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Segmental and Suprasegmental Mismatch in Lexical Access

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Four cross-modal priming experiments in Spanish addressed the role of suprasegmental and segmental information in the activation of spoken words. Listeners heard neutral sentences ending with word fragments (e.g., *princi-*) and made lexical decisions on letter strings presented at fragment offset. Responses were compared for fragment primes that fully matched the spoken form of the initial portion of target words, versus primes that mismatched in a single element (stress pattern; one vowel; one consonant), versus control primes. Fully matching primes always facilitated lexical decision responses, in comparison to the control condition, while mismatching primes always produced inhibition. The respective strength of the contribution of stress, vowel, and consonant (one feature mismatch or more) information did not differ statistically. The results support a model of spoken-word recognition involving automatic activation of word forms and competition between activated words, in which the activation process is sensitive to all acoustic information relevant to the language's phonology.

Key Words: stress; vowels; consonants; features; lexical access.

Subjective experience tells us that recognizing words in a spoken utterance is an effortless process. Words are simply heard, and then efficiently accessed in our lexical memory. However, the subjective impression may be highly misleading, for the process is not at all trivial. Understanding a spoken word involves computing from a continuous and highly variable signal the information cueing one word among tens or even hundreds of thousands, some of them differing only slightly from the word actually uttered. There is ample evidence that speech input activates a number of different words with which it is temporarily or partially consistent (Connine, Blasko, & Wang, 1994; Connine, Titone, Deelman, & Blasko, 1997; Marslen-Wilson, 1990; Zwitserlood, 1989). This can occur even when the possible candidate words are embedded within longer words (Gow & Gordon, 1995; Shillcock, 1990) or when they span a word boundary in the intended utterance (Tabossi, Burani, & Scott, 1995). The lexical candidates that are fully or in part consistent with the input (i.e., that are activated) compete with one another (Goldinger, Luce, & Pisoni, 1989; McQueen, Norris, & Cutler, 1994). For instance, McQueen et al. (1994) found that detection of a word in a nonsense string was more difficult (slower and less accurate) when this string was itself the beginning of a real word than when it was not. The word MESS, for example, was less efficiently detected when it was embedded in the nonsense string *domess* than when it was embedded in

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nemess; the former forms the onset of a real English word (i.e., domestic, and its morphological relatives) that, being consistent with the input signal, inhibits the target word *mess*. However, the other nonsense string, *nemess*, activates no competing word, so that *mess* receives no inhibition and thus can be recognized sooner. The outcome of this multiple activation and competition process is, in most cases, that the input can be unambiguously mapped onto a sequence of individual lexical items.

Although the processes of lexical activation and retrieval have been intensively studied in recent years, most current models of spoken-word recognition are more concerned with correct capture of the phenomena of multiple concurrent activation and interword competition than with the detailed simulation of the input level to lexical access (see, however, Elman & McClelland, 1986, for an attempt to implement a detailed phonemic description of the input). Thus in the majority of models computational simulations begin with an input coded as a string of phonetic segments, e.g., in Shortlist (Norris, 1994) and in the Neighborhood Activation Model (Luce, Pisoni, & Goldinger 1990). In TRACE (McClelland & Elman, 1986), phoneme nodes are activated by input from a bank of feature detectors. The first version of the cohort model (Marslen-Wilson & Welsh, 1978) assumed an input consisting of a string of discrete phonemes, but later work within the framework of this model (e.g., Marslen-Wilson & Warren, 1994) incorporated the knowledge that information about phoneme identity can overlap in time. In none of the empirical programs associated with these models, however, has explicit attention been given to testing these input assumptions. In contrast, it is often accepted that the assumptions are merely placeholders for more detailed and faithful implementations to be undertaken at a future time (see, e.g., McClelland & Elman, 1986: p. 14; Norris, 1994: p. 208). Furthermore, no current model augments the segmental information (the phonemes) in the input with suprasegmental information (that is, information in the pitch contour, amplitude contour, or timing which varies with lexical identity: lexical stress, lexical tone, or lexical pitch accent). This may reflect merely the fact that all current models are based on data from experiments in English, and there is evidence that in English lexical stress does not play a strong role in word form activation (Cutler, 1986). However, there are now many experimental demonstrations, from other languages, of the importance of suprasegmental information in lexical access; English may be atypical in this respect (see Cutler, Dahan, & Van Donselaar, 1997, for a review).

Some recent behavioral studies have also examined the effects of segmental mismatch between input and lexical representation. In these studies the input is usually a nonword that in some way mismatches a real word. Connine et al. (1997) found that phoneme-monitoring responses were faster in nonwords that closely resembled real words than in nonwords that were unlike any real word. Boelte (1997), Cutler, Sebastian-Gallés, Soler-Vilageliu, and Van Ooijen (2000), and Van Ooijen (1996) investigated how listeners reconstructed real words when they were given nonwords that differed from real words by a single phoneme (i.e., the string *kebra*). When two solutions were available, one requiring substitution of a vowel (i.e., *cobra*) and the other substitution of a consonant (i.e., *zebra*), the vowel-substitution solution was consistently easier (faster and more accurate) to reconstruct (Cutler et al., 2000; Van Ooijen, 1996). In a lexical decision task, responses are faster if an immediately preceding item overlaps with the current target in all but a single phoneme than when the preceding item is unrelated to the target (Cutler, Van Ooijen, & Norris, 1999; Radeau, Morais, & Segui, 1995), although the facilitation is transient (Cutler et al., 1999).

These studies certainly support the claim that lexical activation is sensitive to all available information; a partial match can produce partial activation. But they do not fully elucidate the role of match and mismatch between input and lexical representations in normal spoken-language processing. In order to arrive at the correct sequence of spoken words in the input, listeners must be able to reject all words that are *not* part of the correct sequence, even though there may be very many words that differ only minimally from those in the correct sequence, and even though, as so much empirical evidence attests, those minimally differing words may be temporarily activated and thus may engage in the competition process.

The listener's interest is best served if a mismatch between input and lexical representations has an immediate and substantial effect on the pattern of activations. The original cohort model (Marslen-Wilson & Welsh, 1978) indeed proposed such a drastic effect: a single-phoneme mismatch would produce total exclusion of mismatched words from the set of words under consideration. However, this claim cannot hold; the many demonstrations of activation despite partial mismatch have established that. In models involving interword competition, such as TRACE (McClelland & Elman, 1986), or the Shortlist model (Norris, 1994), the effect of a mismatch on the activation of a word depends on the competition process. As a function of the number of other words currently activated, and the degree to which they in turn are matched/mismatched by the input, a word that has suffered a mismatch may still play an effective role in the ongoing competition. In Shortlist, for instance, a mismatch in the input will penalize the mismatching word (i.e., reduce its activation); but a word penalized in this manner will not necessarily be excluded from the shortlist of activated words. However, the competition process will then result in inhibition, spreading from the more highly activated word that received the greater support from the input to the less favored mismatched word; that is, the continued presence of the mismatched word in the competition set will be observable from the fact that its recognition will be more difficult (i.e., it is inhibited).

This inhibition effect should be visible not only when such minimal word pairs are presented as wholes but also with fragments of words that minimally mismatch part of another word (i.e., "solu" should produce activation of *solution* and inhibition of *solicit, solicitor*, and so on). Indeed, mismatch as a means of distinguishing between such fragments is presumably the most common occurrence in the normal situation of spoken-word recognition. In the studies reported here listeners received input matching the initial part of one word and mismatching another, and we measured the resultant facilitation versus inhibition (compared with a control condition) for the matched and the mismatched word respectively. This experimental technique, sometimes called fragment priming, is a variant of the cross-modal priming paradigm (see Zwitserlood, 1996, for a review) by which word-initial fragments reliably activate the representations of words with which they are compatible (Zwitserlood, 1989). Participants made lexical decisions on visually presented words, and we compared response times and accuracy to a given visual target as a function of the type of auditory prime that preceded it—a control word fragment, a matching word fragment, or a minimally mismatching word fragment. We assume that compatible primes will activate the representation of the target (as in Zwitserlood, 1989), leading to facilitation in comparison to a control prime. The contribution of a given type of information to the lexical activation process will then be indicated by the extent to which activation is reduced—i.e., responses are inhibited relative to the control—by minimal mismatches in such information. We chose this task for various reasons. First, this study was only possible using fragments of words (for reasons explained below) and the described technique is known to be sensitive to priming effects produced by partial input. Second, lexical decision in the priming paradigm taps into automatic word activation processes underlying speech perception (rather than, for instance, explicitly directing observers' attention to a given phonological aspect of speech such as individual phonemes).

Using this method, we compared several types of information. First, and most crucially, we addressed the effect of suprasegmental mismatch and that of segmental mismatch. Although evidence from lexical tone languages (e.g., Fox & Unkefer, 1985), lexical pitch-accent languages (e.g., Cutler & Otake, 1999), and lexical stress languages (e.g., A. Cutler & W. Van Donselaar, submitted manuscript) attests that suprasegmental information can constrain lexical access, no study has undertaken a direct comparison of suprasegmental versus segmental mismatch. Second, we compared, within segmental mismatch effects, vowel mismatch against consonant mismatch. Again, evidence from tasks involving the reconstruction of words from nonwords has shown asymmetric effects of vowel and consonant mismatch (Cutler et al., 2000; Van Ooijen, 1996), but no study has compared vowel versus consonant mismatch with the present activation paradigm. And finally, within consonantal mismatch we compared the effect of a mismatch on one versus many phonological features. This too is a dimension that has been shown to affect responses given nonword input (e.g., Connine et al., 1997) but has not been examined systematically using primes that activate competing words.

In order to make our comparison between suprasegmental and segmental mismatch as close as possible, we needed to conduct our experiments in a language in which minimal pairs of words can be distinguished either segmentally or suprasegmentally, and in which segmental and suprasegmental structure are not necessarily interdependent. In many languages, there is such interdependence, in that suprasegmental effects co-vary with segmental effects—for instance, vowels are reduced in unstressed syllables in English. Such confounds do not occur in Spanish. All polysyllabic Spanish words have one syllable marked for primary stress; this primary stress can occur in any syllabic position, and stressed and unstressed syllables do not differ in their vocalic makeup. There is no vowel reduction; all vowels are full, whether they occur in stressed or in unstressed syllables (see Navarro-Tomás, 1968, for detailed descriptions). Note that Castilian Spanish has only five vowels, and that these are widely separated in phonological space (Skelton, 1969; Stockwell & Bowen, 1965.) Thus minimal pairs of words, or of word fragments, can differ in stress but can be identical in segmental structure—the necessary prerequisite for the comparison we wished to undertake. Accordingly we chose to conduct this study in Spanish.

As in other languages with variable lexical stress, it is not easy to find pairs of unrelated words in Spanish that are only distinguished suprasegmentally, such as *saBAna* (“savannah”) versus *SAbana* (“sheet”; uppercase denotes the primary-stressed syllable). It might as a consequence be argued that cues to stress have little to offer the Spanish listener, since it will not often be necessary to refer to stress pattern to distinguish one word-form from a segmentally identical alternative. However, Spanish presents many minimal pairs of *related* words. Thus for example, *CAso* is, besides a noun meaning “case”, also the first person singular present tense of the verb “to marry”, while *caSO* is the third person singular past tense of the same verb. Changes in the stress pattern of stems frequently indicate differences in grammatical function (for instance, noun versus verb) or, as in the above example, different forms of verbal inflectional morphology. Thus Spanish listeners can use suprasegmental cues to distinguish between different forms of the same stem. Furthermore, with continuous-speech input that may activate multiple candidate words overlapping with one another, lexical stress information could help to distinguish between otherwise identical fragments of speech, and thus to provide mismatch information that can help rule out potential competitors. That is, listeners may quite regularly have recourse to stress information in order to distinguish precisely such fragments as those used in the present study. Experiment 1 addresses the constraints exercised by suprasegmental information in lexical activation.

EXPERIMENT 1

In the present experiment, as in the following ones, word onset fragments (the two first syllables) were presented at the end of carrier sentences as auditory primes. The visual target appeared immediately at prime offset, and lexical decision times to the target were measured from this point. Reaction times and accuracy were evaluated as a function of prime type. In the *match* condition prime fragments consisted of the onset of the target word pronounced aloud (*PRINci-* for the target *PRINcipe*). In the *mismatch* condition prime fragments came from the onset of a word with identical segmental information in the two first syllables but different stress pattern (*prinCI-* from the word *prinCIpio*, for the target *PRINcipe*). Finally, a *control* condition was included to obtain a baseline measure of the target word activation (the fragment *mos* from the word *mosQUIto,* for the target *PRINcipe*). One-syllable fragment primes were chosen as unrelated controls in order to avoid obvious lexical stress information being conveyed by the prime in this condition. Since lexical stress might be assessed (in Spanish) by comparison of pitch, amplitude, and duration between neighboring syllables, a two-syllable fragment prime would always be associated to a stress pattern. However, the use of prime fragments of different syllabic length than the experimental primes (one vs two syllables) may seem a problem for interpreting inhibition or facilitation effects obtained. As a check on the neutrality of the control primes here used, it is expected that they always yield performances not better than those for the matching primes, and not worse than those for the mismatching ones. This condition was met in every one of the experiments here presented.

If the two types of experimental primes (match and mismatch) prove equally effective in facilitating lexical decisions to the target, we may conclude that lexical stress is not used in the lexical activation process, and that only segmental information—the same in both types of prime—is relevant. However, if positive priming effects appear for the match condition but not for the mismatch condition, we may conclude that, in Spanish at least, suprasegmental information is used in lexical activation, producing a situation in which only one of the possible candidate words completely matches the input while the other mismatches. The mismatching condition may in this case be equivalent to the control condition; this would suggest that the mismatching prime effectively ruled the target out of the initial activation set completely. Alternatively, the mismatching condition may show inhibition relative to the control condition; this would be an indication of initial activation followed by suppression as a result of competition from more favored candidate words.

Method

Participants. Forty-three undergraduate students at the University of Barcelona volunteered for this experiment. All were native Spanish speakers, with normal or corrected vision and no reported problems in hearing. They received course credits for their participation. To balance the number of participants in each list, we excluded data from three participants selected at random (leaving a total of 10 in each version of the experiment). Therefore the analyses were based on data from 40 participants.

Materials. Twenty-four experimental word pairs were selected according to the following criteria: they were three or four syllables long, they were segmentally identical up to the onset of the third syllable, they were not semantically and/or morphologically related, and they differed in stress pattern. An example pair is *PRIN.ci.pe–prin.CI.pio* ("prince"–"beginning"; syllable boundaries are marked with dots). The selected words were 46 nouns and 2 adjectives; no items were compounds, and in no item did the initial two syllables form a word. We matched the frequency of the word pairs as far as possible (we used the LEXESP database that contains frequency counts on a 5,020,930-word body of written material; Sebastián-Gallés, Martí, Cuetos, & Carreiras, 2000); the mean log frequency of the target words[1] was 3.61, SD = 1.5; mean absolute difference in log frequency between members of the same pair was 1.77, SD = 1.15. In addition, for each pair, one control noun, without phonemic overlap in the first syllable with its associated pair, was chosen (in the above example the control word was *mos.QUI.to*). A complete list of items is given in Appendix A.

From each of these 24-word triplets, six prime–target pairings resulted: Every possible prime word in the triplet (the two experimental words plus the control) was paired with each of the two target words (the two experimental words) in the same triplet. Table 1 shows the six prime–target pairings for the chosen example.

For each of these 144 pairings (24 × 6), one sentence containing the prime word at the end was constructed. All sentences were semanti-

[1] These, and the remaining frequency averages presented in the paper, were assessed using only the items included in the analyses.

TABLE 1

Example of the Six Prime–Target Pairings Constructed from One of the Selected Triplets and the Associated Carrier Sentences

Prime type	Sentence	Prime	Target
Match	Todos habían oido hablar del (Everybody had heard about the. . .)	PRIN.ci.(pe)	PRINCIPE
	Él vió un libro sobre el (He saw a book about. . .)	prin.CI.(pio)	PRINCIPIO
Mismatch	Todos habían oido hablar del	prin.CI.(pio)	PRINCIPE
	Él vió un libro sobre el	PRIN.ci.(pe)	PRINCIPIO
	Nadie supo leer la palabra	mos.(QUI.to)	PRINCIPE
Control	(Nobody knew how to read the word. . .)		
	Todos los diarios hablaron del (All newspapers talked about the. . .)	Mos.(QUI.to)	PRINCIPIO

Note. Each word triplet (experimental pair plus control word) yielded six prime–target pairings (two in each condition). Carrier sentences were balanced for each condition between the experimental pairings. Parentheses in the prime column indicate the cutoff part of the prime word.

cally neutral and not syntactically biasing toward either word of the pair. As some target pairs had different gender, their carrier sentences were constructed in such a way that they were not syntactically biased toward one of the genders (i.e., using constructions like "*El niño no sabía escribir la palabra*. . ."; "The kid did not know how to write the word. . ."). Sentences corresponding to the same target in the experimental pairs were identical except for the last word[2] (the prime). Sentences containing control primes were different from those containing the experimental words.

We recorded the 144 sentences from a female native Spanish speaker using a digital audiotape. The speaker, who was unaware of the goal of the experiment, was instructed simply to read aloud and clearly from a list in which the full sentences had been randomly mixed. Tape recordings were digitized at 16 kHz and each sentence was saved in an individual audio file. The cutoff points in the prime words were established using a sound editor (Cool Edit v. 1.52, from Syntrillium Software Corp.) in the following way. For each of the 96 sentences containing the experimental primes, the cut was made at the offset of the second syllable of the last word (i.e., the prime). The 48 sentences containing the control words were cut immediately following the first syllable of the prime.

In addition, 48 filler prime/target pairs were constructed and recorded, in 48 new neutral sentences (i.e., constructed in the same way as the ones described for the experimental and control primes), with primes also placed at the end of the sentences. For 32 of the sentences, the cutoff point was at the end of the second syllable of the prime. Of these 32 sentences, 16 were associated with a word target (YES response) that had no segmental overlap with the prime word fragment, and 16 were associated with a nonword target (NO response) that overlapped phonologically with the prime fragment. The remaining 16 filler sentences had the prime cutoff at the end of the first syllable, and were associated to a target nonword that had no phonological relation to the prime fragment.

Four different experimental lists were constructed from the materials as described. For each sentence sextet, each one of the four experimental prime–target pairings was assigned to a different list. In addition, from the same sextet, each control sentence was associated to the two

[2] Therefore, even if one of the two targets were to be slightly favored by the sentence meaning, the effects would cancel out when averaged, given that across the whole experiment, each of the four possible prime/target combinations was associated with each of the two sentences.

lists that did not already contain an experimental sentence with the target word of that control sentence. In the example in Table 1, each one of the match and mismatch sentences would be assigned to a different list. Thus the control sentence associated to the target PRINCIPE would be assigned to the two lists containing the target PRINCIPIO (either in the match or the mismatch condition); the control associated with the target PRINCIPIO would be assigned to the two lists containing the sentences associated with the target PRINCIPE. In this way each list contained 24 experimental and 24 control sentences in which none of the targets or the carrier sentences were repeated. From the 24 experimental sentences, there were 12 matching prime–target pairings, and 12 mismatching prime–target pairings[3] (see Table 2). All 48 fillers were further added to each list for a total of 96 trials per list. Finally, the sentences in each of these four lists were pseudo-randomly ordered (the only restriction being that there could not be more than three YES or NO responses in a row).

TABLE 2

Distribution of Trial Types for Each List in Experiment 1

Prime type	Cutoff point	S.O.	Response	Number
Match	2	YES	YES	12
Mismatch	2	YES	YES	12
Control	1	NO	YES	24
	2	YES	NO	16
Fillers	1	NO	NO	16
	2	NO	YES	16

Note. The cutoff point refers to the number of syllables presented as a prime (counted from the onset of the word). The column labeled S.O. (segmental overlap) indicates whether the prime fragment and its target onset overlapped segmentally. Response refers to the target lexical status (response “yes” to a word target, and response “no” to a nonword target). The last column displays the number of trials of each type in every list.

Procedure. Each participant was seated in front of a computer screen in an individual booth, wearing Sennheiser HD440II headphones. A two-button response box (with labels YES and NO) connected to the computer’s parallel port was used to collect responses. Participants were instructed to respond (as fast as possible) with their decision as to whether the letter string displayed at the end of the auditory sentence was a word or not, while also trying to avoid errors. The trial sequence started with a row of X’s presented at the center of the screen for 1 s. After that, the X’s were replaced by a row of asterisks while at the same moment the sentence began to be presented over the headphones. At sentence offset (i.e., at the cutoff point of the incomplete prime word), the target string, printed in capital letters, replaced the asterisks on the screen. The target presentation onset started the computer’s clock; timing was stopped by the button press, or after a timeout of 2 s. There was an interval of 1 s before the beginning of the next trial.

The entire experiment was under control of a HP-Vectra VL2 4/66 personal computer running the EXPE programming language (Pallier, Dupoux, & Jeannin, 1997). The auditory sentences were played to headphones via a Proaudio Spectrum 16 soundcard at a comfortable sound pressure level. The response box was placed near each participant’s preferred hand.

Participants listened to two blocks of 96 trials corresponding to two different lists among the four described in the materials section. While the order of trials was randomized within each block, the order of blocks was counterbalanced (targets were repeated once between blocks but never within a block, as pointed out in the description of the lists). Block order was counterbalanced with the type of trial, so if a target had been preceded by an experimental prime (match or mismatch) in one block, it would be preceded by the control prime in the other block. Consequently, the carrier sentences associated with a

[3] Although no targets were repeated within any of these lists, both phonologically related targets in the study were included in the same list (i.e., *PRINcipe* and *prinCIpio*). This was done to gain statistial power (24 observations per cell in the experimental conditions rather than 12). The option of including more items in the experiment was not viable because it was not possible to find sufficient additional Spanish words conforming to the criteria for the experiment. Nevertheless, it was always the case that one of the targets was preceded by the control prime and the other target by an experimental prime (either a match or a mismatch), and that the two trials containing targets of the same experimental pair were presented in different halves of the experiment.

target were always different across the two blocks. The total duration of the experiment was about 25 min.

Results

Two items (together with their experimental pairs) were excluded from the analyses because of a high error rate (15% or more, overall), leaving a total of 44 items. None of the participants made more than 10% errors on average in the experimental conditions. Erroneous responses were excluded from the RT analyses. In this and the following experiments, responses that had RTs faster than 250 ms or were timed out (over 2 s) were also excluded.

Separate ANOVAs were conducted on RTs and on accuracy, across participants and across items (see averages in Table 3). In each the main within-participants/items factor was Prime Type (Match, Mismatch, Control). The RT analyses showed a significant main effect of Prime Type ($F1[2, 78] = 21.1$, $p < .001$; $F2[2, 86] = 14.4$, $p < .001$). Planned contrasts revealed that RTs were faster for matching primes than for control primes ($F1[1, 39] = 20.9$, $p < .001$; $F2[1, 43] = 12.6$, $p < .005$), indicating a significant facilitation effect (+34 ms). The planned contrasts between the mismatching prime condition and the control condition were also significant (although only marginal by participants; $F1[1, 39] = 3.7$; $p = .06$; $F2[1, 43] = 4.9$, $p < .05$), indicating that targets preceded by a word onset mismatching on the position of the primary stress, but otherwise identical, slowed lexical decisions to the target (−18 ms). Although error percentages in this experiment were very low (2.05%, $SE = 0.02$, overall), the same one-way ANOVAs were conducted for the accuracy data. The Prime Type factor did not reach significance in either analysis ($F1[2, 78] = 2.1$, $p = .118$; $F2[2, 86] = 1.3$, $p = .263$). Because there was a repetition of every target across two equivalent halves of the experiment, we also analyzed the results for each half of the experiment alone. The pattern of results was equivalent to that obtained in the experiment as a whole (see Appendix B for the detailed analyses).

Discussion

Experiment 1 shows that two-syllable auditory primes matching the target word's onset both segmentally and suprasegmentally speeded up response times as compared with unrelated control primes. However, prime fragments that were segmentally identical but mismatching in suprasegmental structure slowed down responses. This result clearly shows that Spanish listeners use lexical stress information in lexical access. The two lexical items segmentally compatible with the prime fragment entered the initial candidate set; information from the stress pattern gave an advantage to one of these candidates, thereby biasing the competition process against the mismatching lexical item. The presence of inhibition shows that the target mismatching the prime was indeed initially activated, but then adversely affected by competition from the matching target.

We next ask whether evidence for initial activation and subsequent inhibition can also be ob-

TABLE 3

Average Reaction Times and Error Percentage (+SE in Parentheses) for Each Condition in Experiments 1 through 3

Prime type		Experiment 1	Experiment 2	Experiment 3 1-feature mismatch	Experiment 3, several-features mismatch
Match	RT (ms)	615 (17.6)	617 (16.0)	619 (12.8)	623 (11.6)
	Errors (%)	*1.6 (0.04)*	*1.2 (0.03)*	*1.4 (0.04)*	*0.3 (0.01)*
Mismatch	RT (ms)	667 (18.8)	716 (21.2)	750 (14.7)	744 (12.9)
	Errors (%)	*2.8 (0.05)*	*4.1 (0.03)*	*5.0 (0.09)*	*4.6 (0.08)*
Control	RT (ms)	649 (16.3)	695 (16.9)	710 (14.5)	705 (12.3)
	Errors (%)	*1.7 (0.03)*	*1.7 (0.05)*	*2.4 (0.04)*	*1.6 (0.03)*

served with segmental mismatches. Experiment 2 begins the segmental mismatch investigation with vowel information; vowel match and mismatch are manipulated under the same experimental circumstances as in Experiment 1.

EXPERIMENT 2

In the match condition of Experiment 2, we again presented dissyllabic word onset fragments that completely overlapped with the target word onset. An example is *aban-* (from the word *a.ban.DO.no*; "abandonment") for the target ABANDONO. In the mismatch condition, the prime fragment overlapped with the target word onset except for a vowel in the second syllable (e.g., *abun-* from *a.bun.DAN.cia*; "abundance") for the target ABANDONO. That is, where segmental structure was held constant and stress pattern manipulated in Experiment 1, we here held stress pattern constant and manipulated the nature of a single vowel. Finally, so that any facilitatory/inhibitory effects would be comparable across experiments, primes in the control condition were again one-syllable fragments taken from the onset of unrelated words—for example, *e-* from *e.LAS.ti.co* ("elastic") for the target ABANDONO.

As in Experiment 1, we predicted that matching primes would facilitate responses to the target in comparison with control primes. As before, we would interpret equivalent facilitation from mismatching primes as an indication that vowel information is ignored in lexical activation, no difference between mismatching and control primes as an indication that vowel information is crucial in ensuring membership of the initial set of activated words, and inhibition for the mismatching condition relative to the control as an indication of initial activation and subsequent disadvantage in competition.

Method

Participants. Fifty-one participants from the same population as in Experiment 1 took part in this experiment in exchange for course credits. None had participated in Experiment 1. Data from three participants were discarded due to high error rates (more than 10% overall in the experimental conditions), and the results from one additional participant were lost because she failed to understand the task; seven participants were then excluded to balance the numbers in each version of the experiment (they were selected for exclusion according to their order of arrival). The analyses were therefore again based on data from 40 participants, 10 for each version of the materials.

Materials and procedure. Materials were selected on the same basis[4] as in Experiment 1 except that members of the experimental pairs mismatched in the vowel of the second syllable instead of in stress pattern (that was the same for both members; see a list of materials in Appendix A). Examples of the selected stimuli are shown in Table 4. The overall log frequency of the targets used in this experiment was 2.52 (SD = 1.59), and the mean absolute difference between the log frequency of the members of each pair was 1.73 (SD = 1.45).

Results and Discussion

On the basis of error percentages, 5 items (along with their associated experimental pairs) were removed from the analyses (more than 15% overall error rate), leaving a total of 38 items. Average RTs and error rates for each prime type are shown in Table 3. Analyses of variance on RTs as a function of Prime Type showed a significant effect ($F1[2, 78] = 68.1$, $p < .001$; $F2[2, 74] = 27.9$, $p < .001$). The control versus match planned contrasts reached significance ($F1[1, 38] = 95.9$, $p < .001$; $F2[1, 37] = 37.0$, $p < .001$), as did the mismatch versus control comparisons, although the differ-

[4] In Experiment 2, due to an error during the recording, two of the target pairs that differed in gender were assigned to carrier sentences that were syntactically gender biased. Data analyses excluding these two target pairs along with their controls showed the same effects as the whole data set regarding the facilitation effects in RTs. The inhibition effect (−16 ms difference), did not reach significance in the RT analyses as assessed by the planned contrasts between control and mismatch conditions ($F1[1, 39] = 2.5$, $p = .121$; $F2[1, 33] = 1.9$, $p = .177$), although it was highly significant in the error analysis. In particular, the mismatch condition (M = 3.6% errors, SD = 4.0) was significantly less accurate than the control condition (M = 1.4% errors, SD = 1.9) both by participants and by items ($F1[1, 39] = 8.8$, $p < .005$; $F2[1, 33] = 7.8$, $p < .01$).

TABLE 4

Examples of Prime–Target Pairings for Each Condition in Experiment 2

Prime type	Prime	Target
Match	*a.bun.(DAN.cia)*	*ABUNDANCIA*
Mismatch	*a.ban.(DO.no)*	*ABUNDANCIA*
Control	*e.(LAS.ti.co)*	*ABUNDANCIA*

Note. Parentheses in the prime column indicate the cutoff part of the prime word.

ence was only marginal in the items analysis ($F1[1, 39] = 6.5$, $p < .05$; $F2[1, 37] = 4.1$, $p = .05$). In the error analyses, the effect of prime type was significant ($F1[2, 78] = 9.4$, $p < .001$; $F2[2, 74] = 4.6$, $p < .05$); planned contrasts revealed a significant difference in percentage of errors between mismatching and control conditions ($F1[1, 39] = 11.6$, $p < .005$; $F2[1, 37] = 9.5$, $p < .005$). The planned contrasts between the control and matching condition did not reach significance (both $F < 1$). Analyses across each half of the experiment again revealed a pattern similar to that of the experiment as a whole (see Appendix B).

Thus we observed, again, a facilitation effect in RTs for fragment primes that exactly matched the onset of the target. In addition, both RTs and errors indicated inhibition for targets preceded by vowel-mismatching prime fragments (that were the onset of the competitor word). This effect can be interpreted in terms of multiple activation and competition processes that characterize lexical access. Again, the results suggest that both the matching and mismatching candidates were initially activated, but as soon as the mismatching vowel gave extra evidence favoring the matching candidate, the competition process lead to inhibition of the mismatching word. The present pattern of effects closely resembles that obtained in the stress pattern manipulation (i.e., facilitation for the matching prime and inhibition for mismatching primes). Thus, it appears that lexical stress and segmental information play similar roles in constraining lexical activation for word recognition in Spanish. The relation between stress and segmental information is considered in more detail in the general discussion. First, however, we describe an additional experiment in which we again manipulated segmental match versus mismatch, but in which the manipulations concerned consonants rather than vowels.

EXPERIMENT 3

In many word processing tasks, robust differences appear in the contributions of vowels and consonants. Thus in English, phoneme detection response times are significantly slower for vowels than for consonants (Cutler & Otake, 1994; Hakes, 1971; Van Ooijen, 1994), and Spanish patterns itself like English in this respect (B. Van Ooijen, A. Cutler, R. Sánchez-Casas, & D. G. Norris, submitted manuscript). These results have been interpreted in terms of listeners' sensitivity to vowel variability in natural speech (Cutler, Van Ooijen, Norris, & Sánchez-Casas, 1996). Similarly, in the word reconstruction task, in which listeners turn nonwords into real words by changing a single sound, vowel changes are easier to make than consonant changes (Cutler et al., 2000, for Spanish and Dutch; Van Ooijen, 1996, for English). It is therefore possible that vowel and consonant information might also make different contributions in the present task. The closely similar patterns of results that we have observed in Experiments 1 and 2 cannot conclusively demonstrate that suprasegmental and segmental effects on lexical activation are parallel. Stress differences between syllables are, after all, principally carried by vocalic rather than by consonantal portions of the speech signal; the equivalent results might therefore reflect some property of vowels that would fail to hold for consonants. In Experiment 3 we therefore continue our investigation with a comparison of match versus mismatch using a consonantal manipulation.

Moreover, in this experiment we included an explicit evaluation of the actual phonological distance involved in a segmental mismatch. Such a comparison, it should be noted, is possible with consonant mismatches but difficult or even impossible with stress or vowel mismatches. Syllables are either stressed or unstressed; a range of intermediate possibilities does not exist. Vowels in Spanish (with its five-vowel inventory) are all more or less equally distinct.[5] Phonological distance effects can be examined, however, in consonant mismatch, in Spanish as in other languages. The 20 consonants of Spanish include pairs differing in a single phonological feature—e.g., /t/ versus /p/, differing only in place of articulation—and pairs differing in more features—e.g., /f/ versus /l/, differing in place and manner of articulation as well as in voicing. In Experiment 3 we investigated the effect of single-feature mismatches (an example is *pa.TI.lla–pa.PI.lla*) as well as of mismatches in several phonological features (e.g., *bo.fe.TON–bo.le.TIN*). The logic here parallels that of the previous experiments. Namely, we expect to replicate the typical facilitatory effect of matching primes with respect to the controls, and use the amount of inhibition in the mismatch condition as a measure of the magnitude by which the manipulated property (here, one or more than one phonological feature) contributes to reduction the activation of competing lexical candidates.

Method

Participants. Ninety-six participants were recruited from the same population as in Experiments 1 and 2. Data from one participant were lost because of experimenter error, data from three participants were discarded due to an overall error rate above 10% in the experimental trials, and data from eight more participants were excluded in order to balance the number of participants in each version of the lists and each experimental group. No participant had taken part in either of the previous experiments, nor did any report problems in hearing or vision. Participants were divided into two groups according to the set of materials with which they were tested (one-feature mismatch and several-feature mismatch, 40 in each).

Materials and procedure. Two complete sets of materials were selected according to the same criteria as in the previous experiments except that members of each experimental pair were matched in stress pattern and all vowels, but they had a mismatch in the consonantal sound at the onset of the second syllable. In one set of materials the consonantal mismatch consisted of one feature whereas in the other set of materials it was of more than one feature (2.58 features on average, $SD = 0.5$).

The experimental procedure was exactly the same as in previous experiments. Examples of the selected stimuli are shown in Table 5, and the materials are listed in Appendix A. The overall log frequency of the targets used in the one-feature mismatch set was 2.58 ($SD = 1.82$), and the mean absolute difference between the log frequencies of the members of each pair was 1.42 ($SD = 0.88$). The overall log frequency of the targets in the several-features mismatch set was 3.09 ($SD = 1.34$), and the mean absolute difference between the log frequencies of the members of each pair was 1.35 ($SD = 0.84$).

Results

Three items (along with their experimental and control pairs) were removed from the data collected with the one-feature mismatch set because of a high error rate (above 15% overall), leaving a total of 42 items for that data set. No items from the several features mismatch set had to be removed from the analyses because accuracy was above 85% for all of them. We conducted ANOVAs on RT and the accuracy data, including prime type as a within-participants factor and mismatch group (one- vs. several-feature mismatch) as a between-participants factor.

In the RT analyses, neither the between-participants factor mismatch group (both Fs $<$ 1) nor the interaction between mismatch group and prime type (both Fs $<$ 1) approached sig-

[5] Even in other languages, a vowel-based comparison of degrees of phonological distance would be difficult to achieve. Although in English, for instance, the vowels of *bat* and *bet* are very close while the vowels of *bought* and *beet* are far apart, it proves difficult to find pairs of words with three or more syllables in which the first two syllables are identical except for a difference between two such selected vowels. This fact reflects interesting characteristics of the patterning of vowels and consonants in vocabulary structure, and these may in turn underlie the vowel–consonant differences in some processing tasks; however, for the present purposes, the effect is to render impossible an investigation of vocalic distance in a fragment priming experiment of the kind used in the present study.

TABLE 5

Examples of Prime–Target Pairings for Each Condition in Experiment 3

Mismatch group	Prime type	Prime	Target
1-feature mismatch	Match	*pa.PI.(lla)*	*PAPILLA*
	Mismatch	*pa.TI.(lla)*	*PAPILLA*
	Control	*ce.(NE.fa)*	*PAPILLA*
Several features mismatch	Match	*bo.fe.(TON)*	*BOFETON*
	Mismatch	*bo.le.(TIN)*	*BOFETON*
	Control	*ga.(vi.LAN)*	*BOFETON*

Note. Parentheses indicate the cutoff part of the prime word.

nificance. The effect of prime type was significant ($F1[2, 156] = 254.7$, $p < .001$; $< F2[2, 176] = 161$, $p < .001$; see Table 3). Planned contrasts showed that there were significant differences between the control and matching prime conditions ($F1[1, 78] = 235.8$, $p < .001$; $< F2[1, 88] = 173$, $p < .001$) and between the control and mismatching prime conditions ($F1[1, 78] = 46.7$, $p < .001$; $< F2[1, 88] = 34.4$, $p < .001$).

The main effect of mismatch group also failed to reach significance in the accuracy analyses ($F1[1, 78] = 2.0$, $p = .156$; $F2[1, 88] = 1.5$, $p = .212$). The interaction between mismatch group and prime type was also insignificant (both Fs $<$ 1). The effect of Prime Type in the accuracy data was significant both by participants and by items ($F1[2, 156] = 30.3$, $p < .001$; $F2[2, 176] = 21.7$, $p < .001$). The planned contrasts showed that the accuracy in the mismatching condition was lower than in the control condition ($F1[1, 78] = 21.4$, $p < .001$; $F2$ $[1, 88] = 15.3$, $p < .001$) and that accuracy in the match condition was higher than in the control condition ($F1[1, 78] = 16.2$, $p < .001$; $F2[1, 88] = 14.2$, $p < .001$). Separate analyses for each half of the experiment within each group of participants showed the same pattern of results as that seen in the experiment as a whole (see Appendix B).

Discussion

Experiment 3 produced a pattern of results remarkably consistent with the findings of Experiments 1 and 2; fully matching primes facilitate decisions to a target word, whereas mismatching primes inhibit responses. These results clearly suggest that listeners use information about the phonological makeup of words in exactly the same way whether this information is suprasegmental or segmental, vocalic or consonantal. Most remarkably, the effect of a consonantal mismatch appears to be quite comparable irrespective of whether the mismatch involves a single phonological feature (inhibition due to mismatch 40 ms) or more (39 ms). Phonological distance, in other words, is not a relevant factor in the activation and competition process: *cackle* is as effective as *camel* in mismatching *cattle*. The absence of significant interactions between mismatch magnitude and prime type in the present experiment suggests equivalence in the contribution of each type of consonantal mismatch to lexical competition. Under the same logic, we addressed whether any of the mismatches evaluated in the other experiments presented in this study produced a significantly different amount of inhibition. Taking into account that every other aspect of the method is equivalent across the present experiments, differences in the amount of inhibition would suggest differences in the contribution of the type of mismatch to lexical access. We conducted a cross-experiment statistical comparison including data from all the experiments in the present study and found no statistical differences in the amount of inhibition that any type of mismatch (stress, vowel, consonant one-feature, and consonant several features) produced with respect to the control condition. Detailed analyses are reported in Appendix C.

GENERAL DISCUSSION

Our series of experiments has assessed the effects of suprasegmental (lexical stress) and segmental (vocalic and consonantal) information in lexical access, evaluating their contribution in a cross-modal priming lexical decision task. The results were remarkably clear: In all experiments, we found that matching primes facilitated responses to a visually presented target, whereas mismatching primes inhibited lexical decision responses. We observed comparable effects of segmental and suprasegmental mismatch, of vocalic and consonantal mismatch, and of single-feature versus multi-feature mismatch. These results motivate a number of general conclusions.

First, consider the equivalence of the contributions of suprasegmental and segmental information to the activation of word forms. The differences between mismatch and control conditions were in the same direction (i.e., inhibition in the mismatch condition) in all four experiments and for each of the data sets analyzed (participants and items RTs and accuracy). This remarkable consistency in the data makes it safe to conclude that, at least qualitatively, the effects of every type of mismatch were equivalent. That is, mismatches in stress pattern and in segmental structure apparently affected activation of candidate words in the same way: One activated word was favored, the other disfavored, and the consequent competition between these words led to inhibition when targets were mismatched by primes. This is clear evidence that Spanish-speaking listeners take account of suprasegmental information in computing the phonetic code that accesses stored lexical entries. As we described in the introduction, no current model of spoken-word recognition takes account of the contribution of suprasegmental information to word-form activation; our findings strongly suggest that they should. Suprasegmental information can constrain activation in the same way as segmental information does.

Similar conclusions have been drawn for Dutch, based on results from semantic judgment tasks (Koster & Cutler, 1997), gating (Jongenburger, 1996), and word spotting (A. Cutler & W. Van Donselaar, submitted manuscript). Evidence from cross-modal associative priming suggests a different state of affairs for English (Cutler, 1986); in this language, suprasegmental information is largely redundant for word discrimination, since interword differences in stress pattern nearly always involve vocalic differences, and thus listeners profit little from taking account of suprasegmentals in word-form activation.[6] However, when such redundancy is reduced (Dutch) or entirely absent (Spanish) suprasegmentals can usefully reduce the number of potential candidate words. We predicted, therefore, that an effective role of suprasegmental information would be observed in Spanish, and our results were fully in accord with this prediction. For the first time, moreover, the relative contributions of suprasegmental and segmental information have been directly compared statistically, and, as we have observed, the contributions appear to be equivalent. It is not clear that a direct metric can be established across different types of features such as consonant or stress. However, when the average RTs in all four experiments were equated (therefore, controls were at the same level of performance for each; see Appendix C), there were no differences in the actual size of the inhibitory effects produced by each feature mismatch, suggesting that their actual effects on speech recognition must not be very disparate in magnitude.

Some previous investigations of spoken-word recognition in Spanish have shown effects of lexical stress. Syllabic match effects in syllable detection (faster responses to targets that correspond to the syllable divisions of the target-bearing word than to targets that do not) are stronger in disyllables with stress on the second syllable (e.g., *caSO*) than in disyllables with stress on the first syllable (e.g., *CAso*; Sebastián-Gallés, Dupoux, Segui, & Mehler, 1992). Phoneme-monitoring responses to word-initial sounds, likewise, show a larger advantage of word over nonword items in *caSO*-type than in *CAso*-type disyllables (Sebastián-

[6] Vowel quality is perceptible by itself from a few pitch periods while stress requires at least more time, and usually reference to another syllable for comparison. This is the reason that it is stress and not vowel quality that is overridden at this stage of processing (see Cutler, 1986, for a full discussion of this matter).

Gallés, 1996). These results were interpreted as possible evidence that unstressed syllables in Spanish are less efficient than stressed syllables in activating word forms. Our present results do not lend direct support to such an argument, and we here propose an explanation of the earlier stress effects in terms of the competition process. Specifically, there are more Spanish words with unstressed initial syllables than with stressed initial syllables (87% vs 13% as assessed in the LEXESP database of Spanish words; Sebastián-Gallés et al., 2000), and since we now know that lexical activation is indeed sensitive to stress in this language, an unstressed initial syllable will presumably activate more potential word candidates than a stressed initial syllable will. This increased activation of word forms would then translate into increased level of inhibition for mismatching candidates, leading to the effects observed in Sebastián-Gallés (1996).

What is clear is that the role of lexical stress placement cues in the activation of words has been firmly established by the present findings, and that this role appears to be in no way disadvantaged in comparison to the part played in the same process by segmental information. As Cutler et al. (1997) concluded, there is no reason to view the contribution of suprasegmental and segmental information in spoken-word recognition as differing in any principled way; listeners exploit all information that can be of use to them. Lexical stress information is not always useful, of course. In English it is less useful, simply because it nearly always varies redundantly with vowel quality. It is likewise of little value in languages in which the prosodic pattern of words does not vary freely, like in French (Dupoux, Pallier, Sebastián-Gallés, and Mehler, 1997). In Spanish, even though there are (as in all stress languages) very few (morphologically unrelated) word pairs that are distinguished solely by stress, stress pattern information is useful because it can cut down the population of competing word forms during the processing of ongoing speech. To this end, as our study has shown, listeners use it.

There are other examples supporting that listeners' use of information in the speech signal is tailored to the phonological structure of their native language (Cutler, 1997). For instance, although across many languages it appears that listeners exploit metrical structure to locate word boundaries in speech, the nature of the metrical structure and the consequent manner in which it is exploited differ in languages such as English (Cutler & Norris, 1988; Cutler & Butterfield, 1992), French (Cutler, Mehler, Norris, & Segui, 1986; Mehler, Dommergues, Frauenfelder, & Segui, 1981), Catalan (Sebastián-Gallés et al., 1992), and Japanese (Cutler & Otake, 1994; Otake, Hatano, Cutler, & Mehler, 1993). Information that is available in a particular language but has no counterpart in other languages is easily exploited by native listeners—thus vowel harmony in Finnish is exploited as a cue for word segmentation in that language (Suomi, McQueen, & Cutler, 1997). Stress, then, can be seen as another such language-specific cue in the recognition of spoken language. It is irrelevant to word recognition in languages without variable stress, and even within the group of variable-stress languages it does not always provide a useful cue; however, it is exploited by listeners whose experience with the native language has taught them that stress can usefully contribute in lexical selection.

A second conclusion from our study concerns the equivalent effects of consonant and vowel information in constraining word-form activation, contrasting with the robust differences observed when using other tasks. Thus studies using the word reconstruction paradigm (Cutler et al., 2000; Van Ooijen, 1996) have shown that vowel information seems to be less constraining for listeners than consonant information (i.e., suggesting that vowels carry less weight than consonants in lexical access). Given a free choice, listeners are significantly biased (both in RTs or in preference) toward turning a nonword into a real word by substitution of a vowel rather than a consonant—i.e., they prefer to change *kebra* into *cobra* rather than into *zebra*. These results hold in English, Dutch, and Spanish, languages that differ in the balance of vowels and consonants in their phonemic inventory. Other studies have also revealed processing differences between consonants and vowels; phoneme detection is faster for the former than for the latter in both English and Spanish (B. Van Ooijen et al., submitted manuscript). Vowels are in general longer than consonants; they are more resistant to noise masking (Nooteboom & Doodeman, 1984) and less often misreported in slips of the ear (Bond & Garnes, 1980). It may thus seem somewhat remarkable that they should be disadvantaged in these processing tasks.

Nevertheless, robust as these vowel-consonant differences appear to be in the phoneme detection and word reconstruction tasks, similar asymmetries do not appear to arise in lexical decision. Support for this claim, in addition to the results of the present study, is available from a study by Cutler et al. (1999) involving two different types of lexical decision experiments. First, Cutler et al. tested whether spoken words like *kebra* would prime lexical decision responses to written words like COBRA or ZEBRA. No difference was found between these primes and an unrelated control condition; certainly there was no evidence that mismatches in vowels versus consonants exercised differing effects. Second, Cutler et al. examined repetition priming in auditory lexical decision in Dutch. A continuous sequence of spoken items was presented for lexical decision, and response times to a given target item were compared as a function of whether a preceding item in the list was or was not similar to this target. Cutler et al. found that responses to Dutch words were facilitated (in comparison to a control condition) if the item immediately preceding the target mismatched with the target on only a single phoneme (vowel or consonant). Responses to the word *kaper* (“pirate”) were faster after *kamer* (“room”) or *koper* (“buyer”) than after *gretig* (“greedy”), and this result also held for nonword primes (i.e., responses to *lepel*, “spoon”, were faster after the nonwords *lopel* or *lemel* than after the nonword *gukte*). Thus in lexical decision, in contrast to phoneme detection and word reconstruction, there appears to be no observable asymmetry in the contribution of vowel versus consonant information.

There is a potentially important difference among these various tasks that can help explain the discrepancy in the results. Both phoneme detection and word reconstruction require listeners to attend to a phonemic level of representation. Phoneme detection demands monitoring for a phonemic target, and word reconstruction requires substitution of a single phoneme of the input string; hence it asks the listener to consider the input as a sequence of individual phonemes. At this level of explicit decisions about phonemes, clear differences arise in the processing of vowels and consonants. Lexical decision, however, requires attention only to the lexical level: is this input string (of letters or of sounds) an actual word or not? Prelexical processing for lexical activation is sensitive to match versus mismatch between input and stored representations, but there does not appear to be a categorical difference between vowels and consonants in the type of contribution they deliver at this level.

Our third conclusion from the present study concerns the failure of phonological distance to modulate the consonant mismatch effect. A consonantal mismatch is equally effective whether it involves difference in one or more phonological features. This does not, of course, imply that phonetic similarity has no role to play in spoken-word recognition. Studies of phonetic confusability (e.g., Wang & Bilger, 1973) show that sounds that differ in more features are less often confused with one another than sounds that differ in fewer features; under difficult listening conditions, such as in a noisy room or on a faint telephone connection, the input may not be sufficiently clear for similar phonemes to be distinguished (though clear enough for dissimilar phonemes not to be confused). In such a case, if the vocabulary contains two words that happen to differ only by containing one each of two highly confusable sounds, then both of these two words may be equally well supported, and neither of them mismatched. This is much less likely to happen with two words that differ in dissimilar phonemes, and in this way phonetic similarity is obviously important in activation. However, when the input is clear, so that even similar phonemes can be distinguished, a phoneme that gives support to one word but mismatches another will add activation to the matched word, which will then triumph over the mismatched word in the competition process, and this will happen whether the difference at that point between the two words involves similar or dissimilar sounds.

Note that this mismatch effect is specific to the case where the distinction involves two competing word candidates; it relies on a crucial choice having to be made in favor of one word that diverges at that point from another. Any mismatch is enough; once one of the two competitors has been advantaged, the competition process automatically leads it to inhibit its competitor. The situation is different in the case of a mismatch when no competitor is involved. Suppose an English listener hears *encyclo-*; there is only one English word that is likely to be activated by this onset fragment and it will thus be the most active candidate, with no real competitor. If the next phoneme in the input is /b/, instead of the appropriate /p/, a mismatch will result, but it will have little effect (indeed it may not even be noticed); substitution of a dissimilar phoneme for the /p/, for instance /z/, will, however, have a stronger effect. This is known from studies of mispronunciation detection (e.g., Marslen-Wilson & Welsh, 1978) and phoneme detection (Connine et al. 1997). However, as Experiment 3 shows, when input is consistent with two competing words except for a single mismatch, the number of features involved in the mismatch is immaterial.

The fourth and final conclusion to be drawn from our findings concerns the role of inhibition in the lexical recognition process. The robust and consistent inhibitory effect that we have observed in our experiments offers, we would argue, strong support for models of spoken-word recognition in which lexical selection occurs as the outcome of a competition process between alternative candidate words simultaneously activated by the input. Such models include TRACE (McClelland & Elman, 1986) and Shortlist (Norris, 1994). In these models, the competition process is instantiated via the mechanism of lateral inhibition. At a given level of processing, simultaneously active nodes are connected by mutual inhibitory links, and the more any given node is activated, the more it passes inhibition to the other nodes at the same level to which it is connected. Thus the inhibition observed in our lexical decision experiments arises when (for example) one of two simultaneously activated words becomes activated to a greater extent than the other; it succeeds in passing inhibition to the other, thus reducing that word's activation level, and this process continues, with the first word's activation steadily increasing and the second word's activation steadily reducing. When separately arriving information, however, demands (re-) activation of the inhibited word in order for a correct response to be made, the inhibition arising from the competition process must first be overcome. As we pointed out in the Introduction, experimental evidence already exists in favor of such competition-based models (e.g., Goldinger et al., 1989; McQueen et al., 1994); the present study clearly adds further support.

In summary, our three experiments have provided evidence in favor of the general hypothesis that listeners of a language will use all available cues for lexical access that usefully serve to distinguish between words of the language in question. If the language contains pairs of words that differ suprasegmentally but are segmentally identical, then listeners will use suprasegmental information in lexical activation. Moreover, the relative contributions of suprasegmental and of segmental information in the lexical activation process seem quite equivalent. Similarly, there seems to be no categorical difference in the contribution made by vowels versus consonants, or by single-feature versus multi-feature differences between phonemes. Any incoming speech information that favors one lexical candidate but mismatches a simultaneously active competitor will be equally effective; the competition process is ruthless, and once one word has an advantage it will be able to triumph, regardless of the type of speech information providing the advantage. Finally, the results offer further support for models of spoken-word recognition involving automatic activation of word forms and competition between activated words.

APPENDIX A: LIST OF MATERIALS IN EXPERIMENTS 1 THROUGH 3

Experiment 1 (stress mismatch; stressed syllable is underlined)

ANGULO (angle)	ANGUILA (eel)	INDICE (index)
ARTICO (Artic)	ARTICULO (article)	CABALLO (horse)
COMEDIA (comedy)	COMEDOR (dining room)	DELITO (crime)
DISCIPULO (pupil)	DISCIPLINA (discipline)	BOLIGRAFO (pen)
EJERCITO (army)	EJERCICIO (exercise)	CLASICO (classic)
ESPECTRO (ghost)	ESPECTACULO (performance)	ARABE (Arabian)
ESPIRITU (spirit)	ESPIRAL (spiral)	ALIJO (unloading)
ESTAMPA (engraving)	ESTAMPIDA (stampede)	FISICA (physics)
ESTATUA (statue)	ESTATUTO (statute)	MARIDO (husband)
GALERA (galley)	GALERIA (gallery)	CAMARA (room/camera)
INCENDIO (fire)	INCENTIVO (incentive)	PETARDO (firework)
LITERA (bunk bed)	LITERAL (literal)	DECADA (decade)
MARISCO (shellfish)	MARISCAL (marshal)	LAVABO (toilet)
MEJILLA (cheek)	MEJILLON (mussel)	CANTARO (pitcher)
PELOTA (ball)	PELOTON (squad)	MACETA (flowerpot)
PRESIDIO (prison)	PRESIDENTE (president)	MODULO (module)
PRINCIPE (prince)	PRINCIPIO (beginning)	MOSQUITO (mosquito)
PROCESO (process)	PROCESION (procession)	MEDICO (doctor)
PROYECTO (project)	PROYECTIL (missile)	CASTILLO (castle)
SECRETO (secret)	SECRETARIO (secretary)	VICARIO (curate)
SERENO (calm)	SERENATA (serenade)	REPLICA (answer)
SUCESO (event)	SUCESION (succession)	TEJADO (roof)

Experiment 2 (vocalic mismatch)

ABONADO (subscriber)	ABANICO (fan)	OSADO (daring)
ABUNDANCIA (abundance)	ABANDONO (abandonment)	ELASTICO (elastic)
ACOTAR (to limit)	ACATAR (to obey)	ENFILAR (to thread)
ALUMBRADO (lighting)	ALAMBRADA (wire fence)	ASENTIR (agree)
APETITO (appetite)	APATIA (apathy)	ELEGIDO (selected)
ASTURIANO (Asturian)	ASTERISCO (asterisk)	ENCIMERA (worktop)
CABELLERA (hair)	CABALLERO (gentleman)	SOLEDAD (loneliness)
COMPETIDOR (competitor)	COMPATIBLE (compatible)	TONTERIA (silliness)
EMBESTIDA (charge)	EMBUSTERO (liar)	ANGUSTIA (distress)
ESCONDITE (hiding place)	ESCANDALO (scandal)	ALMENDRO (almond tree)
FRANQUICIA (franchise)	FRANQUEZA (frankness)	CRISTALINO (limpid)
HISTERIA (hysteria)	HISTORIA (history)	ALMEJAS (clam)
INDUCIDO (induced)	INDECISO (undecided)	ARTILUGIO (gadget)
MINORIA (minority)	MINERIA (mining)	CALAMIDAD (disaster)
OCTUBRE (October)	OCTAVO (eighth)	ESTUFA (heater)
RELLENO (filling)	RELLANO (landing)	VISITA (visit)
REPORTERO (journalist)	REPERTORIO (repertoire)	FILANTROPO (philanthropist)
RESULTADO (result)	RESALTADO (highlighted)	COBALTO (cobalt)
SARDINA (sardine)	SARDANA (Catalan dance)	MANTILLA (mantilla)

Experiment 3 (1-feature consonantal mismatch)

AFILADOR (sharpener)	AGILIDAD (agility)	UNIVERSAL (universal)
APARATO (device)	AVARICIA (greed)	ELEGANTE (elegant)
APESTOSO (stinking)	ATESTADO (testimonial)	EFECTO (effect)
APROBADO (approved)	ACROBACIA (acrobatics)	EDREDON (quilt)
CALIDAD (quality)	CARIDAD (charity)	JUVENIL (young)
CAMERINO (dressing room)	CAÑERIA (piping)	MONITOR (monitor)
CAMINO (path)	CABINA (cabin)	PELIGRO (danger)

CATETO (yokel)	CADETE (cadet)	LINAJE (lineage)
COCINERO (coock)	COJINETE (bearing)	DEGOLLADO (beheaded)
CONCESION (concession)	CONFESION (confession)	GESTACION (gestation)
DELEGADO (representative)	DENEGADO (denied)	FINALISTA (finalist)
DIMISION (resignement)	DIVISION (division)	RELIGION (religion)
EPICO (epic)	ETICO (ethic)	AGUILA (eagle)
ESPIRAL (spiral)	ESTIRON (jerk)	ANDALUZ (andalusian)
MATERIA (matter)	MADERA (wood)	TOMILLO (thyme)
PAPILLA (baby food)	PATILLA (sideburn)	CENEFA (trimming)
PROCESION (parade)	PROFESION (career)	CLARIDAD (clarity)
RECADERO (messenger)	REGADERA (sprinkler)	LITERARIO (literary)
REDENCION (redemption)	RETENCION (retention)	DIMENSION (dimension)
TEMIDO (feared)	TEÑIDO (dyed)	MOROSO (bad payer)
TRAFICO (traffic)	TRAGICO (tragic)	CRITICO (critic)

Experiment 3 (2 or more features consonantal mismatch)

AFONICO (voiceless)	ANONIMO (anonymous)	ILICITO (ilegal)
AGOSTO (August)	APOSTOL (apostle)	HORRENDO (horrible)
ATENTADO (assault)	AVENTURA (adventure)	ILUSTRADO (illustrated)
BOFETON (smack)	BOLETIN (bulletin)	GAVILAN (sparrowhawk)
CALIDAD (quality)	CAVIDAD (cavity)	TOCADOR (dressing table)
CARTELERA (billboard)	CARCELERO (jailer)	MERMELADA (jam)
CINICO (cynical)	CIVICO (civic)	FASICO (phasic)
COLISION (colision)	COMISION (comitee)	TEJEDOR (weaver)
DEDICADO (devoted)	DELICADO (delicate)	MACERADO (macerate)
INCENTIVO (incentive)	INVENTARIO (inventary)	ARGENTINO (Argentinian)
INFECCION (infection)	INYECCION (injection)	HERMANDAD (brotherhood/sisterhood)
INFERIOR (inferior)	INTERIOR (interior)	ESPIRAL (spiral)
MAJESTAD (majesty)	MALESTAR (discomfort)	CORRECTOR (proofreader)
MIMICA (mimicry)	MITICO (mythical)	COLICO (colic)
PAPILLA (baby food)	PASILLO (corridor)	BELLEZA (beauty)
PROTECTOR (protective)	PROYECTIL (projectile)	TRILLADOR (threshing machine)
RECATADO (polite)	RELATIVO (relative)	CAMILLERO (stretcher bearer)
REFERENCIA (reference)	REVERENCIA (reverence)	SOÑOLIENTO (sleepy)
REPENTINO (sudden)	RESENTIDO (resentful)	CALENDARIO (calendar)
SAGITARIO (Sagittarius)	SANITARIO (sanitary)	TORREFACTO (roasted)
SEGADOR (reaper)	SENADOR (senator)	CABEZON (bigheaded)
SINFONIA (sinphony)	SINTONIA (tuning)	DESMEDIDO (disproportionate)
TONALIDAD (tonality)	TOTALIDAD (whole)	FACILIDAD (easiness)
VISCERA (entrails)	VISPERA (eve)	
TOMBOLA (raffle)		

A list of the complete carrier sentences can be found at http://www.idealibrary.com

APPENDIX B: ANALYSES INCLUDING THE EXPERIMENTAL HALF AS A FACTOR

As each participant was presented with two sets of materials that included a repetition of the targets (albeit no given prime–target combination), we were concerned to establish whether repetition effects might have contaminated the overall effects. Here we present analyses testing the effect of the experimental half and its interaction with the prime type factor. The main effect of Prime Type is ignored here, as it can be found in the Results of the corresponding experiments.

Experiment 1. RTs were faster ($F1[1, 39] = 101.1$, $p < .001$; $F2[1, 43] = 106.4$, $p < .001$) and responses more accurate ($F1[1, 39] = 13.5$, $p < .005$; $F2[1, 43] = 5.3$, $p < .05$) in the second half of the experiment as compared to the first half. The interaction between experimental half and Prime Type did not reach significance for RT (both Fs < 1), but experimental half interacted with prime type for accuracy ($F1[2, 78] = 8.4$, $p < .005$; $F2[2, 86] = 8.0$, $p < .005$). Both the first and second halves of the experiment showed a main effect of prime type ($F1[2, 78] = 6.4$, $p < .005$; $F2[2, 86] = 4.1$, $p < .05$ and $F1[2, 78] = 3.1$, $p < .05$; $F2[2, 86] = 4.2$, $p < .05$, respectively). Planned contrasts for each half of the experiment separately showed that in the first half of the experiment responses were more accurate in the matching condition than in the control condition ($F1[1, 39] = 6.3$, $p < .05$; $F2[1, 43] = 5.3$, $p < .05$), and marginally less accurate in the mismatching condition than in the control condition ($F1[1, 39] = 3.1$, $p = .08$; $F2[1, 43] = 2.5$, $p = .121$]; in the second experimental half matching primes again yielded more accurate responses than control primes ($F1[1, 39] = 3.2$, $p = .08$; $F2\ [1, 43] = 4.3$, $p < .05$), but here there were no differences between control and mismatch prime conditions (both Fs < 1).

Experiment 2. RTs were faster ($F1[1, 39] = 74.5$, $p < .001$; $F2[1, 37] = 136.1$, $p < .001$) and responses were more accurate ($F1[1, 39] = 17.7$, $p < .001$; $F2[1, 37] = 10.8$, $p < .005$) in the second half of the experiment than in the first half. The interaction between experimental half and prime type was significant for RT ($F1[2, 78] = 5.6$, $p < .01$; $F2[2, 74] = 6.1$, $p < .005$); the difference between mismatching and control conditions was significant in the first half of the experiment ($F1[1, 39] = 5.1$, $p < .05$; $F2[1, 37] = 4.5$, $p < .05$) but not in the second half ($F1[1, 39] = 2.8$, $p > .1$; $F2[1, 37] = 1.2$, $p > .2$). The matching vs control difference was significant in both halves (all $p < .001$).

The accuracy data also showed an interaction between experimental half and prime type ($F1[2, 78] = 5.6$, $p < .01$; $F2[2, 74] = 6.1$, $p < .05$). Here the error rate was significantly higher in the mismatching condition than in the control condition in the first half of the experiment ($F1[1, 39] = 11.7$, $p < .005$; $F2[1, 37] = 8.4$, $p < .01$) but not in the second half ($F1[1, 39] = 1.5$, $p = .2$; $F2[1, 37] = 1.2$, $p = .2$). The matching and the control conditions did not differ in either half of Experiment 2 (2.2% vs 2.1% in the first half, and 0.6% vs 1.1% in the second half).

Experiment 3: One-feature mismatch group. The main effect of experimental half was significant both for RT ($F1[1, 39] = 128.3$, $p < .001$; $F2[1, 41] = 131.8$, $p < .001$) and accuracy ($F1[1, 39] = 21.3$, $p < .001$; $F2[1, 41] = 25.7$, $p < .001$) in the same direction as in the preceding experiments. In RTs, the interaction between experimental half and prime type was significant ($F1[2, 78] = 4.7$, $p < .05$; $F2[2, 82] = 4.2$, $p < .05$). In fact, the prime type effect was significant in both halves of Experiment 3 (1st: $F1[2, 78] = 92.0$, $p < .001$; $F2[2, 82] = 56.2$, $p < .001$; 2nd: $F1[2, 78] = 72.1$, $p < .001$; $F2[2, 82] = 53.0$, $p < .001$); the source of the interaction was a difference in the size of the mismatch vs control effect (-55 ms in the first half and -29 ms in the second, both significant, $p < .001$ and $p < .05$, respectively). The matching vs control difference was significant and equivalent for both experimental halves (92 and 83 ms, $p < .001$ and $p < .005$).

The accuracy data also showed an interaction between experimental half and prime type ($F1[2, 78] = 4.8$, $p < .05$; $F2[2, 82] = 3.8$, $p < .05$); the effect of prime type was significant in the first half of the experiment ($F1[2, 78] = 10.5$, $p < .001$; $F2[2, 82] = 6.5$, $p < .005$) but not in the second ($F1[2, 78] = 1.6$, $p = .208$; $F2[2, 82] = 1.9$, $p = .153$). Planned contrasts for the first experimental half revealed that the prime type effect was due to a significant difference between the mismatching and the control condition ($F1[1, 39] = 8.6$, $p < .01$; $F2[1, 41] = 4.5$, $p < .05$), and a marginal difference between control and matching conditions ($F1[1, 39] = 4.0$, $p = .06$; $F2[1, 41] = 2.8$, $p = .1$).

Experiment 3: Several feature mismatch group. Responses were faster ($F1[1, 39] = 72.4$, $p < .001$; $F2[1, 47] = 161.0$, $p < .001$) and more accurate ($F1[1, 39] = 17.9$, $p < .001$; $F2[1, 47] = 10.5$, $p < .005$) in the second half of the experiment than in the first half. The interaction between experimental half and Prime Type did not reach significance in the RT analyses ($F1 < 1$; $F2[2, 94] = 1.9$, $p = .145$) or in the accuracy data ($F1[2, 78] = 2.6$, $p = .075$; $F2[2, 94] = 1.9$, $p = .154$)

APPENDIX C: CROSS-EXPERIMENT ANALYSES

The pooled data of all experiments were submitted to analyses of variance (we included the two groups of Experiment 3 as two different experiments in these analyses). Given that the main effect of Prime Type was significant in all experiments, it is not surprising that here too it was significant, both in the RT and the error analyses; on both measures, the differences between the control condition and each of the other two conditions were separately significant. We report in detail only effects involving the factor Experiment, specific to these pooled analyses.

In the accuracy analyses, there was no main effect of Experiment and no interaction of this factor with Prime Type. In the RT analyses, the main effect of Experiment was marginally significant by participants and significant by items ($F1[3, 156] = 2.3$, $p = .08$; $F2[3, 168] = 7.4$, $p < .001$), indicating overall differences in mean RT across the different experiments. Pairwise comparisons (Bonferroni) on the mean RTs across items indicated that responses were faster in Experiment 1 than in Experiment 2 ($p < .05$), and than in both groups of Experiment 3 ($p < .001$ in both). These differences did not reach significance in the analysis by participants. No other pairwise comparisons reached significance. The interaction between Experiment and Prime Type was also significant ($F1[6, 312] = 9.6$, $p < .001$; $F2[6, 336] = 5.1$, $p < .001$). Planned contrasts revealed that the source of the interaction was a significant difference in the size of the control vs match effect ($F1[3, 156] = 10.6$, $p < .001$; $F2[3, 168] = 6.2$, $p < .001$) across experiments. Pairwise comparisons (Bonferroni) showed that there was less facilitation for matching primes in Experiment 1 than in the other experiments ($p <. 001$ for all comparisons involving the matching effect of Experiment 1 with that of the other experiments). The size of the control vs mismatch effect, on the other hand, did not significantly differ across experiments[7] ($F1[3, 156] = 1.7$, $p > .1$; $F2[3, 168] = 1.1$, $p > .3$).

The faster RTs in Experiment 1 than in Experiments 2 and 3 are presumably due to the higher frequency of items in Experiment 1 ($M = 3.61$, $SD = 1.5$) as compared to items in Experiments 2 ($M = 2.52$, $SD = 1.59$) and both groups of Experiment 3 ($M = 2.58$, $SD = 1.82$; $M = 3.09$, $SD = 1.34$, for one- and several-feature mismatch sets, respectively). The fact that the significant differences were restricted to the

[7] This result remains the same after we exclude the gender-biased item in Experiment 2; $F1[3, 156] = 2.0$, $p = .113$ and $F2[3, 164] = 1.2$, $p = .286$ in the RTs analyses; and both Fs < 1 for the error analyses.

items analysis further supports this account. However, this overall difference in RTs, renders the interpretation of the rest of effects in the analysis difficult (since the detected interaction may be related to overall differences in RTs). In order to circumvent possible confounds due to overall differences in RTs, further analyses were conducted. We filtered the data in the following way. For the participants' analyses, we excluded the 12% of the participants with faster average RTs in Experiment 1, and the 12% of the participants with slower average RTs in Experiments 2, and in each of the groups of Experiment 3. For the items analyses we excluded 25% of the items with fastest RTs in Experiment 1 and the 25% of the items with slowest RTs in Experiments 2, and 3 (each group separately).

Data filtering ensured that the main effect of the factor Experiment did not approach significance (both Fs < 1) in these analyses. However, the interaction between Prime Type and Experiment reached significance again ($F1[6, 272] = 7.9$, $p < .001$; $F2[6, 302] = 7.4$, $p < .001$). The planned contrasts indicated that the difference between the control and match conditions differed across experiments ($F1[3, 136] = 8.9$, $p < .001$; $F2[3, 151] = 8.6$, $p < .001$). Pairwise comparisons (Bonferroni) revealed significant differences in the size of the facilitation effect in Experiment 1 as compared to the rest of the experiments ($p < .005$ for the comparison with Experiment 2, and $p < .001$ each for the comparison with both groups of Experiment 3). Planned contrasts between the control and the mismatch condition remained not significant ($F1[3, 136] = 1.7$, $p > .1$; $F2[3, 151] = 1.2$ $p = .2$), as in the previous analysis.

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