

Speech Research 12

Editors

Vincent J. van Heuven

Louis C.W. Pols

Mouton de Gruyter
Berlin • New York

Phonological Structure
and Language Processing
Cross-Linguistic Studies

Edited by

Takashi Otake
Anne Cutler

Mouton de Gruyter
Berlin • New York 1996

Lexical access in continuous speech: Language-specific realisations of a universal model

Anne Cutler—Dennis Norris—James McQueen

1. Introduction: The language-specificity of segmentation procedures

Continuous speech input is the norm; only relatively rarely do we hear isolated spoken words, and even less often do we hear multi-word sequences in which the individual words are separated one from another by, for instance, pauses. In most spoken language, one word follows on from the next with no intervening pause, and indeed, in the majority of cases with no exploitable cue to the presence of a boundary between any word and the word which follows.

Nevertheless, the recognition of speech must involve *segmentation* of utterances into their component words, since only the component words, not the entire utterance, will be represented in the listener's lexical memory. Despite the rarity of clearly marked word boundaries, however, listeners can rapidly and reliably recognise individual words in utterances in their native language.

Research summarised by other contributors to this volume deals with procedures for explicit segmentation of continuous speech input. The chapters by Morais et al., Otake et al., Peretz et al. and Mehler et al. all deal with this issue in greater or lesser detail, and for this reason it will not be spelt out again here. But the important point to note is that for the most part, proposed solutions to the segmentation problem are essentially language-specific. The reason for this is that they exploit aspects of the phonological structure of the input language. Languages differ quite fundamentally in phonological structure, and hence any procedure exploiting the phonology of Language A will only work for languages which share A's phonology (or, more precisely: the relevant aspects of A's phonology). If Language B has a different phonological structure, then the associated segmentation procedure will of necessity also be different.

In the earliest investigations within this line of research, studies with French listeners suggested that they segment spoken utterances into syllables (Mehler, Dommergues, Frauenfelder & Segui, 1981; Segui, Frauenfelder & Mehler,

1981). Studies with English listeners, on the other hand, produced evidence of the use of a stress-based segmentation procedure (Cutler & Norris, 1988; Cutler & Butterfield, 1992). Since French does not have English-like stress, there was clearly no opportunity for French listeners to employ the procedure characteristic of English listening. Note, however, that no such implication holds for the use of the characteristic French procedure, syllabic segmentation, by English listeners: syllabic segmentation is a procedure potentially open to all language users, since the syllable is a unit of phonological description applicable to all languages. Nevertheless, syllable *boundaries* are not well signalled in English (or, indeed, in any stress language), suggesting that syllabic segmentation might not prove efficient for English; indeed, explicit experimental test revealed no evidence of syllabic segmentation in English (Cutler, Mehler, Norris & Segui, 1986).

This early research thus revealed segmentation procedures which were apparently quite different being used by speakers of two languages which were historically very closely related, and indeed by the standards of world language variation must still rank as extremely close. French and English are, however, phonologically dissimilar in certain respects, and it is precisely these dissimilarities which appear to be relevant for the segmentation of spoken language.

The findings concerning French and English in conjunction led to the proposal for a language-universal umbrella covering the apparent language-specificity. This proposal was that speech segmentation could be based on language rhythm, and it was motivated simply by the observation that English is characterised by a stress-based rhythm and English listeners use stress-based segmentation, while French has syllabic rhythm and French listeners use syllabic segmentation. This line of argument then led in turn to the prediction that moraic structure, the basis of Japanese rhythm, would prove to be relevant for speech segmentation by Japanese listeners.

This prediction was indeed confirmed, by further research described in the present volume (see the chapter by Otake et al., and also Otake, Hatano, Cutler & Mehler, 1993; Cutler & Otake, 1994). Moreover, moraic segmentation was shown to be used neither by French listeners (Otake, Hatano, Cutler & Mehler, 1993) nor by English listeners (Otake, Hatano, Cutler & Mehler, 1993; Cutler & Otake, 1994). Like stress-based and syllabic segmentation, moraic segmentation seemed to be a language-specific segmentation procedure. Again, phonological dissimilarities between languages were mirrored by dissimilarities in the procedures used by listeners to segment speech signals for lexical access.

These findings have very obvious implications for the learning of one language by speakers already in command of the other: application of the native segmentation procedure to the second language may prove to be inefficient. Indeed, listeners *do* apply their native segmentation procedures to foreign-language input; French listeners have been shown to apply syllabic segmentation to English, for example (Cutler, Mehler, Norris & Segui, 1986) and to Japanese (Otake, Hatano, Cutler & Mehler, 1993), while Japanese listeners apply moraic segmentation where possible to input in English (Cutler & Otake, 1994; but see also Kearns, 1994, for evidence that misapplication of native procedures can be limited). Here, however, we are concerned less with the practical implications of the language-specificity of segmentation procedures than with defining their range and establishing the extent to which they actually function in on-line speech processing by adult listeners.

2. Universal segmentation procedures for adult listening

The focus of our research is on the question of actual use by listeners of segmentation procedures of this type. Models of spoken word recognition exist which involve no explicit segmentation at all, but hold instead that word boundary information arises from the normal processes of recognising words.

Two basic classes of such alternative models have been proposed, those based on strictly sequential processing and those based on processes of competition between word candidates. The sequential segmentation models date from the 1970s (e.g. Cole & Jakimik, 1978; Marslen-Wilson & Welsh, 1978) and have now largely become no longer viable as a result of evidence from large vocabulary analyses made possible by current computational techniques. The claim originally embodied in these models was that recognition of words in temporal order allows unambiguous information about each word's onset to be automatically provided by successful recognition of the preceding word. However vocabulary studies have shown that most polysyllabic words have other words embedded within them (McQueen & Cutler, 1992) and that most shorter words can be continued to form longer words (Luce, 1986); the implication is that unambiguous segmentation of speech signals into words in strict temporal order is rarely possible. McQueen, Norris and Cutler (1994) and McQueen, Cutler, Briscoe and Norris (1995) spell out this argument in greater detail.

A more serious challenge to the necessity of segmentation procedures in adult listening is provided, however, by current connectionist models of

spoken word recognition such as TRACE (McClelland & Elman, 1986) and SHORTLIST (Norris, 1991, 1994). These models also avoid the need for explicit segmentation procedures, but they avoid them by postulating a process of competition between word candidates, out of which segmentation arises via the eventual success in the competition of the particular sequence of candidates which uniquely accounts for all of the input string.

Note that there is one quite different kind of argument in favour of incorporating explicit segmentation procedures in a model of lexical processing, namely that in principle this offers a solution to the segmentation problem which is simultaneously applicable to the case of adult and infant listeners. The infant's speech processing situation does not, in the first instance, involve recognition at all, because the infant possesses no stock of known words to recognise. Nevertheless the infant must achieve segmentation of the input in some way, in order to identify which parts of the speech signal need to be stored as units, i.e. in order to begin the process of compiling a personal lexicon. Explicit segmentation procedures such as those described in the preceding section provide a way of tackling the segmentation problem which is in principle accessible to the prelinguistic infant, and they are therefore attractive for the very reason that they would provide a unified solution to this problem as it is experienced both by the infant and by the mature listener (for further consideration of this point see Christophe, 1993, Cutler, 1994, and the chapter by Mehler et al. in this volume).

Nevertheless, it is obviously a logical possibility that no such unified situation exists. The infant situation is a special case and it may well be that once the initial segmentation problem has been solved and a sufficient lexical stock has been assembled, processes of explicit segmentation are rendered unnecessary because the normal processes of recognition achieve segmentation without them. Thus explicit segmentation would be used by the infant, but adult recognition would involve only lexically driven processes; the evidence for adult segmentation procedures described in other chapters and outlined briefly in section 1 might then be interpreted as indicating either that adult listeners *can* invoke explicit segmentation procedures if they have to, or it might be, in the worst case, that these results could also be accounted for by lexical processes.

Indeed, such an alternative interpretation might in principle be offered for one of the basic results for English, namely that of Cutler and Norris (1988). Their finding was that CVCC words such as *mint* are harder to recognise if they are embedded in nonsense bisyllables such as *miniaɪf* than if they are embedded in bisyllables like *mintef*. The crucial difference between these two

stimuli is that in the first the vowel following the embedded word is strong ([e]), whereas in the second it is weak (schwa). Cutler and Norris argued that stress-based segmentation processes would take any syllable containing a strong vowel as the likely beginning of a new word, so that *mintayf* would be segmented *min-tayf*, rendering detection of *mint* more difficult because the phonetic string corresponding to the word was interrupted by a segmentation point. In *mintefno* such segmentation, and hence no inhibition of detection of *mint*, would arise.

However, the reason that stress-based segmentation - a procedure of assuming that strong syllables are likely to be word-initial - works effectively for English is that most strong syllables *are* indeed word-initial, as Cutler and Carter (1987) showed. The English vocabulary contains many more words beginning with strong than with weak syllables. One could argue, therefore, that the difficulty of detecting *mint* in *mintayf* in comparison with *mintef* might arise from the presence of a larger number of alternative candidate words competing for the second syllable in the first compared with the second case. Thus competition-based models might be held to account for findings apparently supporting explicit segmentation procedures. In the next section we describe a series of experiments which we undertook in English testing the predictions both of competition models and stress-based segmentation models.

3. Competition and segmentation in adult processing of English

Our experiments all used the word-spotting task developed by Cutler and Norris (1988). In this task listeners hear nonsense utterances (which were all isolated bisyllables in these studies as in the earlier one), and are required to press a button whenever they detect a real word in the input. They do not know what words might occur; their task is simply to respond to any real word they hear. When they do detect a real word, they then have to repeat it (and of course if a listener says the wrong word on any trial, (he corresponding response is not included in the reaction time analysis). Both response time and miss rate can be used as measures of word recognition difficulty. In the Cutler and Norris (1988) study, as described above, word recognition difficulty was found to vary as a function of the phonological structure of the utterances: CVCC words in CVCCVC utterances were more difficult to detect if the second vowel was strong than if it was weak. This result was taken as evidence of an explicit stress-based segmentation procedure.

All experiments of the current study investigated effects of inter-word

competition and effects of explicit segmentation procedures in parallel. In Experiments 1-3 (which are reported in full detail in McQueen, Norris & Cutler, 1994), we tested competition effects by manipulating whether or not the matrix utterance (i.e. the nonsense utterance in which the target word occurred) could itself be continued to form another real word. For instance, [dames] is a nonsense bisyllable in itself, but it has the real word *mess* contained within it, and it is also the first two syllables of another real word, *domestic*. Likewise, [sækref] is a nonsense bisyllable which contains the real word *sack* and could be continued to form another real word, *sacrifice*.

If competition between word candidates is occurring during word recognition, then the utterance [dames] should cause competition between *mess* and *domestic*, and [sækref] should cause competition between *sack* and *sacrifice*. The monosyllabic target words should be harder to detect when such competition is occurring than when there is no competition. Therefore we compared detection of words like *mess* and *sack* in the competition contexts [dames] and [sækref] and in non-competition contexts such as [names] and [sækra:k]. The latter are non-competition contexts because neither of them can be continued to form a real word.

At the same time we conducted a further test of stress-based segmentation procedures. Cutler and Norris (1988) proposed that listeners segment speech at the onset of every strong syllable. This means that a real word consisting of a single strong syllable (such as *mess* or *sack*) should be segmented from any syllable that precedes it, but should not be segmented from any weak syllable that follows it. Thus such words should be easier to detect in weak-strong (WS) utterances than in strong-weak (SW); in the above examples, it should be easier to detect *mess* in its two WS contexts than *sack* in its two SW contexts. Of course, that particular comparison could be confounded by effects of competition and by simple differences in detectability between words like *mess* and words like *sack*. So we instituted a more rigorous test of stress-based segmentation by comparing recognition of each word in its non-competition context with recognition of the same word in another non-competition context, with the opposite stress pattern. Thus detection of *mess* in WS [names] was compared with detection of *mess* in SW [mestem], and detection of *sack* in SW [sækra:k] was compared with detection of *sack* in WS [klesæk].

Experiment 1 produced strong effects of both competition and stress-based segmentation. The competition effect showed itself in the comparison between contexts: *mess* was detected both more rapidly and more accurately in the non-competition context [names] than in the competition context [dames], and *sack* was detected more accurately (though not more rapidly) in the

non-competition context [sækrek] than in the competition context [sækref]. The effect of stress-based segmentation showed itself in the comparison between the two stress patterns in the non-competition contexts: *mess* and *sack* were detected more rapidly and more accurately in the WS patterns [names] and [klesæk] than in the SW patterns [mestem] and [sækrek].

Thus in Experiment 1 stress-based segmentation and inter-word competition appeared to be operating simultaneously. In Experiment 2 we made the listeners' word-spotting task a little easier by constraining where in the utterance the words were to be spotted; half of the subjects listened for words occurring at the beginning of the nonsense bisyllables, half of the subjects listened for words occurring at the bisyllables' ends. Exactly the same effect of stress-based segmentation appeared: the words were detected faster and more accurately in WS than in SW contexts (this comparison was in this case between separate groups of subjects, of course). There was also a strong effect of competition for the WS utterances: it was still harder to detect *mess* in [dames] than in [names]. Subjects who were listening for words at the ends of the bisyllables of course had to listen to the whole bisyllable, so *domestic* had the same opportunity to compete with *mess* as in Experiment 1. However there was no effect of competition for the SW words in Experiment 2: *sack* was as easy to detect in [sækraf] as in [sækrak]. This also makes good sense, because in this case the subjects detecting the words in SW bisyllables were instructed to attend only to the beginnings of the utterances. Once they had spotted *sack* at the beginning of either of the items in which it occurred, there was no reason to attend to the second syllable, and it was only in the second syllable that *sacrifice* stopped competing in [sækrek] but continued competing in [sækref].

In Experiment 3 the same bisyllables were presented to a new group of listeners, but they were digitally expanded or compressed so that the embedded monosyllabic words were roughly equal in duration in SW and WS bisyllables. This is because the strong syllables were longer in the original WS utterances than in the SW, and the added duration could have been the source of the apparent stress-based segmentation effect, i.e. the advantage for words in WS over SW patterns. But this was not the case: the same effects of stress-based segmentation as seen in Experiments 1 and 2 reappeared in Experiment 3, in both response time and miss rates. Also there were again strong effects of competition (for the words in WS bisyllables).

In Experiment 4 (reported in full in Norris, McQueen & Cutler, 1995) we adopted a different approach to testing effects of competition. In this study we manipulated the actual number of competing words. To do this we used a large computer-readable dictionary (the *Longmans Dictionary of Contemporary*

English) to establish CV sequences which constituted the onset of many versus few words in the English language. Then these sequences were built into CVCCVC bisyllables, in the second CV position. The target word was a CVCC monosyllable. The final phoneme of the embedded word and its following vowel therefore constituted the onset of many versus few words of English.

For instance, there are many English words beginning with [kʌ] (*cup, couple, custard, cudgel, culinary, cover, cuddle, company*, and so on and on), just as there are many words beginning with [kə] (*canoe, collide, connect, cavort, commercial, corrosion, cathedral, cadet*, and so on). Thus *mask* in both [maskʌk] and [maskək] will have many potential words beginning from its final phoneme. On the other hand, there are few words beginning [tau] (five, in fact: *town, towel, tower, tout* and *tousle*, plus their morphological relatives). Likewise, there are few words beginning [tə] (*terrain, toboggan, telephony* etc.). Thus *mint* in [mɪntaʊp] and [mɪntəp] will have few potential words beginning from its final phoneme.

Each CVCC target word had a matched CVC target word, in the initial position in a CVCCVC context, as a control. Thus *mask* was compared with *pass* (in [paskʌk] and [paskək]), while *mint* was compared with *thin* (in [θɪntaʊp] and [θɪntəp]).

In this fourth word-spotting experiment, then, a competition effect would show itself in a difference between items with many versus few potential words beginning with the second CV in the CVCCVC string. The effect should be expected to be different for CVCC and CVC target words. This is because the crucial second CV overlaps with the final phoneme of CVCC words, so the availability of many competitors might hinder recognition of the target word. However the second CV has no overlap with the CVC target words, so it is possible that the availability of many competitors might actually facilitate recognition of the target word, by emphasising the segmentation point.

Stress-based segmentation should show itself in the same way as in the Cutler and Norris (1988) study: CVCC words should be harder to detect when the following vowel is strong than when it is weak. No effect of the following vowel should be observed with CVC target words (again, this replicates a finding of Cutler and Norris).

The results of this study again showed effects both of stress-based segmentation and of inter-word competition. The segmentation effect showed itself in a replication of Cutler and Norris' findings: CVCC words were detected both more rapidly and more accurately in SW than in SS bisyllables (i.e. *mask* was easier to detect in [maskək] than in [maskʌk], and *mint* was

easier to detect in [mintep] than in [mintaup]). No such effect of the second vowel was observed with CVC target words.

The competition effect showed itself mainly with the CVC words, which were much easier to detect when there were many words beginning with the CV sequence following the target (*pass* in [pask^k] and [pasksk]) than when there were few (*thin* in [eintaup] and [eintep]). This implies that, as expected, the availability of competitors for the second syllable makes the first syllable easier to recognise on its own. In the CVCC words, the competition effect showed itself indirectly: the segmentation effect (advantage of words in SW versus SS bisyllables) was larger in response time when there were many competitors (*mask*) than when there were few (*mint*), and moreover there was a significant segmentation effect in miss rates (fewer targets missed in SW than in SS bisyllables) only when there were many competitors, not when there were few. This implies that when stress-based segmentation has occurred (in SS bisyllables), more competitors exert a stronger pull on the final consonant of the embedded word than few competitors do.

Independently of our studies, Vroomen and de Gelder (1995) also demonstrated an effect of number of competitors in a priming/segmentation task. Dutch CVCC words embedded in the initial portion of CVCCVC contexts produced less priming (i.e. were less highly activated) when there were many potential words beginning from, and hence competing for, the second medial consonant (analogous to our [mask^k] case) than when there were few (analogous to our [mintaup] case).

The results of our Experiment 4, however, go beyond demonstrating that number of competitors exerts an effect in word recognition. Firstly, they show that the stress-based segmentation effect is present irrespective of the number of competitors available - in other words, the results of Cutler and Norris (1988) cannot be ascribed to effects of competition. Secondly, these results show that lexical competition and segmentation effects interact in that increased competitor availability can make the segmentation effect larger.

4. Modelling segmentation with competition in English

The results of our experiments have shown that both inter-word competition, and explicit segmentation via exploitation of stress-based rhythm, play a role in the recognition of spoken words in English. Note that our results constitute direct and unequivocal experimental evidence for inhibitory effects of competing word candidates. Many other studies have shown that words may

be concurrently activated when they overlap in spoken input (e.g. Taft, 1986; Goldinger, Luce & Pisoni, 1989; Zwitserlood, 1989; Cluff & Luce, 1990; Shillcock, 1990; Goldinger, Luce, Pisoni & Marcario, 1992; Gow & Gordon, 1995); but concurrent activation does not necessarily imply active competition. When the availability of other competing words actually inhibits recognition of a given word, though, active competition is attested. Exactly such evidence of inhibition has been provided in the present studies. McQueen, Cutler, Briscoe and Norris (1995) argue that only competition via inhibition can give an account of recognition and segmentation in the processing of continuous speech; models which incorporate simultaneous activation (but no active competition) can account for the recognition of words in isolation, but they fail to address the special problems which arise when words occur in a continuous speech context.

Models of spoken word recognition involving competition have been implemented as connectionist programs. TRACE (McClelland & Elman, 1986) and SHORTLIST (Norris, 1991, 1994) are two such fully worked out models. In their initial formulations, neither model involves explicit segmentation. Both would allow segmentation simply to fall out of the process of inter-word competition. However the present results show that in this respect pure competition models are inadequate as a representation of human word recognition processes. Human listeners do use competition, but they also use explicit segmentation. Can explicit segmentation be incorporated into a competition-based model of word recognition?

Norris et al. (1995) successfully modified SHORTLIST to incorporate a process of explicit segmentation. Note that it would be rather difficult to simulate our present results with TRACE, for practical reasons; TRACE'S speed of operation is highly dependent on vocabulary size, and hence TRACE simulations are usually conducted with only tiny vocabularies of a few hundred words. (This is an artefact of the solution which McClelland and Elman adopted to simulate the temporal nature of speech - TRACE'S entire vocabulary is replicated at each time slice of the input. This implausible architecture does work to simulate competition, but it obviously makes the use of large vocabularies computationally very expensive.) Since our calculations of competitor effects were based on a real dictionary, to simulate our results in TRACE it would be necessary to tailor TRACE'S vocabulary to mirror exactly the proportional distributions in the vocabulary as a whole.

SHORTLIST is a hybrid model which runs effectively on a realistically sized vocabulary - indeed, it operates with a lexicon based on the *Longman Dictionary of Contemporary English* (26000 words in the version used in our

studies). The initial stage of the model is entirely driven by the acoustic/phonetic properties of the input. This initial stage creates a short set of candidate words consistent in whole or in part with the input (the *shortlist*); these words are then wired into a network and allowed to compete among themselves until a winner emerges.

Position:	-1	C	+1	+2	+3	+4
Weak-Strong						
<i>mess</i> in [dɔməs]	0.003	0.148	0.293	0.306	0.306	0.306
<i>mess</i> in [nɔməs]	0.011	0.202	0.311	0.311	0.311	0.311
<i>sack</i> in [klɔsæk]	0.016	0.207	0.307	0.307	0.307	0.307
<i>domestic</i> in [dɔməs]	0.137	0.263	0.021	-0.103	-0.144	-0.157
Strong-Weak						
<i>sack</i> in [sækɾɔf]	0.088	0.210	0.184	0.168	0.222	0.290
<i>sack</i> in [sækɾɔk]	0.088	0.210	0.191	0.244	0.308	0.308
<i>mess</i> in [mɛstɔm]	0.080	0.249	0.269	0.281	0.309	0.310
<i>sacrifice</i> in [sækɾɔf]		-0.009	0.072	0.212	0.116	-0.057
<i>sacrifice</i> in [sækɾɔk]		-0.009	0.041	-0.027	-0.109	-0.151

Table 1. Mean activation values of the target words and the embedding words from Experiments 1-3, over time, in SHORTLIST. Values are given for both weak-strong and strong-weak strings. In the weak-strong utterances, mean activations are given for targets embedded in competition (e.g. *mess* in [dsmss], the onset of *domestic*), and in non-competition contexts (e.g. *mess* in [names], *sack* in []). Also given are the activation values of the embedding words in the competition contexts (e.g. *domestic* in [dames]). In the strong-weak strings, values are again given for targets embedded in competition (e.g. *sack* in [saskɾaf], the onset of *sacrifice*) and non-competition contexts (e.g. *sack* in [seekɾak], *mess* in [mestam]). Also shown are the values for embedding words both in competition (e.g. *sacrifice* in [sækɾaf] and non-competition contexts (e.g. *sacrifice* in [seekɾak]). The values are aligned with the last consonant of the target word ("C"). Positions before C are for each phoneme working back through each item; positions after C are for following segments or silence markers.

Table 1 shows how SHORTLIST models the recognition of the target words used in Experiments 1 to 3. Activation values are shown for successive points representing time (in phoneme-sized slices), where the point labelled C represents the final consonant of the target word. In the WS utterances the points following C represent silence. It can be seen that the activation of *mess* is lower in [dɔməs] than in [nɔməs] at the final consonant (because of competing activation from *domestic*); *mess* in [dsmss] does not recover until silent slices of time have occurred and effectively removed *domestic* from competition. In the SW utterances the activation of the target word (e.g. *sack*) at C is equivalent in competition ([sækɾaf]) and non-competition contexts

([sækrek]), but it rises when subsequent phonetic information removes the competitor in the non-competition context. In the competition context activation of the target word only rises later, when silence has removed the competitor from that context as well (note that these values are averaged over many items; in most cases the disambiguating phonetic information arrived at the second phoneme after the target word although in a few cases, such as [[sækref/[sækrek] it arrived at the third).

Thus SHORTLIST very accurately models the competition effects which we observed in Experiments 1 to 3. But the segmentation effects that we observed there are not directly captured in this simulation, SHORTLIST in this unaugmented version also does not capture the segmentation effects we observed in Experiment 4, which amounted to a more rigorous test of segmentation, with competition controlled. Table 2 shows the relevant activation values for the CVCC target words; it can be seen that although the targets have lower activation values at and beyond C when there are many competitors than when there are few, activations do not differ as a function of whether the following vowel is strong or weak.

Position:	-2	-1	C	+1	+2	+3
Many competitors						
<i>mask</i> in [máskák]	-0.053	0.196	0.262	0.288	0.556	0.615
<i>mask</i> in [máskək]	-0.053	0.196	0.262	0.275	0.507	0.509
Few competitors						
<i>mint</i> in [míntaup]	-0.048	0.152	0.389	0.600	0.620	0.620
<i>mint</i> in [míntəp]	-0.048	0.152	0.389	0.492	0.517	0.543

Table 2. Mean activation values of the CVCC target words from Experiments 4, over time, in SHORTLIST, with no segmentation procedure implemented. Values are shown for targets in strong-strong strings and strong-weak strings, in which there were either many competitor words beginning from the last consonant of the target (e.g. *mask* in [máskák] and [máskək]), with many words beginning from the medial [k]), or few competitor words (e.g. *mint* in [míntaup] and [míntəp]), with few words beginning from the [t]). The values are aligned with the last consonant of the target word ("C"; e.g. the [t] in *mint*). Positions before C are for each phoneme working back through each item; positions after C are for following segments or silence markers.

To incorporate the effects of stress-based segmentation in SHORTLIST, Norris et al. (1995) added two features to the model. Firstly, we instituted a penalty on lexical candidates containing no strong syllable onset where there is one in the input. This mechanism was intended to simulate Cutler and Norris' stress-based segmentation proposal in that it stipulates that strong

syllable onsets are to be viewed as segmentation points. Secondly, we provided an activation boost to all word candidates beginning with a strong syllable. This simulated the aspect of Cutler and Norris' stress-based segmentation proposal which proposes that the purpose of segmentation is to initiate lexical access attempts from strong syllables.

Table 3 shows the same items as in Table 2, as modelled by the Norris et al. (1995) version of SHORTLIST. Now it can be seen that activation of the target words is consistently higher, at and beyond C, when the following vowel is weak than when it is strong. Moreover, the difference is much greater when there are many competitors than where there are few. This is exactly the pattern of results observed in Experiment 4. Thus the augmented version of SHORTLIST correctly captured both the presence of inter-word competition and the use of explicit stress-based segmentation.

Position:	-2	-1	C	+1	+2	+3
Many competitors						
<i>mask</i> in [maskak]	-0.053	0.196	0.213	0.001	0.337	0.499
<i>mask</i> in [maskak]	-0.053	0.196	0.262	0.275	0.507	0.509
Few competitors						
<i>mint</i> in [mɪntaʊp]	-0.048	0.152	0.324	0.350	0.505	0.505
<i>mint</i> in [mɪntəp]	-0.048	0.152	0.389	0.492	0.517	0.543

Table 3. Mean activation values of the target words from Experiments 4, over time, in SHORTLIST, with the stress-based segmentation procedure implemented with a combined penalty and boost (see text for details). Values are shown for targets in strong-strong strings and strong-weak strings, in which there were either many competitor words beginning from the last consonant of the target (e.g. *mask* in [maskak] and [maskek], with many words beginning from the medial [k]), or few competitor words (e.g. *mint* in [mintaʊp] and [mintep], with few words beginning from the [t]). The values are aligned with the last consonant of the target word ("C"; e.g. the [t] in *mint*). Positions before C are for each phoneme working back through each item; positions after C are for following segments or silence markers.

5. Conclusion: The model is universal even though the realisation is language-specific

The viability of explicit segmentation procedures in human speech recognition is not compromised by the power of inter-word competition as a basic component of the word recognition process. Competition could in principle make explicit segmentation unnecessary. And competition does indeed play a role in word recognition by human listeners, as our experiments in English,

and those of others in English and other languages, have shown. But listeners do not rely on competition alone: they also make use of explicit segmentation procedures - specifically, the English listeners in our studies make use of stress-based segmentation.

We have shown that explicit segmentation procedures can be incorporated in a competition-based model of word recognition, and that the model then simulates the experimental findings from English very accurately. But exactly this type of solution would also work for other languages. We happen to have implemented SHORTLIST with an English dictionary, and we augmented it with the stress-based segmentation procedure characteristic of English listeners. But SHORTLIST is not itself a model of English word recognition; it is a universal model of human word recognition. Thus extension of the present technique to the modelling of word recognition in other languages is quite straightforward. The model would work in just the same manner if given a dictionary of French and input in French, or a dictionary of Japanese and input in Japanese, and so on: the input would serve to activate a shortlist of potential word candidates, which would then compete among themselves for recognition. Likewise, the segmentation procedures used by listeners in other languages lend themselves as well to incorporation in SHORTLIST as stress-based segmentation does. Thus the syllable-based segmentation procedure characteristic of French listeners, and the mora-based segmentation procedure characteristic of Japanese listeners, could each be implemented in an augmented version of SHORTLIST, with an appropriate dictionary, and applied to speech input in the relevant language. Norris, McQueen, Cutler and Butterfield (submitted) propose a very general framework within which such specific procedures could be realised in SHORTLIST.

The modelling of lexical access from continuous speech input has made great progress in recent years. Competition techniques are a very powerful addition to the modelling repertoire. Moreover, empirical findings suggest that models which incorporate competition by inhibition offer a true picture of how human listeners achieve lexical access from continuous speech input. The universal model of human word recognition should, therefore, be one of this type. Competition exists in conjunction, however, with principles of explicit speech segmentation, for which there is also abundant empirical evidence. Such segmentation principles can be incorporated into competition-based models in a straightforward and efficient way. The fact that segmentation procedures vary across languages, however, implies that correct modelling of lexical access requires language-specific realisations of the underlying universal word recognition model.

Acknowledgements

This research was supported by the Human Frontier Scientific Program and the Joint Councils' Initiative in Cognitive Science (U.K.). We thank the Longman Group (U.K.) for permission to use the *Longman Dictionary of Contemporary English*.

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