi-syllabic words with short and long first vowels. The authors found that listener’s segmentation decisions were affected by vowel length, supporting theoretical predictions, but were cautious in drawing conclusions from these findings due to the possibility that responses were colored by production constraints. A similar relationship between vowel length and syllabic structure in Dutch was investigated in a study by Zwitserlood, Schriefers, Lahiri, and van Donselaar (1993) using a syllable monitoring task. They found significant segmentation effects due to vowel length in both clear and ambiguous syllabic environments. In this study, segmentation “ambiguity” was the result of disparate segmentation cues provided by vowel length and the consonant cluster resulting in an “ambi-syllabic” segment.

While there is no vowel length distinction in standard French, Pulgram (1970) suggests that the distinction in vowel aperture for French may play a similar role in syllabification as vowel length in English. It is suggested that there is an ongoing process of neutralization for the six mid-vowels (/o, õ, e, œ, ø, œ/) in such a way that they are grouped into three pairs of phonetically neighboring open and close types (/o/ /o/, /õ/ /õ/, and /e/ /e/), with open vowels (/o, õ, e/) regularly occurring in non-final, and close ones (/ø, e, œ/) in final position. In southern French this neutralization is already evident, losing the contrastive distinction between open and close variants of the three mid-vowel types (/o/ /o/, /õ/ /õ/, and /e/ /e/). In this accent only three mid-vowels remain (/o, /õ/, and /e/), leaving a purely phonetic relationship between vowel and syllable aperture, with open mid-vowels generally produced in closed syllables and close mid-vowels in open syllables (Durand, 1990).

In “standard,” that is Parisian French, all three of the mid-vowel types (/o/ /o/, /õ/ /õ/, and /e/ /e/) still remain contrastive; however, the relationship between vowel and syllable aperture for each of the types is not uniformly valid (Tranel, 1988). In word-final syllables both /e/ and /õ/ play a distinctive role in open syllables (e.g., fée – /fe/ & fait – /fõ/, “fairy” & “done”), but in closed syllables there is a neutralization of the pair, and only the open vowel /e/ is permitted (e.g., belle – /bõl/, “beautiful”). In the /o/ /e/ and /õ/ /õ/ types there is neutralization in open syllables, restricting these types to the close vowels /o/ (e.g., feu – /fõ/, “fire”) and /õ/ (e.g., gros – /gro/, “fat”), while in closed syllables open and close vowels generally play a distinctive role (e.g., haute – /ot/ & hotte – /õt/, “high” & “basket”; beugle – /bõgl/ & aveugle – /avõgl/, “bellows” & “blind”). In non-final syllables, these rules are subject to much greater variability, with the pattern of rules for vowel neutralization seen in word-final syllables reducing to tendency. For example, a search of the French words from the Lexique lexicon (New, Pallier, Ferrand, & Matos, 2001) revealed that in open non-final syllables the occurrence of /õ/ was 5.35 times more likely than /e/. In closed non-final syllables, with a tendency towards the neutralization of /e/, the vowel /õ/ was 23.35 times more likely than /e/.

3 Vowel aperture (open/close) is defined in APA style.
The theories of Pulgram (1970) suggest that French vowel aperture may provide a syllable segmentation cue that is independent of cues arising from consonantal structure, similar to that seen with vowel length in English (Treiman & Danis, 1988) and Dutch (Zwitserlood et al., 1993). However, as yet no psycholinguistic study has investigated the possibility that, when vowel aperture plays a distinctive linguistic role, there may be a perceptual relationship between vowel and syllable aperture, with the aperture of the vowel having a direct influence over that of the syllable. Therefore, the main aim of this study is an investigation of the general hypothesis that close vowels induce open syllables, and open vowels induce closed syllables. Our examination of this hypothesis is focused upon two syllable segmentation experiments, each designed to examine different aspects of the possible role of vowel aperture in syllable segmentation. In the first experiment we sought to quantify the scope and impact of this potential cue by examining its influence upon the segmentation of non-final syllables in a metalinguistic task. These findings were then followed up by a re-examination of the “syllable effect” to ascertain the possible role of vowel aperture in the perception of syllables using an online paradigm.

In both of these experiments we tested listeners from Swiss Romande (the French speaking area of Switzerland), a region identified with the Franco-Provençal dialects, which also includes the area between Grenoble, Lyons, and Geneva, and the Aoste Valley in Italy. This family of dialects is distinct from that of both “standard” French, associated with the dialects of Oïl in the north, east, west, and south-central areas, and the dialects of Oc, which cover the south part of France. However, with respect to the three mid-vowel pairs (/o/, /e/, and /œ/) the Franco-Provençal dialects are similar to those of the “standard” Oïl dialects, where vowel aperture still plays a distinctive role (Battye, Hintze, & Rowlett, 2000; Rash, 2002; Singy, 2002). Nevertheless, prior to the syllable segmentation experiments we sought to verify whether the listeners from the Swiss Romande area retained the perceptual distinction between open and close mid-vowels via a vowel aperture discrimination experiment. This allowed us to ascertain whether the participants tested in the segmentation experiments were able to consistently distinguish vowel aperture in each of the three vowel types, an essential prerequisite of the use of vowel aperture as a syllabification cue.

2 Experiment 1: Vowel aperture discrimination

In this experiment we investigate the ability of listeners from the Swiss Romande region to discern between the open and close vowel aperture pairs /o/, /e/, and /œ/ in both open and closed syllable carriers. In a forced choice vowel discrimination task participants were presented with pairs of CV or CVC non-word stimuli with matching consonantal structure; the only factor that could be used to distinguish the two being the nature of the vowel. Half of the stimuli pairs presented to the participants were phonologically matched (e.g., /pøz/ – /pøz/), while the remaining half were differentiated only by the aperture of the vowel (e.g., /pæz/ – /pøz/). The accuracy of discrimination responses from this set of stimuli were also compared with a second set of stimuli, designed as a kind of “benchmark” to allow us to compare the accuracy of vowel aperture discrimination with vowels that are differentiated by other features.
2.1 Method

2.1.1 Stimuli

2.1.1.1 Test items  Non-word stimuli pairs were generated suitable for AX discrimination of vowel aperture, with each combination of three vowel types (/o/ /œ/, /ɛ/, and /œ/) and two carrier types (CV and CVC) resulting in four stimulus pairs. Each of these pairs shared the same consonantal form, differing only in the aperture of the vowel (e.g., /rœ/ – /rœ/, /zœl/ – /zœl/, /nek/ – /nek/). For one pair both vowels were close (e.g., /vod/ – /vod/), for another both vowels were open (e.g., /vœd/ – /vœd/), one with the first vowel open and the second close (e.g., /vœd/ – /vod/), and the last with the first vowel close and the second open (e.g., /vœd/ – /vœd/). Two examples of each of the six CV and CVC carriers were produced by a trained phonetician (a female monolingual French speaker with a Parisien accent) from a randomized list of the carriers. In each case different utterance examples were used to represent the first and second member of the pair, preventing simple acoustic matching of phonologically identical pairs. In addition, each of the stimulus pairs in this category was repeated, each using a different order (in the case of identical pairs) or example (in the case of different pairs) of utterance from the previous pair. This resulted in a total of 48 pairs, four identical and four different pairs for each combination of the three vowel and two carrier types.

For the benchmark category 11 CV and CVC non-word pairs were generated using a wider variety of vowels (including /u/, /i/, /y/, /œ/), chosen such that vowels would differ in features other than the higher-to-lower height difference of the mid-vowels tested in the previous category. These include the features of backness (two pairs), nasalization (four pairs), and higher to higher-mid height differences (six pairs). Of these stimuli 10 had identical phonological representations (e.g., /ry/ – /ry/), while the others differed by a variety of vowel features (e.g., /rœ/ – /ryl/, /zœl/ – /zol/). Again, two examples of each of the stimuli were produced by the same speaker as those of the vowel aperture category to prevent simple acoustic matching of phonologically identical pairs.

A list of all stimulus pairs used in this experiment can be seen in Appendix A.

2.1.1.2 Training items  A total of 20 training stimuli pairs were also produced, chosen to represent a similar distribution of stimuli to that of the test items. These consisted of 10 identical pairs, six pairs which differed by vowel aperture, and four which differed by other vowel features. These stimuli used different combinations of consonants and vowels from those found in the test items.

2.1.2 Procedure

Participants were asked to discriminate stimulus pairs using a forced choice procedure for same and different responses. For each trial the first in the pair of stimuli was presented 300 ms after a short warning beep, the second stimulus following 300 ms after the first. The participant was then required to press a button with their favored
hand if the stimuli were identical, and another if they were different. Trials were presented continuously, every two seconds, from a randomized list containing all of the stimulus pairs from both the vowel aperture and benchmark categories.

At the start of the experiment a short training block of 20 stimuli pairs was presented.

2.1.3 Participants

The 19 participants (18 female, 1 male) had an average age of 23.5 (ranging from 19 to 39). All of the participants in this, and all other experiments described in this study, were students of the Université de Genève and native speakers of French from the Swiss Romande area with no known hearing defects. They received course credits for their participation.

2.2 Results

2.2.1 Experimental error rates

Null response errors, where the participant failed to respond to stimulus accounted for 1.58% of the possible responses from the vowel aperture category of stimuli pairs, and 2.16% of the possible responses from the general vowel category of stimuli pairs. None of the experimental factors was found to have a significant effect, \( p > 0.05 \), over the distribution of errors in either category.

2.2.2 Vowel discrimination

Analyses of the relative frequencies of correct and incorrect vowel discrimination responses, summarized in Figure 1, revealed that participants were able to successfully distinguish open and close vowels across all three of the mid-vowel types (/o/\(\alpha\), /e\(\varepsilon\)/, and /œ/\(\alpha\)) in both CV and CVC carriers. Goodness of fit \( \chi^2 \) measures calculated on the distribution of correct and incorrect responses revealed performance that was significantly above chance, \( p < 0.0001 \), for each combination of vowel and carrier type, including the benchmark category of vowels.

Further analyses of potential differences in vowel discrimination ability between different vowel and carrier types also revealed a number of significant disparities. A log linear analysis revealed a significant interaction between vowel type and carrier type upon the relative frequencies of correct and incorrect responses, \( G^2 = 41.83 \), d.f. = 7, \( p < 0.0001 \). To examine this interaction in greater detail further \( \chi^2 \) tests of association were conducted between each of the vowel types in both CV and CVC carrier conditions.

These analyses revealed that in CV carriers discrimination accuracy for /o/\(\alpha\) (\( \chi^2 = 5.43, p = 0.019 \)) and /œ/\(\alpha\) (\( \chi^2 = 10.58, p = 0.001 \)) vowel types were significantly lower than that of the /e\(\varepsilon\)/ type, while there was no significant difference between the accuracy of /o/\(\alpha\) and /œ/\(\alpha\) types (\( \chi^2 = 0.66, p = 0.41 \)). Also, when comparing
the benchmark vowel category with each of the mid-vowel types it was found that
discrimination accuracy was significantly lower for /o//c/ (χ² = 4.35, p = 0.037) and
/o//œ/ (χ² = 9.56, p = 0.002) types, but not for the /e//ε/ type (χ² = 0.06, p = 0.81).

Turning to responses to closed, CVC, syllables we found a different pattern of
disparities. With these carriers discrimination accuracy for the /o//c/ vowel type was
significantly lower than both the /e//ε/ (χ² = 10.99, p < 0.001) and /o//œ/ (χ² = 10.24,
p = 0.001) types and the benchmark vowel category (χ² = 16.99, p < 0.001). No significant
differences were found between /e//ε/ and /o//œ/ vowel types (χ² = 0, p = 1), nor between
these vowel types and the benchmark category of vowels (/e//ε/ and benchmark:
χ² = 0.21, p = 0.64, /o//œ/ and benchmark: χ² = 0.36, p = 0.55). These findings indicate a
significant reduction in open/close aperture discrimination in /o//c/ vowels; although
cross carrier analyses would suggest that this is limited to the context of closed syllable
carriers. Comparisons of the discrimination accuracy for the three vowel types, plus
the benchmark vowel category, between CV and CVC carriers revealed that the only
significant (p < 0.05) difference was in the /o//c/ vowel type (χ² = 7.14, p = 0.007), which
was less accurate in CVC carriers.

2.3 Discussion
One of the main findings of this experiment was that French speaking participants
from the Swiss Romande area were generally able to differentiate between mid vowels
that differed only in aperture with a significantly high degree of accuracy (average
80% accuracy across all vowel types and carriers). However, although our listeners
could successfully discriminate open and close vowels from all three of the tested vowel types (/o/\(/\), /ε/\(\)), and /œ/\(\)), their success was affected by combined context of the vowel type and its occurrence in open or closed syllables.

In open syllables the pattern of performance mirrored the production restrictions predicted for “standard” French. In these syllables the production of /æ/ and /o/ is restricted, resulting in a reduction in discrimination accuracy for the /o/\(/\) and /œ/\(\) vowel types as both aperture variants are not normally seen in this syllabic context. However, both the open and close variants of the /ε/\(\) vowel types are unrestricted in closed syllables, which was reflected in the finding that discrimination of this vowel type was no different to that of other vowels tested in the benchmark category.

In closed syllables the expected restrictions on vowel aperture production are different; in these cases both the open and close variants of /o/\(/\) and /œ/\(\) are possible, but only the open vowel /ε/ from /ε/\(\). Based upon the findings for the open syllables we might have expected that the discrimination of /o/\(/\) and /œ/\(\) types would be similar to the benchmark category, with a reduction in accuracy for /ε/\(\) due to the restricted nature of vowel aperture production in this context. However, our results showed that the discrimination of aperture in both /o/\(/\) and /ε/\(\) were no different from the benchmark category in closed syllables. The only significant difference was a relative reduction in the accuracy of aperture discrimination in the /o/\(/\) type. This could point towards a movement towards a loss in the /o/\(/\) contrast in the Swiss Romande accent of French, although this inference has to be qualified by the finding that the participants could still successfully discriminate the aperture of /o/\(/\) in 66% of cases.

To summarize, these findings show that French listeners from the Swiss Romande area are generally highly proficient in perceiving the difference between vowels in both open and closed syllables even when they are discriminated purely by aperture. Therefore, this raises the possibility that differences in vowel aperture could have a significant effect over syllable segmentation, as predicted by our original hypothesis. However, with significant differences in the accuracy of aperture discrimination between the three vowel types, dependent upon the syllabic context, it is possible that similar disparities could also be evident in the magnitude of the effect.

### 3 Experiment 2: Examination of the effect of vowel aperture in syllable repetition

In this experiment we use a metalinguistic syllable repetition task to establish whether the aperture of the vowel preceding intervocalic consonant or cluster has any influence upon segmentation. However, while these types of metalinguistic tasks can be particularly enlightening, allowing both qualitative and quantitative analyses of possible segmentation cues, their results are also highly susceptible to coloration by production constraints (see Treiman & Danis, 1988). For example, if asked to produce the first part of the non-word /svi/ participants would find it difficult to respond with /s/, indicating /V.CV/ segmentation, as the initial open vowel is usually only produced in a closed syllable. Similar constraints can also limit responses in...
the repetition of the second part of stimuli. In the case of the non-word /ozlu/ the
/V.CCV/ segmentation response is problematic as it would require the production of
/zlu/, which starts with an illegal syllable onset. As we can see, in cases such as these
the responses in a repetition task are more likely to reflect production constraints
rather than the syllable segmentation perceived by the participants.

To avoid these potential problems we limited responses in this experiment
to the repetition of the final syllable of non-words constructed using a range of
single intervocalic consonants and Obstruent-Liquid (OBLI) intervocalic conso-
nant clusters. In both cases second syllable production is unconstrained, and can
lead segmentation resulting in either open or closed initial syllables. According to
previous segmentation studies in French adults (Goslin & Frauenfelder, 2001) and
pre-literate children (Goslin & Floccia, 2007) both single intervocalic consonants
and OBLI clusters should be segmented with an open initial syllable. Therefore, by
combining each of these types of consonant cluster/singletons with each of the open
and close variants of the three mid-vowel types (/o/ /e/ /ø/ /œ/) it is possible
to analyze the possible segmental influence of vowel aperture while maintaining the
same consonantal cues.

3.1 Method

3.1.1 Stimuli

3.1.1.1 Test items In this experiment /VCV/ and /VCCV/ non-word stimuli were
constructed by combining three intervocalic OBLI clusters (/gl/, /vr/, and /br/) and
10 single intervocalic consonants (two selected from each the nasal, fricative, liq-
uid, and plosive feature classes) with six initial mid-vowels (/o/ /e/ /ø/ /œ/). Final vowels were randomly selected from [/u/, /i/, /a/, /ã/ /y/, /
] to form the /VCV/ or /VCCV/ stimuli (e.g., /evi/, /ε va/, /oglu/, and /
/gla/). This organization resulted
in 18 /VCCV/ and 48 /VCV/ tokens, half of which started with an open vowel, and
half with a close vowel. A full list of stimuli used in this experiment is shown in
Appendix B.

3.1.1.2 Distractor and training items To increase the variability of stimuli a
number of additional non-word fillers were added with consonantal cues indicating
a closed initial syllable. These stimuli were constructed using the non-OBLI con-
sonant clusters /zl/, /ps/, and /lm/ and the triple intervocalic clusters /rbl/ and /kst/.
These items were constructed using the same constraints as the test stimuli, result-
ing in six tokens for each of the consonant clusters. Ten additional training items
were also generated using a similar distribution of forms to that found in the test
and distractor sets, but using different intervocalic consonants and clusters.

All stimuli were produced by a female monolingual native French speaker
(Parisien accent) that was naïve to the aims of the experiment. Stimuli were produced
from a randomized list of non-words with a pause of three seconds between the
production of each stimulus. Participant responses were transcribed by a trained
French phonetician who was also naïve to the aims of the experiment.
3.1.2 Procedure

In this experiment the segmentation decisions of our participants were elicited by asking them to repeat the second part of the bi-syllabic stimuli as quickly as possible. Experimental stimuli were randomly assigned to three blocks, in which stimuli were presented on a continuous basis (with a short warning tone heard 300 ms before each stimulus) every two seconds without pause until the end of the block. After each of these test blocks a filler block was included where participants were asked to repeat the first part of each of the stimuli. The filler blocks consisted of the same stimuli found in test blocks, but were ordered such that block repetitions (for test and filler) were never adjacent to each other. These filler blocks were included to prevent the participants from adopting an artificial segmentation strategy in which they concentrated upon cues originating from the second syllable of the stimuli. By including first syllable repetition it was hoped that participants would be encouraged to use all available segmentation cues, including those originating the aperture of the initial vowel.

At the start of the experiment participants were asked to repeat both the first and second parts of 10 training stimuli.

3.1.3 Participants

The 36 participants (34 female, 2 male) had an average age of 22.1 (ranging from 18 to 39).

3.2 Results

3.2.1 Error rates

Errors consisted of missing responses, the repetition of the total stimulus (both syllables), and the mispronunciation of syllable repetitions; that is, the use of phonemes not found in the original stimuli. Analyses of the errors, averaging 1.35% of all responses, revealed no significant distributional disparities ($p > 0.05$) between any of the experimental factors.

3.2.2 Analyses of the influence of the vowel aperture upon syllable segmentation

To analyze the influence of vowel aperture upon syllable segmentation we compared the relative frequency of second syllable repetition responses that would result in an open initial syllable (/V.CV/ or /V.CCV/) for stimuli with open or close initial vowels. $\chi^2$ tests of association showed that the relative frequency of open syllable responses was greater for stimuli with close initial vowels (83.19% of responses) than open initial vowels (88.57%), with a significant difference of 5.34% ($\chi^2 = 13.52, p = 0.0002$). This difference was larger in /VCCV/ (9.37%) than /VCV/ (3.65%) stimuli, although the inverse relationship between vowel and syllable aperture was still significant in both single ($\chi^2 = 10.02, p = 0.001$) and double intervocalic stimuli ($\chi^2 = 6.13, p = 0.01$).
To analyze potential differences in the segmental influence of vowel aperture between the three vowel types a log-linear analysis was conducted upon the relative frequencies of open and closed syllable decisions between the factors of vowel aperture (open or close) and vowel type (/o/ /œ/, /e/ /ɛ/, and /Ø/ /œ/). This analysis revealed a significant interaction between open and close segmentation decisions and the factors of vowel aperture and vowel type ($G^2 = 24.3$, d.f. = 7, $p = 0.001$), implying that there were disparities in the influence of vowel aperture between the three vowel types. By separating segmentation decisions for open and close vowel stimuli between the three vowel types, shown in Figure 2, it can be seen that vowel aperture has the greatest influence in the /o/ /œ/ contrast (8.8% more open syllable decisions with close initial syllable), followed by /Ø/ /œ/ (3.9%), with the /e/ /ɛ/ contrast having the least effect (3.3%). Separate $\chi^2$ tests of association between the frequencies of open and closed syllable decisions and vowel aperture for the three vowel types showed that the inverse relationship between vowel and syllable aperture was only significant in /o/ /œ/ ($\chi^2 = 10.96$, $p < 0.001$) and /Ø/ /œ/ ($\chi^2 = 3.42$, $p = 0.032$) types, but not in /e/ /ɛ/ ($\chi^2 = 1.43$, $p = 0.12$).

3.3 Discussion

The primary aim of this experiment was to investigate the hypothesis of a link between the aperture of the vowel at the syllable’s nucleus and the aperture of the syllable, with open vowels encouraging closed syllables and vice versa. Analyses of open
syllable segmentation responses from this experiment support this hypothesis, with a significantly greater incidence of open syllable responses for close, rather than open vowels.

However, further analyses of the differences revealed significant disparities in the segmental influence of vowel aperture over the three vowel types (/o//, /e//, and /ø//). While the close vowels /o/ and /ø/ prompted a significantly greater number of open syllable segmentation decisions than the open vowels /e/ and /ø/, the inverse relationship between vowel and syllable aperture did not reach significance with the /el/ or /œ/ contrast. This pattern of disparity is thought to relate to the tendency of vowel aperture neutralization in standard French, with the neutralization of /e// and /æ/ in open syllables, and /ø/ in closed syllables. In this experiment all of the consonantal syllable segmentation cues provided by the stimuli indicate an open first syllable, either /V.CV/ or /V.CCV/. As there is a tendency towards the neutralization of /e// and /æ/ in open syllables the presence of these vowels provide a salient syllable segmentation cue that is in contrast with that of the consonantal cues, indicating that the first syllable should be closed. However, as there is no neutralization of the /el/ or /œ/ vowel type in open syllables the saliency of the contrast between the aperture pairs is reduced, as the difference between the frequency of occurrence of the close and open vowels is not as great as with the other vowel types.

Another effect seen in this experiment was the marked disparity in the magnitude of the influence of vowel aperture between the single and double intervocalic consonant stimuli. A possible explanation for the relatively low degree of segmentation shift seen in single intervocalic stimuli could be linked to a reluctance in our participants to break the most widely accepted segmentation principle, that of the obligatory onset. The Obligatory Onset Principle (Hooper, 1972) states that, wherever possible, the onset of a syllable must contain at least one consonant. This principle is also known as the Principle of Maximum Open Syllabicity (Malmberg, 1963; Pulgram, 1970), stated as a preference in the Head Law of Vennemann (1988), and inherent, if not stated, in other theories of syllable structure (Clements, 1990; Selkirk, 1982). For single intervocalic consonant stimuli the closure of the first syllable, indicated by an open initial vowel, would be in violation of this principle, as the onset of the following syllable would be empty. With a suppression of closed initial syllables due to the obligatory onset this would reduce the segmentation shift between open and close vowel conditions. This is not the case in double intervocalic consonant stimuli, as closed initial syllables can be formed while leaving an obligatory consonant for the onset of the following syllable.

These findings, together with the differences seen in the effect of vowel aperture in three vowel types, indicate that disparities in the magnitude of the vowel aperture effect are a symptom of conflicting segmentation cues arising from the syllable nucleus and consonantal structure. If valid, this supposition would indicate that the segmental information provided by disparate cues has an additive effect on the probability of segmentation decisions. Experiment 3 uses an online experimental paradigm to corroborate the findings of this experiment, and also to investigate the relationship between consonantal and vowel aperture segmentation cues in greater detail.
4 Experiment 3: Fragment detection and the syllable effect

One of the strongest arguments for the use of the syllable, rather than the phoneme, at the pre-lexical level of speech processing comes from studies using the fragment detection experimental paradigm. In the original study, by Mehler et al. (1981), French participants detected CV or CVC targets in spoken carrier words that varied in syllabic structure. Carrier pairs each shared the same initial three phonemes (CVC) but differing syllable structure, with one having a null offset (CVC), the other having a single consonant onset (CVC.) (e.g., /pa.lace/ and /pal.mier/ respectively). Detection latencies showed that there was a cross-over interaction between target type and carrier syllable structure, such that responses were faster when the target corresponded to the initial syllable of the carrier, the “syllable effect.”

In Experiment 3 we investigate the role of vowel aperture in syllable perception by examining its influence over the “syllable effect.” In the original, and all subsequent implementations of the fragment detection task the syllable structure of the carrier items was determined by the phonotactics of the intervocalic consonant cluster used in the carrier. In this experiment we have expanded the syllabic context of the carriers to include segmentation cues from the aperture of the first vowel as well as consonantal structure. This allows an insight into the possible interaction between these two cues by examining cases in which they provide congruent or conflicting segmentation evidence. For example, when presenting the carrier non-word /εlma/ we would expect that the target fragment /εl/ would be detected faster than /ε/ because both consonantal and vowel aperture cues indicate a closed initial syllable. However, if the aperture of the initial vowel is changed then the segmentation cues are in conflict, as the close initial vowel indicates that the first syllable should be open. In this case the consonantal segmentation cues still indicate faster detection for /el/ in the carrier /elma/, while the close vowel now indicates that the target /ε/ should be detected faster. If the influence of the cues from vowel aperture and consonant cluster is additive then the ambiguity arising from carriers with conflicting cues should significantly reduce any detection latency differences between target pairs when compared to those of carriers with congruent cues. If the cues are hierarchical, with primacy to consonantal cues, then vowel aperture should have a minimal impact upon target detection latencies, which would be dominated by the cross-over interaction between target type and consonantal segmentation cues, as shown in the original study.

4.1 Method

4.1.1 Stimuli

4.1.1.1 Test stimuli  Carrier stimuli consisted of /VCCV/ non-words, constructed by combining two OBLI (/vr/ and /gl/) and two non-OBLI consonant clusters (/ps/ and /lm/) with six initial mid-vowels (/o/ /ɛ/ /Ø/ /œ/). This selection resulted
in six carrier items for each cluster, one for each of the /o/, /ɔ/, /ɛ/, /ɛ/, /ø/, and /œ/ first vowels. For each of the 24 carriers V and VC targets consisted, respectively, of the first vowel and first vowel and consonant of the carrier item. As can be seen in Table 1 the combination of intervocalic consonant clusters and initial vowels used in this design produce stimuli with both congruent (both cues indicate the same syllable boundary) and conflicting (each cue indicates a different syllable boundary) segmentation cues. A full list of carriers can be seen in Appendix C.

Table 1
Design of stimuli in Experiment 3 showing syllable boundaries indicated by vowel aperture (1) and consonantal (2) segmentation cues

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<th>Initial vowel</th>
<th>Intervocalic consonant cluster</th>
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<td>/VC^1_CV/</td>
</tr>
<tr>
<td>Close /ø/, /ɛ/, /œ/</td>
<td>/ps/ &amp; /lm/</td>
<td>/VC^2_CV/</td>
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</table>

4.1.1.2 Foils For each carrier, two foil “targets” were generated; a V and VC foil. The V foil consisted of an isolated mid-vowel, different from that used as the initial vowel of the carrier (e.g., for the carrier /gla/ the foil /o/ was used). For the VC foil the vowel matched that of the carrier, but the consonant was different to that of the first consonant of the carrier. (e.g., for the carrier /epsa/ the foil /sm/ was used). The purpose of the VC foil is to ensure that participants could not respond on the basis of a partial match on the first segment of the target.

4.1.1.3 Training items A total of 10 training carrier items was selected from the double consonant cluster stimuli of Experiment 3 not used in the test carrier items. As in the test stimuli, for each carrier, V and VC targets and foils were also created. This resulted in a total of 20 target carrier, and 20 foil carrier training items.

One monolingual French speaker was used to produce the target and foil items, and another in the production of the carrier items to avoid the possibility of simple target carrier acoustic matching. Both speakers were trained female phoneticians with Parisian accents, and had no knowledge of the aims or procedure of the experiment.

4.1.2 Procedure
Participants were asked to press a button as rapidly as possible if the target stimulus was present at the beginning of the carrier. Target stimuli were presented after a short warning tone, followed by the carrier stimulus 300 ms afterwards. Each participant received all of the carriers four times, once for each of the V target and VC targets, and once each of the V and VC foils. Target and carrier stimuli pairs were presented in random order without pause, with one pair presented every two
seconds. At the start of the experiment a training block was presented, consisting of 20 target and carrier stimuli pairs and 20 foil and carrier pairs presented in random order.

4.1.3
Participants
The 19 participants (18 female, 1 male) had an average age of 23.5 (ranging from 19 to 39).

4.2
Results

4.2.1
Error rates
Errors for test items consisted of missed responses, which accounted for 2.2% of all expected responses. Participants erroneously detected 7.3% of the foil targets in carrier items. No significant relation could be found between the distribution of errors and the experimental variables.

4.2.2
Analyses of reaction time differences for V and VC targets
To analyze the reaction times for V and VC targets a repeated measure ANOVA was conducted with four within-subject factors; consonant cluster type (OBLI or non-OBLI), vowel type (/o/ or /e/ and /Ø/), vowel aperture (open or close), and target type (V or VC).

The analyses revealed no significant main effects ($p < 0.05$) for any of the experimental factors. In addition, the only significant interactions between the experimental factors were a two-way interaction between vowel aperture and target type, $F(1, 18) = 16.69, p < 0.001$, and a three-way interaction between vowel aperture, target type, and cluster type, $F(1, 18) = 6.29, p = 0.022$. The former interaction, shown in Figure 3, shows that participants were faster in detecting V targets than VC targets in target carrier pairs with close vowels, with the reverse for target carrier pairs with open vowels. However, the three-way interaction between vowel aperture, target type, and cluster type, shown in Figure 4, reveals that in OBLI carriers this cross-over interaction is not complete, as V targets with a close vowel were not detected significantly faster than those with an open vowel. Separate ANOVA analyses for each consonant cluster and target type revealed a significant effect of vowel aperture with V, $F(1, 18) = 7.94, p = 0.011$, and VC, $F(1, 18) = 16.42, p < 0.001$, targets in non-OBLI clusters, but only for VC targets in OBLI clusters, $F(1, 18) = 5.58, p = 0.030$, not V targets, $F(1, 18) = 0.23, p = 0.80$.

Unfortunately, although these findings indicate an interaction between segmentation influences arising from consonantal and vowel aperture cues, the interpretation of these findings is complicated by inconsistencies in the effects of consonantal segmentation cues. According to the predictions of the original “syllable effect,” VC targets should have been detected faster than V targets with non-OBLI consonant clusters (normally segmented as /VC.CV/), with the inverse for OBLI consonant
clusters (normally segmented as /V.CCV/). However, the expected cross-over interaction between consonant cluster type and target type was not found to be significant, $F(1, 18) = 0.41, p = 0.53$, in this experiment. Further ANOVA analyses for each individual consonant cluster revealed that the main effect of target type reached significance in only one consonant cluster, /lm/, $F(1, 18) = 14.70, p = 0.01$. In this case VC targets (average latency of 538 ms) were detected faster than V targets (average latency of 491 ms), in agreement with previous expectations as this consonant cluster is normally segmented as /C.C/. Focusing upon the results of stimuli using this consonant cluster, the interaction between segmentation cues arising from the consonantal structure and vowel aperture are clearly visible. As can be seen in Figure 5, differences in target detection latency are only evident when the two segmentation cues are congruent; the open vowel combined with this non-OBLI cluster. This interaction appears to be due to conflicting segmentation cues. For example, if a non-OBLI consonant cluster, normally segmented as /C.C/, was combined with a close vowel then the segmentation effects from the two cues would tend to cancel each other out, resulting in a flat response. Thus, it would appear that, in this case at least, the effect of disparate syllable segmentation cues is additive.

Finally, because of the dual-coding proposals of Dupoux (1993) and Sebastián-Gallés et al. (1992), and the relatively slow reaction times in this experiment (average
517 ms for carrier length of 530, compared to an average of 360 ms in the original study of Mehler et al. (1981)), fast and slow reaction times were compared by splitting participants into two groups. The first group consisted of the nine participants with the fastest average reaction times (average reaction time of 443 ms), the second consisting of nine slowest participants (average reaction time of 591 ms). ANOVA analyses were repeated, adding a factor of subject speed (two modalities, fast and slow) to the previous factors of consonant cluster type, vowel aperture, and target. These analyses revealed no significant interactions between subject speed and any other experimental factor ($p > 0.05$) suggesting that subject speed had no effect on the previous findings of this experiment.

### 4.3 Discussion

As predicted by our original hypothesis, target reaction times revealed a “syllable effect” interaction with vowel aperture, with VC targets detected faster than V targets in carriers with open vowels and vice versa for carriers with close vowels, confirming the results of Experiment 2. This experiment also allowed a more detailed insight into

**Figure 4**

Reaction times for target carrier pairs with OBLI and non-OBLI carriers in Experiment 3
the relationship between syllabic cues arising from the vowel and consonant cluster. In Experiment 1 the effect of vowel aperture was only evident in the relative differences in the segmentation of syllables with open and close vowels. In this experiment it was possible to analyze the effect of each vowel aperture in isolation. The result of this analysis suggests that the nature of the relationship between disparate segmentation cues was additive, rather than hierarchical, allowing for both conflicting and complementary cues that can either reinforce or reduce the probability of certain segmentation decisions. This behavior was exemplified by the differences in target reaction times between carriers with open and close vowels containing the /lm/ cluster. For the other three clusters used in this experiment the relationship is more difficult to interpret as they had no significant effect over target detection latencies.

In the original study of Mehler et al. (1981) the “syllable effect” was a result of interaction between target-carrier matching of syllabic structure around a liquid pivotal consonant in single and double intervocalic consonants. In our experiment we replicated this effect in the only one of the clusters tested, /lm/, the only cluster which also had a liquid pivotal consonant. These findings are similar to those of Content et al. (2001), who also found that the French “syllable effect” could only be reproduced when the carrier stimuli used a liquid pivotal consonant, and not those from other consonant categories.
Based upon the theories of Pulgram (1970) our original hypothesis stated that if the vowel of a syllable is open, this will induce syllable segmentation that results in the syllable being closed, and if the vowel is closed, this will induce open syllables. The aim of this study was to investigate whether the behavior predicted by this hypothesis is evident in the segmentation behavior of listeners where mid-vowel aperture plays a distinctive role.

In our first experiment we were able to verify that listeners from the French-speaking region of Swiss Romande were able to accurately distinguish between open and close mid-vowels in both open and closed syllables, a prerequisite of the following segmentation experiments performed by participants from the same area. In the first of these experiments a metalinguistic syllable repetition task was conducted to examine whether the vowel aperture of syllable nuclei preceding intervocalic consonants or clusters would influence the closure of the syllable. The results of this experiment showed that initial vowel aperture had a significant effect on the participant’s segmentation of bi-syllabic non-words, with open vowels increasing the prevalence of closed initial syllables, and close vowels reducing this prevalence. However, this inverse relationship was only found to be significant for two out of the three mid-vowel aperture pairs, /o/ and /ø/æ/, but not in the pair /e/ɛ/. A similar, although inverted, pattern of vowel type disparities were also noted in the vowel aperture discrimination task used in Experiment 1. In open syllable carriers it was found that participants were more effective in discriminating the aperture pair /e/ɛ/ than /o/ or /ø/æ/. It is suggested that the similar pattern of disparities seen in both Experiments 1 and 2 are due to differences in the tendency towards vowel aperture neutralization in open syllables, with the /o/ and /ø/æ/ types reduced to the close vowels /o/ and /ø/. As all of the stimuli used in Experiment 2 contain consonantal segmentation cues that indicate an open initial syllable the open vowels /e/ɛ/ and /ø/æ/ provide a salient cue that contrasts with that provided by the consonantal cue. Because of the tendency towards the neutralization of these open vowels their presence, over that of their close counterparts /o/ and /ø/, provides a greater contrast to that of the vowel type /e/ɛ/, as there is no neutralization of /e/ɛ/ in this context. These findings indicate that segmentation cues arising from vowel aperture and consonantal structure are independent, and that their effects are additive, becoming evident when the two cues provide contrary indications of syllable structure.

To investigate this relationship in greater detail an additional experiment was conducted, designed to examine the interaction between consonantal and vowel aperture cues in an online task. In Experiment 3 we used a fragment detection task in an attempt to reproduce the “syllable effect,” originating from the study of Mehler et al. (1981), arising from the match or mismatch of syllable boundaries between target and carrier stimuli. However, in our study we examined differences in detection latencies due to syllabic cues originating from vowel aperture, as well as the consonantal cues used in the original study. The findings of this experiment revealed a “syllable effect” interaction between vowel aperture and target type predicted by our hypothesis.

However, the original “syllable effect” cross-over interaction of Mehler et al. (1981) resulting from consonantal segmentation cues was not found in our study. In further analyses it was found that only one cluster, /lm/, had a significant effect on
target detection latencies, with faster detection times for /VC/, rather than /V/, targets. Similar results were also found in a study of Content et al. (2001), where an attempt was made to replicate the findings of the original study of Mehler et al. (1981) using a wide range of carrier clusters. Whereas in the original study carriers and targets consisted of only a single vowel, /a/, and liquid pivotal consonants (/l/ and /r/), Content et al. (2001) used a wider range of vowels and pivotal consonants from stop, fricative, and liquid classes. They found, as did we, that the requisite components of the cross-over interaction were only found when a liquid pivotal consonant was used. These limitations are said to be inconsistent with the hypothesis of a general syllable classification mechanism, including the dual-coding proposal of Dupoux (1993) and Sebastián-Gallés et al. (1992), and hard to reconcile with that concept that pre-lexical processing is based upon a “bank of syllabic recognizers” (Mehler, Dupoux, & Segui, 1990). Instead, Content et al. (2001) propose an acoustic-phonetic process, based upon the continuous evaluation and matching of phonetic and sub-phonetic information, where syllable onsets form privileged alignment points for lexical segmentation. One possible explanation for the special status of liquid pivotal consonants could lie in the findings of Treiman and Danis (1988), and their vowel to consonant adherence hypothesis. This hypothesis stems from the study of the syllabification of English intervocalic consonants, where the adherence between the consonant and preceding vowel was found to increase from stops, to fricatives, to nasals, to liquids, with maximal adherence for glides. While liquids only form a limited subset of these possible consonant categories, statistical analyses of their occurrence in French indicate that they occur far more frequently than might be imagined. A statistical investigation of all /CVC.CV(C)/ words found in the French lexicon Lexique (New et al., 2001) revealed that there were nearly twice as many words with liquid pivotal consonants as those without (1979 with liquid first consonant, 1051 with other types of consonant) and that the total frequency of the former words (8413) was nearly three and a half times greater than the latter (2458). Therefore, although the critical component of the syllable effect, where /CVC/ targets are detected faster than /CV/, may be restricted to a subset of consonant clusters, they are by no means atypical.

Another tentative explanation for the differences in segmentation behavior between the consonant clusters tested in Experiment 3 could lie in segmentation consistency differences related to legal ambiguity. It has been found (Goslin & Frauenfelder, 2001) that segmentation decisions are significantly more consistent in clusters with a single legal syllable onset, rather than those with a choice of legal onsets. In Experiment 3 three of the four clusters could be legally segmented as either /CC/ or /C.C/, while /lm/ could only be segmented as /l.m/ as /lm/ is not a legal word onset in French. Therefore it is possible that the syllable effect can only be reproduced in a completely unambiguous segmentation environment. As we have seen in the /lm/ cluster, differences in target detection latencies were only found when the segmentation cues were unambiguous, and not when those from the consonant cluster and vowel aperture were in conflict.

Returning to the central aim of this study, it appears that while the findings of Experiment 3 are ambiguous as regards the precise pre-lexical status of the syllable, they do give support for the use of vowel aperture in French syllable segmentation, with vowel aperture producing the requisite detection latency interaction. Whether the effect of vowel aperture can be generalized across a wider consonantal environment, other than the four double intervocalic clusters used in Experiment 3, remains an open
question. However, the presence of the vowel aperture effect in stimuli with potentially ambiguous consonantal cues, due to multiple legal syllable onsets segmentation, and in /lm/, where there is no ambiguity, may indicate that the effect could also be found in similar stimuli, including those with single intervocalic consonants, although the results of Experiment 2 do show a lesser effect of vowel aperture in this case. It must also be noted that all of the stimuli used in Experiment 3 were non-words, unlike the original study of Mehler et al. (1981), although Leclercq, Content, and Frauenfelder (2002) directly compared word and non-word stimuli in a similar fragment detection task and found no consistent differences between these types of stimuli, although, as in the study of Content et al. (2001), they were not able to reproduce a general syllable effect. Nevertheless, while there are certain qualifiers to the results of Experiment 3, it does provide robust support to the findings of Experiment 2, confirming the hypothesis that segmentation decisions are influenced by independent cues originating from both intervocalic consonantal structure and vowel aperture.

Currently the majority of research into syllabic segmentation, especially in French, has largely concentrated upon a single source of segmentation cues, the structure of intervocalic consonants and clusters. This view is reflected in the approach used in current segmentation models where the segmentation problem has been reduced to the search for a deterministic transform for splitting intervocalic structures between syllables. However, even an optimal segmentation model based upon this approach, provided by Laporte (1993) for French, cannot explain all of the variation found in segmentation behavior (Goslin & Frauenfelder, 2001). It is now clear that at least some of this variation must be due to the segmentation effect of vowel aperture. Evidence from Experiments 2 and 3 would suggest that the vowel aperture plays a significant role in syllabic segmentation, with open vowels stimulating closed syllable responses and vice versa. In addition, our findings suggest that the relationship between the segmentation cues found in consonantal structure and vowel aperture is additive. Segmentation cues from both the consonantal structure and vowel aperture appear to act independently such that when cues are in agreement the probability of the mutually supported segmentation decision is higher than if they are in conflict.

With multiple independent, and more importantly, conflicting cues, we can no longer rely on simple deterministic segmentation models to provide unambiguous decisions on how intervocalic consonant clusters should be shared between syllables. Currently the standard approach to deal with segmentation uncertainty is to label problematic segments as being “ambisyllabic.” For example, in the study of Zwitserlood et al. (1993) when syllabic cues from vowel length and consonant cluster in Dutch were in opposition the first intervocalic segment was simply labeled as ambisyllabic. However, our findings have shown that all segments are “ambisyllabic” to some degree or another, dependent upon a wide syllabic context. The current categorical, deterministic approach to syllable segmentation fails to capture the complex interplay of syllabic cues that influence segmentation decisions. This segmentation environment is more suited to a stochastic model of syllabification which can combine conflicting evidence to predict where a syllable boundary is likely to be located, based on known syllabification cues. Such a strategy can take advantage of information found in syllable nucleus, coda, and onset, broadening the search for segmentation cues to take account of the complete context surrounding syllable boundaries.
References


**Appendix A: Stimulus pairs used in Experiment 1**

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<th>Vowel aperture</th>
<th>General vowel</th>
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### Appendix B: Stimuli used in Experiment 2

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### Appendix C: Stimuli used in Experiment 3

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