A Comparison of Theoretical and Human Syllabification*

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Key words

segmentation

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Abstract

A review of phonological syllabification theory reveals considerable controversy, with a number of conflicting theories put forward to explain this process. In this study the performance of five, French specific, syllabification procedures were compared and contrasted both against each other, using lexical analysis, and against human syllable boundary placement, using a metalinguistic syllable repetition task. Lexical analysis revealed substantial, practical differences in the application of procedures, with disagreements rising along with consonant cluster complexity. Results from the syllable repetition task showed differences in participant's syllabification consistency due to experimental condition, that is, syllable onset or offset detection, and the consonant cluster used in the stimuli. Comparison between the predictions of syllabification procedures and human segmentation show greater agreement for procedures based upon phonotactic regularities than sonority. Furthermore, segmentation by maximizing the length of syllable onset, practiced in most procedures, was not reflected in our results. Instead participants preferred single consonant onsets, apart from the case of obstruent-liquid clusters, which are considered as a single indivisible unit.

1 Introduction

Perhaps the most oft used subword unit next to the phoneme is that of the syllable, of importance across all fields of speech and language research including phonology, linguistics, psycholinguistics, and now of increasing interest to engineers of speech technology. Whilst the phoneme has the benefit of a relatively stable, clear, and uncontroversial definition, being "the smallest distinctive unit within the structure of a given language" (Trubetzkoy, 1939), the syllable does not share the phoneme's good fortune in this area. Perhaps the most general, and least controversial of the available definitions for the syllable is that it is a stretch of speech that consists of a vowel, with or without one or more accompanying consonant sounds immediately preceding or following. Unfortunately, even this highly generalized definition is not without its problems. It makes two claims, first that the vowel acts as the

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syllable nucleus, and second, that one or more consonants may be appended onto the syllable nucleus, those before known as the *onset*, after, the *coda*. Examining the first claim we find complications which arise from the possibility that some of the phonemes may function as either consonants or vowels, or indeed the occurrence of syllables without vowels, where syllabic consonants may act as the syllable nucleus. The second claim is less controversial, that a syllable may have an onset and coda may be safely accepted at face value mainly because it specifies so little, perhaps of greater interest is what remains unspecified.

Given the task of counting the number of syllables in an utterance, naive listeners will have little difficulty, and will generally be in agreement. This task can be said to be roughly analogous to the counting of syllable nuclei stated in the first claim of our syllable definition. However, when listeners are asked to state exactly where the syllable *boundaries* lie between those nuclei, great difficulties are encountered with differences of opinion arising between listeners. In reference to the second claim of the syllable definition, the possibility of syllable onsets and codas is defined, but not where, when segmenting a polysyllabic utterance, the coda of a preceding syllable stops and the onset of the next begins. It is this specification of syllable structure, or boundary location, that goes unstated in the original definition of the syllable, that is most controversial, but crucial if the definition of the syllable is to be complete.

Because of such problems, it has been suggested that the syllable is of no interest to linguistics (Lebrun, 1966), or that it is an unnecessary, even a harmful concept (Kohler, 1966). However, others (e.g., Hooper, 1972; Pulgram, 1970; Vennemann, 1988) have suggested that there can be no descriptively adequate phonology without reference to the syllable, or that, whilst, you can avoid reference to the syllable, the syllable reduces the need for ad-hoc devices. Evidence for the necessity of the syllable is also available in the field of psycholinguistics where the syllable is a popular candidate for the primary perceptual unit for access to the mental lexicon (Cutler, Mehler, Norris, & Segui, 1986; Mehler, Dommergues, Frauenfelder, & Segui, 1981). Whilst theoretically very useful in the examination of speech and language, it is handicapped by an inadequate definition, especially when there is need for an accurate prediction of the syllable boundary.

Many theories have been put forward concerning syllable structure and syllable segmentation, however thus far no consensus has been formed such that an accepted view of syllable segmentation is available. In this article we will review a number of the most prominent generic phonological theories of syllable segmentation, examining the commonalities and contradictions of the various principles of syllable boundary placement. Taking these principles as a basis of syllabic theory we will also examine a number of language specific implementations, in this instant, for the French language, such that we may examine the merits of the different methods of syllabification. The first step in this process was a practical examination of these models, through their application on all intervocalic consonant clusters and singletons found in the French lexicon BDLex (Calmès & Pérennou, 1998). After lexical analysis it was necessary to use another, empirical, form of analysis for the clarification of syllable boundary placement. In order to extract the syllable boundary placements used by naive listeners, a metalinguistic syllable repetition experiment was performed using a broad range of singular, double, and triple consonant stimuli. Using the preferential segmentation of participant’s responses, it was possible to form a test set of consonant clusters and singletons such that we could calculate an objective measure of agreement between human syllabification and theoretical predictions. This comparison can then be used to ascertain the merits of each of the syllabification procedures, and show the shortcomings of current phonological theories of syllabification.

1.1
General syllabification models

Probably the best starting point for a review of the major phonological theories of syllable structure is our original definition of the syllable given in the introduction of this article. Here we briefly touched upon the problems with an exclusive relationship between vowels and syllable nuclei. In obviating this problem many phonological theories (e.g., Hooper, 1972; Kahn, 1976) define the nucleus of a syllable using the [syllabic] binary feature (Chomsky & Halle, 1968). The class of [+syllabic] units, includes not only all the ordinary vowels but also a number of syllabic sonorants, although a rigorous definition of this feature has yet to be achieved. With a one to one relationship between [+syllabic] segments and syllables the next step in the definition of the syllable is the formulation of principles for setting the boundary between each [+syllabic] segment.

Perhaps one of the simplest, and least controversial of these principles is that of the Obligatory Onset Principle (Hooper, 1972), or Principle of Maximum Open Syllabicity (Malmberg, 1963; Pulgram, 1970), also stated as a preference in the Head Law (Vennemann, 1988), and inherent, if not stated, in other theories of syllable structure (Clements, 1990; Selkirk, 1982). This principle is based upon the suggestion that the open syllable (a syllable with no coda) has historic or primitive significance in that all languages have open syllables (some only have open syllables) whereas no languages have only closed syllables (syllables with codas). Therefore, taking the example of a singular intervocalic consonant, the syllable boundary must lie before the consonant (/V.CV/) so creating the preferred open syllable.

Another of the most widely accepted principles of syllabification is that of the Legality Principle (e.g., Hooper, 1972; Kahn, 1976; Pulgram, 1970; Vennemann, 1988), which states that syllable onsets and codas are restricted to those phonotactically possible at word-initial or word-final positions. Evidence for this principle arises from two observations, first that all examples of word medial clusters consist of a possible word-initial followed by a possible word-final cluster. Second, that in cases where the syllabification of medial clusters is unclear, naive speakers never produce syllabifications which involve clusters not found at word margins. However, it has been suggested that the two laws of this principle, the Law of Initials, that legal onsets are found word-initially, and the Law of Finals, that legal codas are found word-finally, do not share equal status, in that a greater number of exceptions are found in the Law of Finals than that of Initials (Vennemann, 1988). This finding is also embodied in the Principle of Irregular Coda (Pulgram, 1970) which states that if an intervocalic consonant cluster cannot be divided into legal onset and coda, then the "illegality" must be borne by that of the coda. This viewpoint is taken a logical step further in the Maximum Onset Principle (Kahn, 1976) which states that the syllable boundary must be placed before the *maximum* allowable legal onset, irrelevant of the legality of the syllable coda. An exception to this principle was proposed for the syllabification of intervocalic consonant clusters which suggests a hierarchy for the choice of the initial onset segment, with obstruents the optimum choice, followed by liquids and nasals, and finally glides (Hooper, 1972).

An alternative approach, built around studies of the "sonority scale" (e.g., de Saussure, 1916), rather than analysis of phonotactic regularities, as those just discussed, is known as the Sonority Cycle (Clements, 1990). According to this principle, segments are ranked along a "sonority" scale such that the preferred syllable type shows a sonority profile that rises maximally toward the peak and falls minimally towards the end of the syllable. Segments are classified in sonority using [syllabic], [vocoid], [approximant], and [sonorant] binary feature categories such that vowels have the highest sonority, followed by glides, liquids, nasals, and finally obstruents (similar to the hierarchy suggested by Hooper (1972), but with the ranking of Nasals and Liquids switched). Using the Core Syllabification Principle, segments are built upon the syllable nucleus (both onset and coda) as long as they are of a lower sonority than that of the preceding segment, however, as in previous theories, the construction of the onset of a syllable has priority over that of the coda of the preceding syllable. Another, closely allied, but differently defined, theory is based upon a similar sonority scale, in this case inverted to form the Universal Consonantal Strength (Vennemann, 1988). This scale of sonority defines a larger number of consonanticity levels than the previous sonority scale, splitting, for instance, obstruents into plosives and fricatives (with the former of highest consonanticity), with descending values for high, mid, and low vowels. Syllable boundary placement is by means of Vennemann's (1988) "Contact Law" and "Contact Embedding" preferences, which describe the same preferred sonority profile as that of the Sonority Cycle.

Thus far all of the theories of syllable boundary placement have been based upon a flat, linear, representation of the syllable. However, an alternative suggestion (Selkirk, 1982) proposes a hierarchical structure of the syllable based upon the onset-rhyme model (Cheng, 1966; Fudge, 1969), with the rhyme consisting of the peak (nucleus) and coda. Allowable syllabic form is dictated by overlaying a template of phonotactic constraints over this hierarchical structure specifying all possible syllable types for a particular language. Suggested advantages for such a representation include the ability to provide explanations for phonotactic constraints without the need to resort to ad-hoc descriptions and the ease with which the description of the syllable may be fitted into higher order hierarchical organizations for the treatment of such phenomena as stress and rhythm.

One influence upon syllabification which has escaped attention in the description of the previous theories is that of stress. It is thought (Kahn, 1976; Selkirk, 1982; Vennemann, 1988) that the stress difference between a preceding, stressed, and following, unstressed syllable, may affect the nature of the syllable boundary. One explanation of this phenomenon suggests that, whilst in slow speech the types of syllabification rules discussed so far hold sway, during fast speech it is possible that medial consonantal segments found between stressed and unstressed syllables become *ambisyllabic* (Kahn, 1976), that is, belong to both the following and preceding syllables. For example, in slow speech the suggested syllabification of "pony" follows the Obligatory Onset Principle, /po.ni/, however, under normal speech, because of the stress on the first syllable the segment /n/ becomes ambisyllabic, resulting in the two syllables /pon/ and /ni/. An alternative explanation for this behavior is that of *resyllabification* (Selkirk, 1982) where, after initial syllabification, the syllable boundary may be moved as a function of stress, using our previous example this results in the change from /po.ni/ to /pon.i/.

In this section we have presented an overview of the major principles of syllabification available at the present time. Unfortunately, any theoretician hoping to bind these principles into a complete definition of the syllable is faced with a number of philosophical and practical conflicts between the different principles available. For example, the French word ‘admettre’ (accept) is syllabified /a.dmεtr/ using the Core Syllabification Principle of the Sonority Cycle, however the Maximum Onset Principle places the syllable boundary at /ad.mεtr/. In order to resolve such conflicts it is necessary to examine these different principles when applied to a specific language, such that an analysis may be made concerning the merits of the various conflicting principles of syllable boundary placement.

1.2 *Syllabification in French*

The French language has a number of advantages when it comes to research on the syllable, it is a syllable-timed language, and therefore does not bear the problems surrounding that of stress-timed languages, such as English, regarding possible ambisyllabicity or resyllabification. The syllable also has special, psycholinguistic, relevance in French, with the discovery of the “syllable effect” (Cutler et al., 1986; Mehler et al., 1981) suggesting the syllable as the primary perceptual unit used in lexical access, whilst similar studies in English have failed to find such an effect (Cutler et al., 1986).

We present five different French syllabification procedures chosen to reflect some of the differing general principles of syllabification outlined in the previous section. The first two (Coursil, 1992; Peereman, 1999) are based upon the concepts of sonority and consonanticity, each with differing hierarchies for the classification of French phonemes. The second pair (Dell, 1995; Laporte, 1993) suggests rules based upon analyses of French phonotactic regularities using the Legality Principle, both giving special consideration to obstruent+liquid type clusters. The final selection is simply that of the Maximum Onset Principle, a complete model of syllabification in its own right, easily applicable to any specific language.

1.2.1 *Coursil (1992)*

Coursil’s (1992) syllabification laws are inspired from that of the sonority scale, describing the same preferred sonority contour as that of the Sonority Cycle. However, following de Saussure’s proposal, Coursil classifies segments into eight aperture categories, with a similar split of fricatives and plosives, and differing values for high, mid, and low vowels to that of the Universal Consonantal Strength. Coursil categorizes segments into the following ascending order of sonority:

1 — minimal aperture: occlusives (p, t, k, b, d, g)
2 — fricatives
3 — nasals
4 — liquids
5 — glides
6 — high vowels (i, y, u)
7 — mid vowels
8 — low vowels (a, a nasal)

Coursil (1992) states that syllable boundaries are assigned through a mechanism originally used by de Saussure. Binary values are assigned to each segment in the speech stream, 1 for those whose aperture rank is higher than that of its following neighbor, 0 for the remaining segments. A syllable boundary is located every time this attribute changes from high to low (1 0). Because the start and end of utterances correspond to syllable boundaries, the start of every utterance is assigned a 0 (unless the first segment is a vowel, then it is assigned 1), the end 1. In the case of two consecutive phonemes of the same aperture rank, such as in geminate segments, they will have the values 1 0, and so mark a syllable boundary.

For example, the word 'moustique' (/mustik/; mosquito) will be syllabified the following way:

	m	u	s	t	i	k
Aperture ranks:	3	6	2	1	6	1
Plosion values:	0	1	1	0	1	1

The syllable boundary is located between the string 10, that is /mus.tik/.

This mechanism operates similarly to that of the Core Syllabification Principle, describing the same preferred syllable boundary. However, some of the problems of *marked* demisyllables (Clements, 1990), containing violations of the sonority cycle in the form of sonority plateaus, are avoided using Coursil's syllabification system.

1.2.2
Peereman (1999)

Peereman's (1999) approach is based upon the concept of consonanticity, similar to that of the Universal Consonantal Strength, suggesting that the syllable is based upon semi-cycles of consonanticity followed by sonority, with the syllable boundary placed just before the consonanticity onset. Segments are assigned consonanticity values according to the following 10 level scale:

0 -	vowels	5 -	/s/
1 -	glides	6 -	voiced fricatives
2 -	/r/	7 -	unvoiced fricatives
3 -	/l/	8 -	voiced plosives
4 -	nasals	9 -	unvoiced plosives

The suggested advantage for such a system, over that of a pure sonority scale, is its ability to present a framework where the /s/+obstruent+(liquid) or clusters are tautosyllabic (these types of cluster commonly form the start of words) as is the case in Selkirk's (1982) suggested hierarchical phonological template of the syllable for English. Peereman's use of the consonant onset is also similar to that of Selkirk (1984), who suggests that syllable onsets begin with segments which have a consonanticity value of at least three greater than that of the next. Using this assumption, plus the special treatment of /s/ segments outlined above, Peereman suggests the following two syllabification rules:

(i) If a consonant is at least three points higher than that of the following consonant they are linked to form an onset (syllable boundary).

(ii) An /s/ can be included in the onset if followed by a consonant of three points or higher (plosives).

However, using the consonanticity scale proposed there are a number of cases where there is not a consonanticity onset between syllable nuclei. Because the consonanticity levels of the segment /r/ and that of glides are below three (the minimum level of consonanticity level for an attack), then no consonantal onset occurs when these segments are placed in the context of singular intervocalic consonants (giving consonanticity levels of 020, or 010) or in Liquid Glide (LG) double intervocalic consonants (0310 or 0210). To avoid this problem Peereman proposes an additional rule, based upon the Obligatory Onset Principle, which proposes that the syllable boundary should be set such that there is a single consonant onset. In these cases the syllabification will be /V.CV/ or /VL.GV/.

Using the syllabification example of the word 'moustique' we can see the different treatment of /s/ clusters from that of Coursil.

	m	u	s	t	i	k
Consonanticity ranks:	3	0	4	8	0	8

Here the syllable boundary is placed /mu.stik/ instead of /mus.tik/ using Coursil's system.

1.2.3
Dell (1995)

Dell's (1995) theories of syllabification stem from an analysis of the distribution of consonant clusters in French corpora, leading him to formulate the following assumptions, in which Dell defines the term "consonant" as 'all the consonantal sounds, but not the glides':

(i) A prevocalic consonant is tautosyllabic with the following vowel.

(ii) In an obstruent+liquid cluster the two consonants are tautosyllabic.

(iii) A postvocalic consonant is tautosyllabic with the preceding vowel provided no conflict arises with (i) or (ii).

(iv) A coda contains at most one consonant.

The second of these assumptions gives special status to obstruent+liquid clusters, as in Kahn (1976) such that the syllable boundary is always placed before these clusters. However, Dell only uses a subset of possible obstruent+liquid clusters, excepting sequences in which both segments are coronal (e.g., /tl/, /dl/, /sl/). This results in eight allowable obstruents, /p/, /t/, /k/, /b/, /d/, /g/, /f/, and /v/, in combination with liquid segments, excepting /tl/ and /dl/. The first and third assumptions can be described as a synthesis of an analysis by means of the Legality Principle with that of the Obligatory Onset Principle, assuring the presence of a syllable onset, if possible, and the legality of that onset. Also, by excluding glides from the term "consonants" Dell ensures that intervocalic clusters consisting of a consonant followed by a glide will be syllabified such that the cluster is tautosyllabic to the following vowel. The fourth assumption ensures that trisyllabic segments such as 'obstiné' (obstinate) are syllabified with a coda /b/ and an onset /st/.

Using these assumptions a simple rule can be formulated which can be used to predict the syllabification of all intervocalic consonants and singletons found in French. This rule includes glides in the set of consonants.

Divide the consonant cluster, or singleton, just after the postvocalic consonant with three exceptions; in these cases divide the cluster just before the postvocalic consonant.

Exception 1 — The postvocalic consonant is an obstruent, immediately followed by a liquid consonant, excepting /tl/ and /dl/.

Exception 2 — There is a single intervocalic consonant.

Exception 3 — The postvocalic consonant is immediately followed by a prevocalic glide.

1.2.4
Laporte (1993)

Laporte's (1993) method of syllable boundary placement was developed from the lexical study of syllable pronounceability, in that syllables are only valid if they can be pronounced in isolation. However, because pronounceability cannot be defined formally, an acceptable approximation of the pronounceability is suggested, which, if a large enough dictionary is used, results in a definition identical to that of the Legality Principle. Using such a scheme the following rules for syllable boundary placement are proposed:

(i) If a medial consonant cluster contains /p/, /t/, /k/, /b/, /d/, /g/, /f/, or /v/ followed by /l/ or /r/ it is treated as a single inseparable symbol.

(ii) Divide the cluster before the last symbol that is not a glide.

As can be seen, Laporte's syllabification procedure is similar to that of Dell's, using a similar subset of obstruent+ liquid clusters, excepting that in this case /tl/ and /dl/ are considered as tautosyllabic. The second rule of Laporte, and the first assumption of Dell though worded differently, has the same implications, both in their use of the Obligatory Onset Principle, and their treatment of glides (although explicitly worded in Laporte, Dell chooses to define his rules by means of consonants, such that prevocalic glides will always be tautosyllabic with the preceding consonant). It is in Dell's final assumption, that the coda contains at most one segment, which these two procedures significantly diverge. For this reason it is of interest to include both of these similar procedures in our review.

1.2.5
Maximum Onset Principle

The Maximum Onset Principle, as defined in the previous section of this article, is perhaps the easiest of the general syllabification principles in its implementation. Through analysis of a large enough lexicon, such as BDLex (~23000 words), it should be possible to approximate all possible onsets of French, and so calculate the Maximum Onset for any intervocalic consonant cluster.

1.3
Syllabification examples

TABLE 1

Syllabification of the words ‘obscène’ (obscene), ‘extase’ (ecstasy), and ‘astral’ (astral) according to five different theories

Model		*Syllabification*	
Coursil	/ɔ.bsɛn/	/ɛks.taz/	/as.tral/
Peereman	/ɔ.bsɛn/	/ɛk.staz/	/a.stral/
Dell	/ɔb.sɛn/	/ɛk.staz/	/as.tral/
Laporte	/ɔb.sɛn/	/ɛks.taz/	/as.tral/
MOP	/ɔb.sɛn/	/ɛk.staz/	/a.stral/

To highlight a few of the differences between the French syllabification procedures, we have presented the various syllabifications for the words ‘obscène’, ‘extase’, and ‘astral’, as shown in Table 1. One of the clearest differences between those procedures based upon sonority and phonotactic regularities can be seen with the syllabification of ‘obscène’. Here the sonority trough, and corresponding consonanticity attack, are before /b/, however, /bs/ is not a “legal” onset, and therefore the remaining procedures place the syllable boundary after /b/. With the triconsonant cluster in ‘extase’ there is greater scope for difference amongst the procedures. Here we can see the special treatment of the /s/ segment in Peereman differing from the sonority contour of Coursil; this effect is also evident in the differences between the Dell and Laporte procedures, /s/ is tautosyllabic in Dell as the coda cannot be of more than one segment. In the final example, that of ‘astral’, the tautosyllabic status of the /s/ plus Obstruent Liquid cluster given by Peereman is highlighted, in agreement with the Maximum Onset Principle, but not with the remaining three procedures.

In making a comprehensive comparison of the performance of the five syllabification procedures it is preferable to base such an analysis on the *impact* of those differences on the syllabification of the words of French. This is because the examination of few contrastive examples simply serve to highlight the differences between models (which are usually evident in rule differences), or require an uncomfortable number of examples for a comprehensive analysis. To such an end we will perform a *quantitative* analysis of the differences in syllable boundary placement between our procedures on a comprehensive lexicon of French words.

2 Lexical analysis of differing syllabification procedures

To achieve a measure of similarity between our target syllabification procedures a search was made of the BDLex French phonetically transcribed lexicon (~23000 words) for commonly found intervocalic consonant singletons and clusters. This analysis found 431 different consonant singleton/cluster types in BDLex with a total of 37221 occurrences (tokens) making an average of 1.68 singletons/clusters per word. These types are distributed as 19 singular intervocalic consonants (26963 tokens), 208 biconsonant clusters (9179 tokens), 172 triconsonant clusters (974 tokens), 28 four consonant clusters (98 tokens), and 3 five consonant clusters (seven tokens). As can be seen, in French, as with most languages, there is a direct relation between the complexity of the consonant cluster, and thus, the syllable, and the frequency of its occurrence in words.

Taking these consonant clusters and singletons each was syllabified using the five target syllabification procedures, with a comparison made of the resulting syllable boundary placement.

TABLE 2

Percentage agreement between syllabification algorithms on intervocalic consonant clusters found in BDLEX (% of types)

	Laporte			*Peereman*			*Coursil*			*MOP*		
# of Cons.	*2*	*3*	*>3*	*2*	*3*	*>3*	*2*	*3*	*>3*	*2*	*3*	*>3*
Dell	99	67	22	81	63	32	78	71	35	86	71	51
Laporte				82	68	35	79	75	51	85	79	58
Peereman							86	81	70	81	73	41
Coursil										79	68	45

TABLE 3

Percentage agreement between syllabification algorithms on intervocalic consonant clusters found in BDLEX (% of tokens)

	Laporte			*Peereman*			*Coursil*			*MOP*		
# of Cons.	*2*	*3*	*>3*	*2*	*3*	*>3*	*2*	*3*	*>3*	*2*	*3*	*>3*
Dell	99	82	9	82	43	12	93	64	14	84	78	80
Laporte				82	44	11	93	66	19	84	69	24
Peereman							85	75	88	89	61	14
Coursil										87	48	16

The percentage of syllabification agreement between procedures for clusters of between two and five consonants, both by type and token, can be seen in Tables 2 and 3. The comparison of single intervocalic consonants has not been included as all procedures agree that these boundaries should be placed according to the Obligatory Onset Principle (V.CV).

Comparing the syllable boundary placement offered by the five syllabification procedures, we can see that agreement levels remain relatively high for double intervocalic consonant clusters, where there are only two possible boundary locations. However, as the length of the consonant cluster increases, the agreement reduces. For the two procedures that share a similar background, those of Dell and Laporte, there exists almost total agreement in the syllabification of double intervocalic consonant clusters (excepting only /tl/ and /dl/ clusters). Agreement in longer clusters is greatly reduced, showing that relatively small and simple differences in syllabification rules can reap large differences when applied across a wide range of stimuli. A partial exception to this finding can be seen with the two procedures based upon the sonority scale, that of Coursil and Peereman. Whilst there is a reduction in agreement as the cluster length increases this agreement still remains relatively high (minimum 71%) even with longer consonant clusters.

These findings are more easily appreciated if our consonant clusters are arranged as a factor of the maximum number of procedures in agreement as to their syllabification. For example, the cluster /ks/ is syllabified /k.s/ by Dell and Laporte, but /.ks/ by the other three procedures, therefore the procedure agreement level for this cluster is three. Because all single intervocalic consonants are syllabified the same way by all procedures there is but a single data point, 100% of singletons with a procedure agreement level of 5. Table 4 represents the distribution of agreement amongst syllabification procedures, showing the percentage of consonant clusters (by token and type) for different levels of procedure agreement.

TABLE 4

Percentage of cluster types and tokens (types, tokens) covered by different levels of algorithm agreement for different lengths of consonant cluster

Algorithm Agreement	*# of Consonants in Cluster* 1	2	3	>3
1	0,0	0,0	0,0	0,0
2	0,0	0,0	9.2,11.5	45.2,72.4
3	0,0	17.3,14.1	19.7,39.6	16.1,6.7
4	0,0	13.9,7.7	21.4,8.9	22.6,8.6
5	100,100	68.8,78.2	49.7,40.0	16.1,15.3

As can be seen, Table 4 shows that as the length of the consonant cluster increases there is less agreement between syllabification procedures. Separating consonant clusters in this way may have an additional benefit, in that the level of agreement amongst syllabification procedures could be used as a measure of syllabification *confidence*. Take, for example, the cluster /lm/, this is syllabified as /l.m/ by all of our procedures, and so has an agreement level of 5. For this cluster, the different procedures of syllabification converge. There is no procedure that suggests that this cluster should be syllabified in any other way. However, taking our previous example, /ks/, we find that there is controversy amongst the syllabification procedures: three predicting the syllabification /.ks/ the remaining two /k.s/. Because, at the present time, we have no means of deciding which of the procedures is "correct," we have no way to decide which of these two segmentations we should use.

One possible solution would be to use the syllabification given by the majority of procedures, however this assumption requires that segmentation "errors" are equally distributed between all procedures. Given the wide theoretical differences between some procedures, and similarities between others, the validity of this assumption is highly unlikely. A workable alternative is the measure of confidence. For those clusters, like /lm/ where there is no controversy surrounding syllable boundary placement we can have a high level of confidence in its syllabification, for others, like /ks/ where the level of agreement is lower we have less confidence. The use of confidence, while not resulting in a definite syllable boundary placement, is useful in highlighting the types of consonant cluster that present the greatest problems and so require further study. This measure could be useful in applications where the correct assignment of the syllable boundary is of utmost importance, in this case, if there is leeway in the choice of consonant cluster under analysis, then priority should be given to those in which we have the greatest syllabification confidence. It is interesting to note that, taking all intervocalic consonant clusters and singletons, just over 58% of types and, more importantly, 93% of tokens, are syllabified with all procedures in agreement, and so at the highest level of confidence. This finding also suggests that those consonant clusters which give greatest problems to syllabification are significantly less frequent in the lexicon than their less controversial counterparts, although it must be stated that this is mostly due to the frequent occurrence of single intervocalic consonants.

To summarize, it appears that even procedures based upon similar theoretical lines, with only minor rule alterations, will yield large differences in syllable boundary placement, especially as the consonant cluster increases in complexity. This finding suggests that each of the syllabification procedures are significant in their own right, and as such it is not possible to ignore any of the procedures because their practical, if not theoretical, behavior matches another. However, even with these differences there exist a significant number of clusters where the procedures converge on syllable boundary placement. In these cases the number of procedures in agreement can be used as a measure of confidence, the larger the degree of convergence, the more confident we can be that that particular syllabification is correct. However, whilst this measure can be useful in our analysis of syllabification it cannot help in the definition of the syllable, only inform where the problems might lie. What is required is a form of benchmark, a set of consonant clusters in which we can be certain of the syllable boundary placements such that the procedures may be tested against an impartial measure, instead of the subjective analysis produced when they are compared against each other. Therefore it is necessary to turn to the only natural source of information for syllable boundary placement, the naive listener, in order to produce such a benchmark.

3 Syllable perception experiment

There has been growing interest in the use of metalinguistic tasks for the comparison of phonological theories of syllabification in order to establish which of the many principles of syllabification are followed by listeners. Thus far a large majority of this work has been performed on the English language (Fallows, 1981; Titone & Connine, 1997; Treiman & Danis, 1988; Treiman & Zukowski, 1990; Treiman, Gross, & Cwikiel-Glavin, 1992), and, to a lesser extent for the Dutch language (Gillis & DeSchutter, 1996). It is only recently that similar studies have been made for French (Floccia, Goslin, Bouketir, & Bradmetz, 1999; Goslin, Content, & Frauenfelder, 1999; see Content, Kearns, & Frauenfelder, in press).

In these studies a number of different tasks have been suggested to elicit syllable boundaries from experimental participants, and may be split into two categories, orthographic, and oral. Orthographic tasks usually involve the presentation of the written form of word, or nonword, for which they have to select the correct hyphenation (Treiman & Danis, 1988; Treiman & Zukowski, 1990; Treiman et al., 1992). Oral syllabification tasks are many and varied, examples of such are first or second syllable doubling (Fallows, 1981) (such that the word 'cobra' is repeated as "cocobra" or "cobrabra"), or the tapping task (Floccia et al., 1999; Liberman, Shankweiler, Fischer, & Carter, 1974) where participants repeat the word tapping at each syllable and inserting a pause at syllable boundaries. Two other tasks, syllable reversal (Treiman & Danis, 1988) ('cobra' repeated as "bra [pause] co"), and first or second syllable repetition (Content et al., in press; Treiman et al., 1992), are very similar, excepting that the repetition of the first and second syllables may be blocked separately for the latter task.

Unfortunately there are a number of unwanted influences which may affect some, or all, of these tasks to a greater or lesser degree. These influences are due to orthography, contingency, and off-line processes. The first of these concerns the possible influence of orthographic division rules, learnt at school, on syllable boundary placements (Pulgram, 1970). Although this is considered of greater importance on written tasks, the orthographic form of a word used in oral tasks may also have an influence upon its syllabification (Treiman & Danis, 1988). The second contaminating influence is that of contingency, that is, both syllables in a segmentation task are extracted in close proximity. This influence, particularly prevalent in the syllable doubling, or tapping task, and to a lesser degree in the syllable reversal task, suppresses the possibility of an ambisyllabic response, as the close proximity of the two syllables makes such a response sound "unnatural." For example, when segmenting the word 'cobra' the participant may repeat "co bra" or "cob ra," but an ambisyllabic response, "cob bra," is unlikely because the repetition of /b/ would not be natural to normal speech. The last influence is related to the metalinguistic nature of all of the previous oral syllabification tasks. As we are interested in the syllabic representation used in real-time speech processing, the role of metalinguistic knowledge, or strategies, in syllabification responses is a potential source of experimental contamination.

Perhaps the optimal task, that which reduces these contaminating influences to the minimum, is that of syllable repetition. In this task nonword stimuli can be used to reduce the possible influence of orthographic knowledge. Also, by separating the repetition of the first and second syllables into different experimental blocks the problem of contingency is virtually eliminated. Finally, by running a speeded task, giving the participants only the minimum amount of time to repeat the required syllable, we hope to reduce the influence of metalinguistic knowledge or strategies to a minimum, although it is acknowledged that this factor may only be reduced with the use of an on-line task.

3.1 *Stimuli*

3.1.1 *Test items*

To present the widest range of possible stimuli suitable for a general study and comparison of syllable boundary placement, stimuli were selected from all consonant types: nasal

(N), fricative (F), liquid (L), and plosive (P). Glides were not used because of their association with the syllable nucleus. Using these natural classes, stimuli were organized into 4 singleton and 16 double (e.g., FN) (refer to Fig. 2 in Section 3.4.2 below for a full list of these categories), and three triple (PFP, LPL, and NPL) consonant categories. Depending upon the availability of consonant clusters, these categories contained between one and three different clusters. Each consonant cluster/singleton was repeated a number of times such that there were always six tokens per category. For example, the consonant category FF contains only one legal cluster, /sf/, whilst FP contains many (e.g., /ft/, /sp/), to make six tokens per category /sf/ must be repeated six times, but for FP three clusters were selected, each repeated twice to make six tokens. This arrangement increases stimuli variation, and experimental coverage, whilst the number of observations per consonant category remains constant. A full list of all consonant clusters and singletons used can be seen in Appendices A, B, and C.

To create a bisyllabic nonword, a random selection of vowels was placed at the start and end of each consonant singleton/cluster (forming VCV, VCCV, and VCCCV stimuli) taken from {/u/, /i/, /a/, /y/}. These vowels were thought not to affect syllabification, unlike the mid vowels, which may induce differences in syllabification between different aperture pairs. The distribution of these vowels are also unaffected by vowel harmony (e.g., Tranel, 1988), constraining the aperture of mid vowels in nonfinal syllables by the aperture of the vowel found in the following syllable. This organization of stimuli resulted in 138 tokens, with 57 clusters/singletons, and 23 consonant categories. Examples of such stimuli are /igla/ or /upy/.

3.1.2
Training items

A total of 10 training items were also generated in similar form to that of the test items using the same distribution of VCV, VCCV, and VCCCV stimuli used in the test set, but using different consonant cluster/singletons.

All stimuli were produced by a monolingual, naive, native French speaker (Parisian accent) from a randomized phonetized list of nonwords, with a pause of three seconds inserted between the production of each stimulus. These nonwords were recorded onto DAT and then digitized at a fidelity of 22.05 kHz, with 16 bits per sample, for storage on computer and presentation to participants over headphones.

3.2
Procedure

Participants were asked to repeat either the first or second part of the bisyllabic stimuli. Experimental stimuli were arranged into three blocks, each of which was presented under two conditions, that is, the repetition of either the first syllable (Condition 1) or second syllable (Condition 2) of the stimuli. Stimuli order for each block was randomized for each presentation. Stimuli in each block were presented on a continuous basis, one every two seconds without pause until the end of the block, where participants were invited to take a short pause. Participants were asked to respond, according to experimental condition, to each stimuli immediately upon presentation, with the quickest possible response. The participants verbal responses were recorded onto DAT and transcribed after the experiment. The experimental condition alternated on each successive block, with blocks ordered such that block repetitions (for the 1st and 2nd condition) were never adjacent to each other. At the start of the experiment, two short training blocks of 10 stimuli were presented, one for each experimental condition.

3.3 *Participants*

All 22 participants were students of the Université de Genève and were native speakers of French with no known hearing defects. They received course credits for their participation.

3.4 *Results*

3.4.1 *Error rates*

Errors consisted of missing responses, mispronounced repetitions (using phonemes not found in the original stimuli) and repetition of the total stimuli (both syllables). Error rates averaged at just under 2% of the possible responses. There was no significant effect of consonant cluster on error rates, with the highest participant error rate at 8%

3.4.2 *Segmentation*

A summary of the segmentation results for single and double intervocalic consonant clusters can be seen in Figures 1 and 2, respectively. Full results for all of the intervocalic consonant clusters and singletons can also been seen in Appendices A, B, and C.

Segmentation responses were analyzed separately for each of the experimental conditions (first and second syllable repetition). For each cluster type a chi-squared was calculated on the frequencies of possible responses for single, double, and triple consonant stimuli to determine whether there was a preferred category of response. In most cases, the chi-squared was higher than the critical level (at $p < .05$, 3.841 ($df = 1$), 5.991 ($df = 2$), and 7.815 ($df = 3$) for ascending lengths of consonant clusters) indicating a preferential segmentation response. Those clusters/ singletons which did not yield significant preferential responses were only found in the first condition, consisting of /ks/ and all single intervocalic consonants excepting /t/, /d/, and /l/.

For all clusters and singletons, bar one, there was agreement between the preferential segmentation of all stimuli within each particular consonant category (FN, PF, etc.). There was also agreement between the preferential segmentations of these consonant categories for each of the experimental conditions, first and second syllable repetition. The exception to both these cases was the obstruent+liquid cluster /vr/, whose preferential segmentation was /v.r/ for the first condition but /.vr/ for the second. This cluster was also at odds with the other found in the FL consonant category, that of /zl/, whose preferential segmentation was /z.l/ in both conditions. However, it should be noted that /zl/ is not considered an obstruent+liquid cluster by Dell or Laporte.

Leaving this cluster aside for the moment, and examining the preferential segmentation of all other consonant clusters and singletons, we find a clear pattern of segmentation

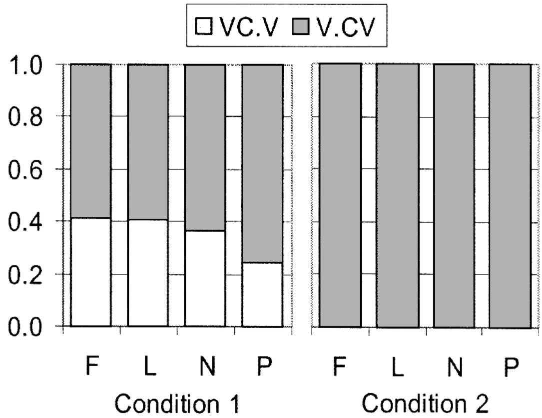

Figure 1

Proportions of subject syllabification responses for experimental Condition 1 and Condition 2 for all consonant categories of single consonant stimuli.

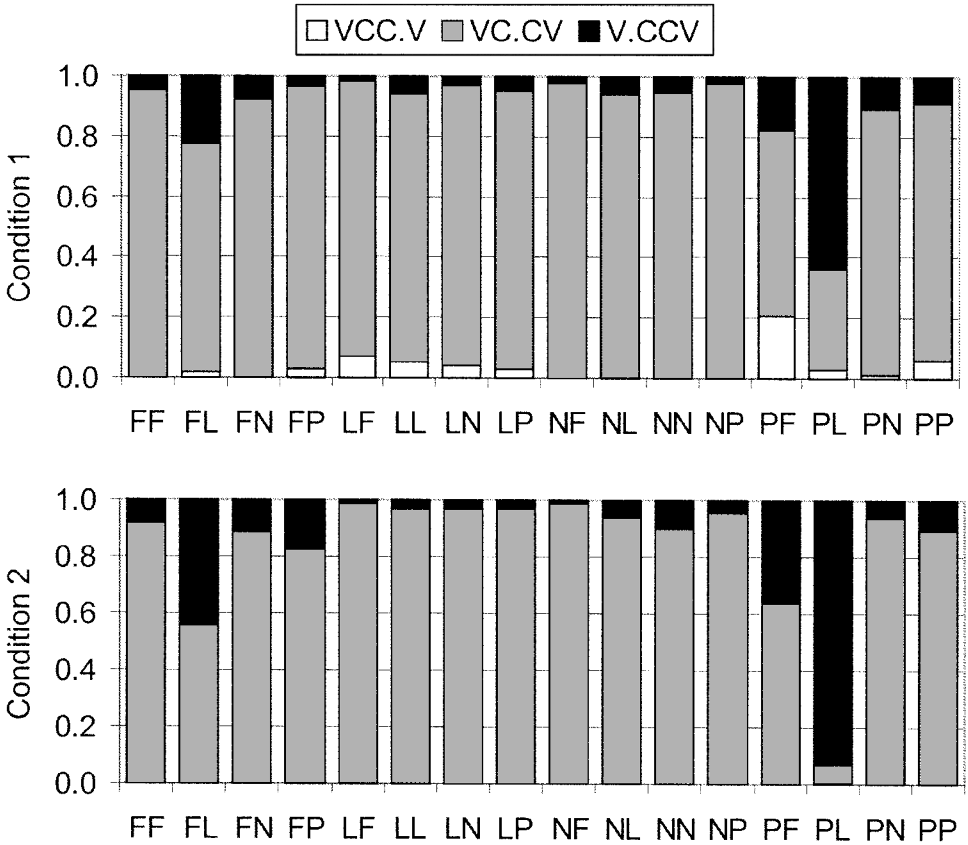

Figure 2

Proportions of subject syllabification responses for experimental Condition 1 and Condition 2 for all consonant categories of double consonant cluster stimuli.

for our stimuli. In single intervocalic stimuli, segmentation occurs before the consonant /V.CV/. For double consonant stimuli, segmentation results in a single consonant onset, excepting obstruent+liquid clusters (/gr/, /br/, and /gl/ from our test data) which are segmented with a double consonant onset /V.CCV/. Triple consonant cluster stimuli are segmented with a double consonant onset for NPL and LPL consonant categories, and a single consonant onset for that of PFP (/ksp/ and /kst/ clusters).

3.4.3
Experimental condition

Another finding of this experiment was the difference in syllable boundary placement consistency between experimental conditions, first or second syllable repetition. As can be seen in Figure 1, and, to a lesser degree in Figure 2, the percentage of participant responses for the preferred boundary placement, that is the segmentation given by the majority of participants, is higher for condition 2 than condition 1 for the majority of consonant categories. In order to test this observation a repeated ANOVA was conducted using participants responses from double consonant stimuli as the dependent variable. The main effect of experimental condition was also found to be significant across all cluster types, $F(1,20) = 13.95$ $p < .01$.

3.5
Discussion

3.5.1
Differences in syllabification consistency between first and second syllable repetition

Our analysis of the results suggests that, with the significant difference in syllabification consistency between conditions, the second condition may be a more reliable measure of syllabification than the first. Apart from that of the cluster /vr/, there is agreement in the preferential segmentation between the first and second conditions. However, whilst all of the clusters and singletons from the second condition yielded a significant preferential response, this was not the case for the responses from the first condition. This disparity in syllabification consistency between the two conditions would appear to suggest that participants found that syllable boundary placement was easier for second syllable repetition than first. This effect is particularly prevalent in the segmentation of single intervocalic consonants. These cases are of particular interest, as in these cases all of the syllabification procedures tested are in agreement, with segmentation following the Obligatory Onset Principle. For responses from the second experimental condition, over 99% of participant responses were in agreement with this principle. However this is not the case for that of the first, with average agreement of only 60%. Similar differences in consistency between the repetition of the first and second parts of stimuli were also found in an unspeeded study of syllable boundary placement in single intervocalic consonant stimuli (Content et al., in press). In this study such effects are cited as evidence against the boundary hypothesis of syllable segmentation, which implies that the offset of a syllable must coincide with the onset of the syllable that follows. Instead, an "onset hypothesis" is suggested in which distinct operations are used to detect syllable onsets and offsets, with the former providing reference points for segmentation and lexical access. These conclusions are drawn by associating the processes of syllable offset and onset detection with the first and second experimental conditions. For first syllable repetition, it is suggested that the syllable boundary is set by the detection of the end of that syllable, its offset. However, for second syllable repetition, the boundary is set by the detection of the start of the syllable, its onset.

If this hypothesis is correct, and there are different mechanisms for the detection of syllable onsets and offsets, this should be reflected in the distribution of syllabification consistency across different consonant clusters/ singletons. If a correlation was found between the consistency of syllable onset and offset placements then it is less likely that distinct operations were used for the detection of syllable onsets and offsets, as different consonant clusters/ singletons are treated in the same manner by both operations. To test this supposition a test of correlation was made between the percentage of participant responses for the preferential segmentation of each cluster/ singleton (excepting that of /vr/, as the preferential segmentation was not the same for both conditions) for condition 1, offset detection, and condition 2, onset detection. The results showed that there was no significant correlation in syllabification consistency ($r = 0.162$, $t(54) = 1.216$) between onset and offset detection. However, further analysis showed that this result was only due to the syllabification behavior of single intervocalic consonants (10 singletons, 17.24% of data set). If these stimuli are removed from the analysis then a significant positive correlation is found ($r = 0.507$, $t(44) = 3.945$ $p < .05$) in syllabification consistency between onset and offset detection. It is suggested that the tenets of the onset principle are upheld when using single intervocalic consonant stimuli. However, for stimuli of greater complexity there is little difference in syllabification consistency between onset and offset detection, with average consistency levels of 87.78% and 90.57% for condition 1 and 2 responses.

Another factor which could explain the differences found between the syllabification consistencies in conditions one and two in single intervocalic consonants is that of stress. In French the influence of stress is limited to the postlexical level, known as rhythmic stress, consisting of final (primary) stress and nonfinal (secondary) stress (Di Cristo, 1998). In the case of the stimuli used in the present study only the influence of final stress needs to be examined, which is regularly assigned to the final full syllable of the last lexical item of a stress group (Di Cristo, 1998). In this case all of the final syllables of our bisyllabic stimuli can be considered as stressed, with the first syllables remaining unstressed. In English the influence of stress upon syllabification is widely acknowledged in linguistic theory (e.g., Hooper, 1972; Kahn, 1976; Pulgram, 1970; Selkirk, 1982), agreeing that VCˈV segments should be syllabified as V.CˈV. In an empirical examination of the syllabification of intervocalic consonant clusters in English, Treiman and Danis (1988) also found a significant effect of stress upon syllable boundary placement. Subjects responded with a greater number of V.CV responses when the second, rather than the first, syllable was stressed. A similar effect could also explain the similar findings of the present study of French syllabification. It is possible that it is the primary stress on the final syllable that is the cause of greater syllabification consistency in second, rather than first, syllable repetition for single intervocalic consonant stimuli. Unfortunately, as only bisyllabic stimuli were used in the present study the possible effects of stress upon syllabification cannot be tested. However, further studies are now being conducted to examine this effect using trisyllabic stimuli.

3.5.2
Differences in syllabification consistency between consonant clusters

Examining the distribution of syllable segmentation shown in Figure 1, other disparities of segmentation consistency can also be seen, this time between different consonant categories of double consonant stimuli. For example, taking results from the second experimental condition, some consonant categories like NF have segmentation consistencies of 98.5%, others, such as PF, have only 63.6% consistency. We propose two different hypotheses to explain this disparity. The first of these is based upon the relative frequency of occurrence of the various consonant clusters, and the second, upon the availability of multiple legal onsets. The first suggests that participants are able to segment those consonant clusters that are relatively common in the language without difficulty, whilst encountering problems with those that are less familiar. In this case, consonant clusters with a high frequency of occurrence will have higher segmentation consistency than those of lower frequency. The second hypothesis is based upon the Law of Initials of the Legality Principle, suggesting that if, for a particular consonant cluster, there are multiple legal onsets available then, because of the choices offered in syllable boundary placement, that consistency will be lower than if only one legal onset were available.

To test the first hypothesis, a measure of the frequency of occurrence has to be found for each of the double consonant clusters. This was produced by searching the BRULEX lexicon (Content, Mousty, & Radeau, 1990), a phonetic lexicon containing word frequency information, with the frequency of occurrence of each consonant cluster calculated as the sum of all word frequencies containing that cluster. Using this information, tests of correlation were made between the proportion of participant responses held by the preferred segmentation for each double intervocalic consonant cluster and the natural log of its frequency for both experimental conditions (onset and offset detection). If the hypothesis is correct there should be a significant positive correlation between these factors, indicating the relationship between consonant cluster frequency and syllabification consistency. The results showed that there were no significant positive correlations for the first ($r = -0.456$, $t(39) = -3.198$) or second $r = -0.26$, $t(39) = -1.7$) experimental conditions, therefore there is no evidence to support the first hypothesis.

To verify the second hypothesis, a search of BDLex gave the number of possible legal onsets, excluding those not in agreement with the Obligatory Onset Principle, for each of the double intervocalic consonant cluster. (e.g., the cluster /ft/ has two legal onsets, /ft/ and /t/, whilst the cluster /mv/ has only one, /v/). Correlations were then made between the proportion of participant responses held by the preferred syllable boundary for each double intervocalic consonant cluster and the number of possible onsets for each cluster for both experimental conditions. If the hypothesis is correct there should be a significant negative correlation between these factors, indicating the inverse relationship between availability of multiple legal onsets and segmentation consistency. For responses from the first experimental condition there was no significant negative correlation ($r = -0.11$, $t(39) = -.692$) between the two factors. However, for syllable onset detection responses there was a significant negative correlation ($r = -0.656$, $t(39) = -5.423$; $p < .05$). Examining the set of obstruent + liquid clusters considered tautosyllabic by Dell and Laporte we found that whilst two onsets were available for these clusters, segmentation consistency remained high. If we follow Dell and Laporte's suggestion and treat these clusters as a special case, such that they only have one possible onset (V.CCV), then the negative correlation increases ($r = 0.706$, $t(39) = -6.218$; $p < .05$).

Whilst the results of the previous section showed little overall difference in syllabification consistency between onset and offset detection, the results of this section suggest that the underlying processes behind both operations may be different. This finding is discussed at greater length in the general discussion.

4 Comparison of human and theoretical syllabification

It is now possible to compare segmentation results from the syllable perception experiment with the theoretical responses of the five syllabification procedures. We applied each of the five syllabification procedures to the test set of 57 consonant clusters and singletons used in the perception experiment. Each resulting syllabification was compared to that of the preferential segmentation obtained from the perception experiment. A similar comparison was also made between the results of the perception experiment, and the syllable boundary placements used for the test set of clusters and singletons in BDLex (those that are not affected by prefix or lexical boundaries). BDLex, being the only French lexicon with phonetic transcriptions including syllable markings, is sometimes used as a reference in the design of experimental stimuli. Therefore, a comparison of the segmentation used in this lexicon and the results of the syllable perception experiments could highlight a possible source of experimental contamination in experiments that investigate or utilize the syllable.

The case of the cluster /vr/, with its different, some might say, ambisyllabic, segmentations found in the first and second experimental conditions was problematic. Which of the two segmentations is used as the reference? It was decided that the segmentation /.vr/, found in syllable onset detection, should be used as the reference for this cluster. This was because this segmentation behavior is more consistent with the other obstruent+liquid clusters tested in this experiment, and also because the proportion of segmentation decisions for /v.r/ in condition 1 (55%) is lower than those for /.vr/ in condition 2 (75%).

As can be seen from Figure 3, the agreement between theoretical and empirical syllabifications is relatively high, with a minimum agreement of 73% of consonant clusters/singletons (for Coursil). Of the five syllabification procedures, it is the two procedures based upon the phonotactic regularities of French that show the best agreement with our participants, responses, with the procedure of Laporte showing complete agreement with their preferential segmentation. Using this test set, the procedure of Dell differs from that of Laporte on only one consonant category, that of PFP (/tl/ and /dl/ obstruent+liquid clusters were not used in the perception experiment). Whilst Laporte, and the participants, segmented this cluster as /PF.P/, because Dell only allows a single consonant coda, he syllabifies this cluster as /P.FP/. For the other triconsonant consonant categories, /NPL/ and /LPL/, there is agreement between the two procedures because the /PL/ in the stimuli used forms an obstruent+liquid cluster, syllabified as /N.PL/.

The remainder of the syllabification procedures, that of Peereman, Coursil, and MOP, show much less agreement with empirical data than those described previously. These disagreements are due to the inherent nature of these procedures, to set the onset of the syllable

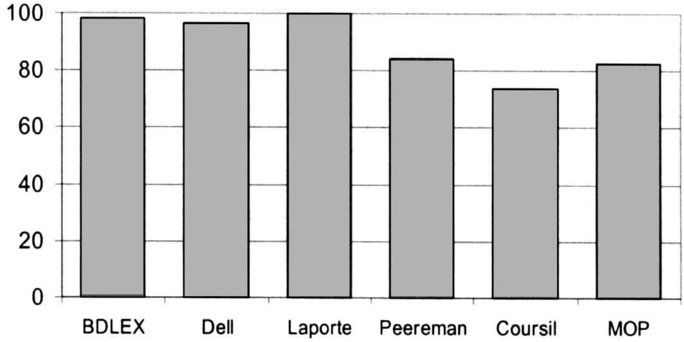

Figure 3

Percentage agreement (%) between the theoretical syllabification predictions and experimental syllabification responses

to the maximum theoretically allowable, be it by measure of sonority, consonanticity, or legality. However, empirical evidence, and the theories of Laporte, point towards the opposite hypothesis, that of reducing the onset to a single consonant or obstruent+liquid cluster (using Laporte or Dell's definition). One of the clearest examples of this behavior is in Peereman's special treatment of the /s/ segment, such that it can be tautosyllabic with a following plosive. Empirical results show that in each of these cases (/st/, /ks/, /ksp/, /kst/) the /s/ forms part of the coda, reducing rather than maximizing the length of the onset.

A comparison of the syllabification markings found in BDLex with those of our empirical results shows a very high level of agreement, with only one conflict between the two, that of the cluster /ml/. In BDLex this cluster is syllabified as /.ml/ instead of the participant's preferential segmentation of /m.l/. This cluster only occurs once in the BDLex lexicon, in the word 'cromlech', a borrowed word. However, taking a similar cluster, like the more frequent /nl/, there is agreement in its syllabification as /n.l/. Therefore it appears that the only disagreement between the syllable markings of BDLex and the responses of our participants is due to an exceptional syllabification used for a loan word.

In the previous section we proposed a measure of syllable boundary confidence for each consonant cluster, calculated from the number of syllabification procedures that agreed on its syllabification. If the theoretical principles on which these procedures are built are influenced by observations of empirical syllabification, then a possible reason for the divergence of syllable boundary placement amongst these procedures may be due to an uncertainty amongst naive listeners as to the syllabification of some consonant clusters. Differences amongst the procedures would then be reflections of this uncertainty, created by conflicting syllabification "evidence" used in the formulation of these procedures. If there is a link between participants, syllabification consistency and the confidence for a particular consonant cluster, then it may suggest that the lack of agreement amongst syllabification procedures may be due, at least in part, to the syllabification inconsistency of listeners. To test this supposition a correlation was calculated between the confidence levels of consonant clusters and the proportion of responses (taken from the second experimental condition) given to the preferential segmentation. This analysis showed a significant, but not strong, positive correlation ($r=0.5$, $t(39)=4.321$; $p<.05$) between confidence levels and syllabification consistency. This suggests that the divergence of some syllabification procedures could have been affected by differences in empirical results used in their formulation, although it is admitted that these results can only point to a possible influence upon this divergence, not a direct causal link.

5 General Discussion

The aim of this paper was to better understand French syllabification, to take the various procedures used in syllable boundary placement, highlighting their similarities and differences, and comparing them against the syllabification of naive listeners. The first step in this process was a practical examination of these procedures, by applying them to all intervocalic consonant clusters and singletons found in the French lexicon BDLex. This analysis uncovered a number of findings. First, for the majority of consonant clusters, and all singletons, there is general agreement in syllable boundary placement across all procedures. However, this agreement is not equal across all types of consonant cluster. As the length of the consonant cluster increases, and the relative frequency of occurrence decreases, there is greater divergence in the placement of the syllable boundary. Second, although some of the procedures have significant philosophical and theoretical similarities, in practice, minor rule differences will yield significant differences in syllable boundary placement, especially as the consonant cluster increases in complexity. This finding suggests that each of the syllabification procedures is significant in its own right, and as such, it is not possible to ignore any of the procedures because their practical, if not theoretical, behavior matches that of another.

As there were significant, practical, differences amongst the proposed procedures, it was necessary to obtain another, empirical, type of data to benchmark syllable boundary placement. In order to obtain syllable boundary preferences from naive listeners, a metalinguistic syllable repetition experiment was performed using a broad range of single, double, and triple consonant stimuli. An examination of the responses from this experiment painted a relatively simple picture of human syllabification, following that of the Obligatory Onset Principle, in that, in the majority of cases stimuli were syllabified with a single consonant onset. The only exceptions to this rule were due to obstruent+ liquid clusters, which were found to be tautosyllabic, forming a double consonant onset. Comparing these results with the predictions of the five syllabification procedures, we find that only one, that of Laporte, provides a perfect match with the preferential segmentation of our participants. Whilst that of Dell is also in total agreement with single and double intervocalic stimuli, it diverges with longer stimuli as Dell only allows a single consonant coda. The human results provide little evidence to support the use of sonority, consonanticity, or the Maximum Onset Principle, embodied in the remaining three procedures.

A comparison of the results of this present study and of other studies comparing theoretical and human syllabification in English reveals a number of similarities between segmentation strategies employed by French and English experimental subjects, if not in the conclusions drawn from these results. Using a similar syllable repetition task, Treiman et al. (1992) found that /s/ + stop and /s/ + sonorant clusters, whilst perfectly legal onsets, were not syllabified according to the Maximum Onset Principle, but split between coda and onset, only obstruent+ liquid clusters were syllabified with a double consonant onset. Because these results run contrary to both the Maximum Onset Principle, and that proposed by the sonority cycle (and also Peereman and Coursil), Treiman et al. (1992) suggest that clusters beginning with /s/ do not form legal onsets. The results of Treiman et al. (1992) are of particular interest in relation to the current study as both the Maximum Onset Principle and Sonority Cycle are claimed to be applicable cross-linguistically (e.g., Clements, 1990; Pulgram, 1970) and are directly applicable to both English and French. Our metalinguistic syllabification experiment, using a broader range of consonant clusters than that of Treiman et al. (1992), show that, in French, the syllabification of clusters with the /s/ segment was no different than any other nonobstruent + liquid cluster. Although the procedure based upon the Maximum Onset Principle, and those proposed by Coursil and by Peereman failed to reproduce our participant's preferential segmentation for these clusters, these procedures also failed on a broad range of other clusters. Therefore, it appears that the mismatch between the predictions of these procedures and the syllabification responses given by French listeners is far more serious than that suggested by Treiman et al. (1992) for English, and cannot be alleviated by granting "special" status to situations, such as the /s/ clusters, where they fail to agree with human syllabification.

Because of the theoretical problems associated with /s/ clusters, other evidence has been presented in defense of the use of sonority in human syllabification. It is suggested (Treiman & Danis, 1988) that, for English single intervocalic stimuli, sonorants are more closely linked to the preceding vowel than are obstruents. This is taken as evidence for the use of sonority as this behavior fits with the preferred contour of a steep sonority rise up to the nucleus of a syllable, and slow decline after. Examining participant responses from the first experimental condition (offset detection) we see similar differences in /VC.V/ responses for plosive and liquid categories (40.8% of responses for Liquid clusters, 24.4% for Plosive) for French listeners. However, no such effect was found in the second experimental condition, onset detection (0.8% response for both categories). Unfortunately, the experimental tasks presented in Treiman and Danis (1988) could not show the disparity between onset and offset detection. A theory of particular relevance to this finding is that of the "onset hypothesis" (Content et al., in press), which suggests that distinct operations are used for syllable onset and offset detection, with the former used for segmentation. If this were the case then, the evidence for the use of sonority, found with singular intervocalic consonants, is moot as it is only found in syllable offset detection, which would be of little importance to syllable segmentation.

Whilst the syllabification consistency results of our experiment are in agreement with the tenets of the onset principle, with higher consistency for onset rather than offset detection, for single intervocalic consonants, this was not the case for more complex, VCCV, and VCCCV stimuli. In addition, it is also possible that the stress on the final, or second, syllable could also have an effect on the differences in syllabification consistency between first (offset), and second (onset) syllable repetition for single intervocalic consonant stimuli. The theoretical effects of stress in these cases would also account for the findings predicted by the onset hypothesis. However, whilst there appears to be little evidence to support the hypothesis that, globally, syllable onsets are detected more consistently than offsets, other analyses suggest that the underlying processes behind these operations may be seperate. These analyses concern disparities in syllabification consistency exhibited between different consonant clusters. Some consonant clusters, PF for instance (63.6% consistency), show low levels of consistency, whilst others, like NF (98.5% consistency), show high consistency levels. Analyses showed an inverse relationship was also found between the number of legal onsets available for a particular consonant cluster (1 or 2) and its syllabification consistency, but only for syllable onset detection, and not offset detection. In addition, it was found that obstruent+ liquid clusters, each with two possible legal onsets, have consistency levels similar to consonant clusters with only one legal onset, supporting the theory that obstruent+ liquid clusters are indivisible. These results support the theory that different processes are used for syllable onset and offset detection, with syllable onset detection influenced by the Law of Initials of the Legality Principle. This suggests that onsets are only chosen from those legally available, and that if there is a choice of legal onsets available for a particular consonant cluster, syllabification consistency is lower than if there were only a single legal onset.

As for syllable segmentation preference laws, we suggest that those of Laporte, with syllable boundary placed before the last segment which is not a glide, with a subset of obstruent+liquid clusters (/p/, /t/, /k/, /b/, /d/, /g/, /f/, or /v/ followed by /l/ or /r/) treated as a single segment, are closest to French behavior. In essence these rules form a Minimum Allowable Onset Principle, that the syllable boundary be placed such that the onset is of minimum length as long as it is in agreement with the Obligatory Onset Principle and the special treatment of obstruent+liquid clusters.

However, though we have proposed a model of syllabification that satisfies the preferential segmentation of our experimental participants, a number of questions remain unanswered. First, will this model reflect the syllable boundary placement of listeners outside of our test set of consonant clusters? The only clear solution to this problem is the implementation of further metalinguistic testing over wider ranges of consonant cluster, as only 57 (13%) of the 431 possible consonant clusters and singletons have been analyzed in this study. Another question concerns the findings of divergent syllabification consistency levels for differing consonant clusters. Although we have proposed a possible explanation as to *when* low syllabification consistency occurs, we have no knowledge of the mechanisms that drive participants in their choice of syllable boundaries in these cases. It must also be noted that this study of syllable segmentation was made in French, a language with a relatively clear syllable structure. What then of other languages, such as English, in which the role of the syllable is more complex or opaque? If current syllabification models cannot explain French syllable structure with accuracy, then it is likely that greater problems would arise in the prediction of syllable boundaries in English.

One of the reasons for syllabification inconsistencies might lie in the approaches used in current phonological syllable segmentation theory. As has been seen, the principles and procedures that have been proposed for syllable segmentation have only a single deciding cue for syllable boundary placement, the nature of the intervocalic consonant cluster. However, analyses have shown that this cue is insufficient in the accurate prediction of syllable boundaries, with varying levels of segmentation consistency for different consonant clusters. Therefore, it appears that improvements to syllable segmentation theory will require the examination of cues which lie outside of the consonant cluster.

One influence which has not been considered in this study is that of the vowel. For English it has been proposed that the nature of the vowel, being lax (short) or tense (long), can have an effect upon syllabification (Pulgram, 1970). Such an effect has been noted in metalinguistic tasks involving the syllabification of single intervocalic consonants (Treiman & Danis, 1988), with lax vowels encouraging closed syllables, and tense vowels the reverse. Although French has no lax/tense differences, similar results have been found in a preliminary study on the effect of vowel aperture on syllable boundary placement (Goslin et al., 1999), with open vowels encouraging closed syllables, and closed vowels the reverse.

If these preliminary studies are correct, then syllable boundary placement *is* affected by factors found outside of the consonant cluster, and the model of syllabification we have proposed is incomplete. Therefore, it appears that the search for an answer to the problem of syllable segmentation is, as yet, unfinished, with further study required on the factors influencing this process before we can achieve a clear definition of the syllable.

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Appendix A

Proportions of segmentation responses for single consonant stimuli in experimental conditions 1 (first syllable repetition) and 2 (second syllable repetition)

		Condition 1		*Condition 2*	
Consonant	*Category*	*/V.CV/*	*/VC.V/*	*/V.CV/*	*/VC.V/*
/s/	F	0.51	0.49	1	0
/z/	F	0.59	0.41	0.98	0.02
/v/	F	0.66	0.34	1	0
/l/	L	0.75	0.25	0.98	0.02
/r/	L	0.43	0.57	1	0
/n/	N	0.60	0.40	1	0
/m/	N	0.67	0.33	1	0
/t/	P	0.86	0.14	1	0
/p/	P	0.57	0.43	1	0
/d/	P	0.83	0.17	0.98	0.02

Appendix B

Proportions of segmentation responses for double consonant stimuli in experimental conditions 1 (first syllable repetition) and 2 (second syllable repetition)

		Condition 1			Condition 2		
Cluster	*Category*	*/V.CCV/*	*/VC.CV/*	*/VCC.V/*	*/V.CCV/*	*/VC.CV/*	*/VCC.V/*
/sf/	FF	0.05	0.95	0	0.08	0.92	0
/vr/	FL	0.42	0.55	0.03	0.75	0.23	0.02
/zl/	FL	0.03	0.97	0	0.15	0.85	0
/zn/	FN	0.07	0.93	0	0.09	0.91	0
/zm/	FN	0.02	0.98	0	0.09	0.91	0
/vn/	FN	0.14	0.86	0	0.16	0.84	0
/st/	FP	0.02	0.90	0.07	0.14	0.86	0
/ft/	FP	0	1	0	0.27	0.73	0
/zb/	FP	0.09	0.89	0.02	0.12	0.88	0
/rʒ/	LF	0	0.90	0.1	0	1	0
/rv/	LF	0.02	0.91	0.07	0.02	0.98	0
/rz/	LF	0.02	0.95	0.02	0.02	0.98	0
/rl/	LL	0.06	0.88	0.05	0.03	0.97	0
/rm/	LN	0.02	0.91	0.07	0.05	0.95	0
/rn/	LN	0.05	0.93	0.02	0.02	0.98	0
/lm/	LN	0.02	0.95	0.02	0.02	0.98	0
/rd/	LP	0.02	0.95	0.02	0.02	0.98	0
/rb/	LP	0.07	0.86	0.07	0.05	0.95	0
/ld/	LP	0.05	0.95	0	0.02	0.98	0
/mv/	NF	0	1	0	0.02	0.98	0
/nv/	NF	0.05	0.95	0	0.02	0.98	0
/nl/	NL	0.05	0.95	0	0	1	0
/ml/	NL	0.07	0.93	0	0.14	0.86	0
/mr/	NL	0.07	0.93	0	0.05	0.95	0
/mn/	NN	0.05	0.95	0	0.17	0.83	0
/nm/	NN	0.06	0.94	0	0.03	0.97	0
/nd/	NP	0	1	0	0	1	0
/mb/	NP	0.03	0.98	0	0.09	0.91	0
/ng/	NP	0.05	0.95	0	0.05	0.95	0
/ks/	PF	0.21	0.31	0.48	0.36	0.64	0
/gz/	PF	0.12	0.79	0.09	0.30	0.70	0
/ps/	PF	0.20	0.76	0.05	0.43	0.57	0
/gr/	PL	0.63	0.33	0.05	0.95	0.02	0.02
/br/	PL	0.68	0.30	0.02	0.91	0.09	0
/gl/	PL	0.60	0.37	0.02	0.93	0.07	0
/gm/	PN	0.07	0.93	0	0.05	0.95	0
/dm/	PN	0.11	0.86	0.02	0.09	0.91	0
/bm/	PN	0.13	0.87	0	0.05	0.95	0
/kt/	PP	0.05	0.81	0.14	0.07	0.93	0
/pt/	PP	0.12	0.84	0.05	0.16	0.84	0
/bd/	PP	0.10	0.90	0	0.09	0.91	0

Appendix C

Proportions of segmentation responses for triple consonant stimuli in experimental conditions 1 (first syllable repetition) and 2 (second syllable repetition)

		Condition 1				Condition 2			
Cluster	*Category*	*/V.CCCV/*	*/VC.CCV/*	*/VCC.CV/*	*/VCCC.V/*	*/V.CCCV/*	*/VC.CCV/*	*/VCC.CV/*	*/VCCC.V/*
/rbl/	LPL	0.03	0.89	0.08	0	0	0.98	0.02	0
/rdr/	LPL	0.05	0.91	0.03	0.02	0.02	0.98	0	0
/ngl/	NPL	0	1	0	0	0	0.98	0.02	0
/ngr/	NPL	0.02	0.94	0.05	0	0	1	0	0
/ksp/	PFP	0.10	0.17	0.73	0	0.05	0.02	0.94	0
/kst/	PFP	0.08	0.25	0.63	0.05	0.06	0.12	0.82	0