The use of sequential probabilities in the segmentation of speech

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The present investigation addresses the possible utility of sequential probabilities in the segmentation of spoken language. In a series of five word-spotting and two control lexical decision experiments, high- versus low-probability consonant-vowel (Experiments 1, 2, 5, and 7) and vowel-consonant (Experiments 1, 3, 4, and 6) strings were presented either in the nonsense contexts of target words (Experiments 1-3) or within the target words themselves (Experiments 4-7). The results suggest that listeners, at least for sequences in the onset position, indeed use sequential probabilities as cues for segmentation. The probability of a sound sequence influenced segmentation more when the sequence occurred within the target words (Experiments 4-7 vs. Experiments 1-3). Furthermore, the effects were reliable only when the sequences occurred in the onset position (Experiments 1, 2, 5, and 7 vs. Experiments 1, 3, 4, and 6).

“To wreck a nice beach” or “To recognize speech”? Ambiguities like this, where the latter utterance can be mistaken for the former, show that the boundaries between words are not reliably marked in speech (Klatt, 1976; Lehiste, 1972; Nakatani & Dukes, 1977; Quené, 1992). However, in order to understand spoken language, the listener has to segment the continuous speech stream into discrete units that convey the meaning of an utterance—that is, into words. People use several strategies to deal with this problem of segmentation.

Although spoken language does not contain the clear demarcation of word boundaries that is provided by spaces in written language, there are several sources of information that can be used, when available, to parse the speech stream into words. Long silences, acoustic-phonetic cues (Gow & Gordon, 1995; Lehiste, 1972; Nakatani & Dukes, 1977; Quené, 1989, 1992, 1993), phonological restrictions (e.g., vowel harmony in Finnish: Suomi, McQueen, & Cutler, 1997; Vroomen, Tuomainen, & de Gelder, 1998), phonotactics (McQueen, 1998), and metrical cues (Cutler, Mehler, Norris & Segui, 1986, for French; Cutler & Norris, 1988, for English; Otake, Hatano, Cutler & Mehler, 1993, for Japanese; Vroomen & de Gelder, 1995, for Dutch) all provide information on the likely locations of word boundaries. More important, there is evidence that

human listeners use all of these boundary cues if they are available in the speech signal and, furthermore, that they seem to use the cues that are most effective in particular situations. If, for example, a stream of speech contains both phonotactic and metrical cues to the location of a word boundary, the adult listener will rely more strongly on the phonotactic information (McQueen, 1998). Matys, Jusczyk, Luce, and Morgan (1999), however, found the reverse to be true for 9-month-olds. They demonstrated that infants rely more strongly on the prosodic information that is available in the speech signal.

But this is not the whole story. Segmentation can arise as a consequence of word recognition: If you know the word, you know the word boundaries. This maxim is the core assumption in two influential models of spoken word recognition: TRACE (Elman & McClelland, 1986; McClelland, 1979, 1987, 1991; McClelland & Elman, 1986; McClelland, & Rumelhart, 1981) and Shortlist (Norris, 1994; Norris, McQueen, Cutler, & Butterfield, 1997). Both models avoid explicit segmentation procedures by allowing the initial activation of multiple word candidates and the subsequent selection of the appropriate candidate from that set. Segmentation occurs as a product of this process. The models settle on an optimal parse of the input—that is, a sequence of words with boundaries between them—and achieve segmentation and recognition at the same time. In TRACE and Shortlist, the selection of the appropriate candidate is the result of competition among activated word candidates in memory. This lexical solution to the problem of segmentation can be integrated with the use of explicit boundary cues in the signal. Through the operation of the *possible word constraint*, candidates that are misaligned with likely boundaries are disfavored (Norris et al., 1997).

But how can you find the boundaries if you don't know the words? How does an infant, learning a language, seg-

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ment fluent speech in the absence of a lexicon of candidates that can compete for recognition? Studies in language acquisition show that, like adults, when infants listen to their native language they are sensitive to both prosodic regularities (Jusczyk, Cutler, & Redanz, 1993; Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993; Turk, Jusczyk, & Gerken, 1995) and phonotactic legality constraints (Friederici & Wessels, 1993; Jusczyk, Friederici, et al., 1993), suggesting that these cues can be exploited by the infant in the segmentation of speech.

Phonotactics constitute the extreme, categorical case of judging the familiarity of a perceived combination of sounds: Is this combination of sounds legal in this language? However, there is evidence that infants are also sensitive to more gradient transitional probabilities. Jusczyk, Luce, and Charles-Luce (1994) found that by the age of 9 months, infants prefer patterns of sounds that are relatively common in their native language over combinations of sounds that are relatively uncommon but not illegal. A recent study by Mattys et al. (1999) examined 9-month-olds' sensitivity to within- and between-word co-occurrence probabilities in speech segmentation and how this interacted with prosodic information. They demonstrated that infants prefer sequences that are very common at word junctures when the prosodic and pause information is consistent with a two-unit structure and that they prefer sequences that have a high probability of occurring inside words when this information is consistent with a single unit. Several computational demonstrations of word segmentation in acquisition (Brent & Cartwright, 1996; Cairns, Shillcock, Chater, & Levy, 1997; Christiansen, Allen, & Seidenberg, 1998) have also confirmed the utility of sequential probabilities as cues to the location of word boundaries.

Sequential probabilities also affect adult speech perception. Saffran and collaborators have shown that both infants (Aslin, Saffran, & Newport, 1998; Saffran, Aslin, & Newport, 1996) and adults (Saffran, Newport, & Aslin, 1996) can utilize transitional probabilities in the segmentation of an artificial language. Vitevitch, Luce, Charles-Luce, and Kemmerer (1997) found that subjects' goodness ratings of spoken nonsense words vary as a function of the sequential likelihood of the segments that they were composed of, and they replicated this finding in a speeded auditory repetition task, showing that it was easier for the subjects to repeat nonwords composed of frequent segments. Using the same repetition task, Vitevitch and Luce (1998) demonstrated that nonwords composed of phonological segments with high-probability sequential patterns are responded to more quickly and accurately than nonwords composed of phonological segments with low-probability patterns. Evidence that listeners use sequential probabilities in making phonetic decisions was found in phoneme-monitoring experiments (McQueen & Pitt, 1996; Pitt & Samuel, 1995) and in phonetic categorization experiments (Pitt & McQueen, 1998). In summary, these studies show that adult listeners are sensitive to transitional probabilities, but so far no experiment has explicitly asked if and how adult lis-

teners exploit these distributional cues in the segmentation of natural speech. The present experiments were designed to address exactly that question. Do adult listeners use the likelihood of a sound sequence in a certain position to direct the search for the boundaries between words?

The word-spotting task offers a way of addressing segmentation issues (e.g., McQueen, 1998; McQueen, Norris, & Cutler, 1994; Norris, McQueen, & Cutler, 1995; Norris et al., 1997). Experiments 1–5 all used the word-spotting task. Although *uncommon* diphones within a syllable or word suggest that there is a boundary between the two sounds, the likelihood of a sequence flanking the boundary should have an opposite effect, if any. If position-specific sequential probabilities are used in parsing the speech stream, it should be easier to spot a word when it is followed (or preceded) by a sound sequence that is often the beginning (or the end) of a word or syllable. For example, it should be easier to detect *boom* (tree) in *boom-dif* than in *boom-douf*.

The sequential probabilities that were manipulated in these experiments were all positionally specific; however, they were not specific for word boundaries. Although there may be more informative word-boundary-specific information available to the adult listener,¹ infant listeners, in the absence of a mental lexicon, are unlikely to have access to such a sophisticated segmentation cue. Furthermore, it has been shown that cues to syllable boundaries (e.g., phonotactic constraints; McQueen, 1998) can provide useful cues for possible word boundaries.

The sequence probabilities that were manipulated concerned either the likelihood that a consonant–vowel (CV) diphone was the beginning of a word or syllable or the likelihood that a vowel–consonant (VC) diphone was the end of a word or syllable. In Experiments 1–3, these likelihoods were manipulated in the context of target words. In Experiment 1, the target words could appear in both the initial (e.g., *boom* [tree] in *boom-dif* vs. *boom-douf*) and the final position (e.g., *veer* [feather] in *beel-veer* vs. *buul-veer*). Experiments 2 and 3 examined whether the observed differences in Experiment 1 were due to the intermixing of initial and final targets. Experiments 4 and 5 examined the use of similar sequential probabilities within the target words (e.g., the detection of *geur* in *pien-geur* vs. the detection of *galg* in *hien-galg*). Because of the design of these last two word-spotting experiments, two lexical decision experiments (Experiments 6 and 7) were run to control for possible differences between the two different groups of target words.

EXPERIMENT 1

In Experiment 1, listeners were asked to listen to a list of bisyllabic nonsense items and to try to spot embedded words at either the beginnings or the ends of the stimuli. In Dutch, there are many words that begin with [di], but only a few words that start with [dau]. It was hypothesized that it would be easier for a listener to detect *boom* (tree), for example, in *boom-dif*, where the Dutch target word *boom* is followed by the high-probability CV onset

[dɪ], than in *boom-douf*, where the same target is followed by the low-probability CV onset [dau]. Similarly, many words in Dutch end with the sequence [e:l], but only a few words end with the sequence [y:l]. It was predicted that it would be easier to spot the Dutch word *veer* (feather) when preceded by a high-probability VC offset (e.g., *veer* in *beel-veer*) than when preceded by a low-probability VC (e.g., *veer* in *buul-veer*).

Method

General Method for Experiments 1, 2, 3, 4, and 5

In Experiments 1–5, the same task and procedure were used, and similar general criteria for the selection of materials were adopted. The experiments differed in design, specific stimulus materials, and the identity of the subjects. In this section, all the identical features will be described.

Sequential probability criteria. Initially, all absolute frequencies of occurrence for all onset/nucleus combinations (1,048 pairs) and for all nucleus/coda combinations² (1,390 pairs) were computed, using the phonological transcriptions in the CELEX computerized database of Dutch (Burnage, 1990).³ These sets were then restricted to all noncomplex pairs, thus yielding all the diphone combinations with a vowel in the Dutch language. For every diphone combination (383 CV pairs and 300 VC pairs), four different absolute frequency counts were collected: the number of occurrences at the beginning (CV) or end (VC) of a syllable in a word type and of a syllable in a word token (weighted with the word frequencies in 42 million words) and the number of occurrences at the edges (beginnings or endings) of word types and tokens. The two sets were then further restricted by including only those pairs that have a frequency larger than zero in the word type count, thus filtering out all pairs that never occur as the onset or offset of a word. The remaining 334 CV pairs and 192 VC pairs were then consecutively ranked by all of the four frequency counts. Low-probability diphones fell in the intersection⁴ of the four lowest quarters of the ranked lists (63 CV and 40 VC candidates); high-probability diphones fell in the intersection of the four highest quarters (39 CV and 25 VC candidates). See Table 1 for the mean frequencies and standard deviations.⁵

Materials. Bisyllabic nonsense words were constructed, where either the initial syllable or the final syllable was a real word in Dutch that contained no other embedded words and where the other syllable (final or initial) was a nonword. Diphone pairs from the four probability sets were used either within the target words (Experiments 4 and 5) or in the nonsense contexts (Experiments 1–3). The target words were selected in such a way that there was a phonotactically mandatory syllable boundary between the target word and the nonsense syllable as often as possible (seven exceptions in a

total of 80 target-bearing bisyllables in Experiments 1–3; nine exceptions in a total of 72 target-bearing bisyllables in Experiments 4 and 5). To obtain large enough sets of materials, some target contexts were used that do not form a phonotactically illegal sequence across the syllable boundary in Dutch; in those cases, the sequence has a very low probability of occurrence within a syllable (in not more than 100 tokens in 42 million). Examples of the materials for all the experiments are given in Table 2. Sets of fillers with no embedded words were created for all the experiments.

Recording. All of the stimuli were recorded in a sound-attenuated booth. All the items were spoken three times in random order by a female native speaker of Dutch. After the recording, all the items were digitized onto a computer at a sampling frequency of 16 kHz. All the materials were measured and cut into separate speech files, using the Xwaves/ESPS speech signal-processing package. For each item, the most natural utterance was selected. The target items were inspected to make sure that all the target-bearing bisyllables were syllabified correctly between target word and nonsense syllable. The most important criterion for naturalness and syllabification was consistency across the conditions. The speech files were then transferred to the hard disk of a personal computer for use in the experiment.

Subjects. The subjects in all seven experiments were members of the subject pool of the Max Planck Institute for Psycholinguistics. None of them reported any hearing problems, and they were all native listeners of Dutch. An equal number of subjects participated in the two different versions of each experiment.

Procedure. The stimuli were presented binaurally via Sennheiser headphones. The presentation of the stimuli, the timing of the manual responses, and the collection of the data were performed by the NESU experimental control software. The subjects were tested two at a time in individual sound-attenuated booths. The subjects were instructed to listen to a series of bisyllabic nonsense words. They were asked to press a response button with their preferred hand whenever they heard a real word embedded in one of the bisyllables and to say aloud which word they had heard. Their answers were monitored on line for false alarms (trials in which they spotted a word other than an intended target word).

Method for Experiment 1

Materials. Eight CV onset+nucleus pairs, four from the high and four from the low sequential probability set, were paired with five different consonants or double consonant cluster C(C) codas to serve as following-target contexts, and similarly, four VC nucleus+coda pairs from both sets were paired with five different (C)C onsets to serve as preceding contexts. The consonants of the four critical diphones of the low- and high-probability sets were matched as far as possible on the identity of the consonant. In those cases in which matching was impossible, the consonants shared manner of articulation and differed only in voicing or place of articulation. This matching was necessary to make the acoustic salience of the syllable boundary as constant as possible across the two different probability conditions. The noncritical VC(C) and (C)CV diphone pairs were all selected from within the second and third quarters of the ranked (C)CV and VC(C) sequential probabilities; these portions of the contexts were, therefore, neither high nor low in frequency. Two sets of 80 target-bearing nonsense bisyllables were constructed, one set consisting of 40 initial CVC target words followed by 40 nonsensical CVC(C) contexts, 20 in each condition, and 40 final CVC target words preceded by 40 nonsensical (C)CVC contexts, again 20 in each condition. The two different target–context pairs for every target were counterbalanced across two different versions of the experiment, so that both versions contained a different context for each particular target word. A target word could appear only once in a single version of the experiment, combined either with a high-probability context or with a low-probability context. Each version therefore contained a total of 80 target-bearing bisyllables (40 initial and 40 final, 20 for each probability condition) and a set of 160 fillers (128 CVC-CVC, 16 CCVC-CVC, and 16 CVC-CVCC) with no em-

Table 1
Frequency of Occurrence of the Experimental Sequences

Condition	Sequence			
	CV		VC	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Low				
Syllable (type)	40.7	39.5	26.1	29.1
Syllable (token)	607.6	774.5	309.4	457.3
Word (type)	14.0	13.6	7.5	7.6
Word (token)	188.6	257.0	172.5	208.9
High				
Syllable (type)	7,573.0	8,982.6	7,949.9	9,998.7
Syllable (token)	460,687.9	428,788.4	555,797.4	499,503.6
Word (type)	2,720.2	3,209.5	2,566.6	3,366.2
Word (token)	314,432.9	268,098.5	404,040.5	361,242.0

Note—Corpus size is 42 million tokens.

Table 2
Design Materials and Examples, Experiments 1–5

Sequential Probability	Target Position	
	Initial	Final
In context sequence	Experiments 1+2	Experiments 1+3
Low	<i>boom</i> (tree) in <i>boom-douf</i>	<i>veer</i> (feather) in <i>buul-veer</i>
High	<i>boom</i> (tree) in <i>boom-dif</i>	<i>veer</i> (feather) in <i>beel-veer</i>
Within word sequence	Experiment 4	Experiment 5
Low	<i>heup</i> (hip) in <i>heup-juik</i>	<i>geur</i> (smell) in <i>pien-geur</i>
High	<i>kap</i> (cap) in <i>kap-juif</i>	<i>galg</i> (gallows) in <i>hién-galg</i>

bedded words. All 80 target words had a frequency in the range of 100–1,000 in 42 million tokens of the CELEX computerized database of Dutch; the items are listed in Appendix A.

Subjects. Forty subjects participated in Experiment 1.

Results

Data Analysis for All Experiments

False alarms were set to zero and treated as missing responses, as were the trials in which the subjects failed to respond entirely. Responses of duration less than 200 msec or greater than 1,800 msec were also treated as missing data. Reaction times (RTs) were measured from (target) word offset. The RTs and the error rates were submitted to analyses of variance (ANOVAs), with both subjects (F_1) and items (F_2) as the repeated measure. For the RT analyses, means were computed per condition, by subjects and by items separately, disregarding the errors.

Results of Experiment 1

As is shown in Table 3, the subjects found it harder to spot words (82 msec slower) that were preceded by a probable word-final context (e.g., *veer* in *beel-veer*) than to detect words that were preceded by an improbable word-final context (e.g., *veer* in *buul-veer*). On the other hand, words that were followed by a very common word-initial context (e.g., *boom* in *boom-dif*) were not detected much easier (26 msec faster) than words followed by a very uncommon word-initial context (e.g., *boom* in *boom-douf*). This result for final targets is the reverse of what was expected.

This pattern of results was observed in the RT analyses (14.5% of the data treated as missing responses). There was a significant effect of boundary probability [$F_1(1,38) = 6.03$, $MS_e = 5,028$, $p < .05$; $F_2(1,78) = 4.58$, $MS_e = 7,108$, $p < .05$] and a highly significant interaction of target position and boundary probability [$F_1(1,38) = 29.10$, $MS_e = 4,046$, $p < .001$; $F_2(1,78) = 21.09$, $MS_e = 7,108$, $p < .001$]. This pattern was also found in the error analyses: a significant effect of boundary probability [$F_1(1,38) = 10.31$, $MS_e = 0.01$, $p < .01$; $F_2(1,78) = 5.41$, $MS_e = 0.01$, $p < .05$] and a significant interaction of target position and boundary probability [$F_1(1,38) = 6.03$, $MS_e = 0.01$, $p < .05$; $F_2(1,78) = 8.81$, $MS_e = 0.01$, $p < .01$]. Overall, the responses to targets in

the high-probability conditions were slower than those in the low-probability conditions, and subjects made more errors on high-probability than on low-probability items. Since there was, in fact, an effect in the opposite direction for initial targets, these main effects of boundary probability are misleading. The interaction was inspected more closely by performing t tests. Pairwise comparisons showed that the only reliable differences in RTs and errors were between the high- and the low-probability conditions for final targets [RT by subjects, $t_1(39) = 4.33$, $p < .001$; RT by items, $t_2(39) = 4.26$, $p < .001$; errors by subjects, $t_1(39) = 5.15$, $p < .001$; errors by items, $t_2(39) = 2.94$, $p < .01$]. For the initial targets, the differences between the high- and the low-probability conditions in RTs were only marginally significant [RT by subjects, $t_1(39) = -2.03$, $p < .05$; RT by items, $t_2(39) = -2.00$, $.05 < p < .1$]. The errors were not different (both $ps > .1$).

On average, the subjects responded 146 msec faster to final targets than to initial targets. This effect of target position on the RTs was highly significant [$F_1(1,38) = 92.85$, $MS_e = 9,154$, $p < .001$; $F_2(1,78) = 30.31$, $MS_e = 29,263$, $p < .001$]. This is in line with earlier findings that initial targets are harder to spot than final targets in a mixed design with both initial and final targets (McQueen et al., 1994). This pattern was repeated only partly in the error analysis: It was significant by subjects [$F_1(1,38) = 17.70$, $MS_e = 0.01$, $p < .001$], but not by items [$F_2(1,78) = 2.47$, $MS_e = 0.05$, $p > .1$].

Discussion

The observed effects do not support the initial hypothesis that it should have been easier for listeners to detect words that were followed by a very likely beginning, and they contradict the prediction that it would be easier to spot words that were preceded by a very likely ending. However, there is a potential problem with the particular task in Experiment 1. The listeners were asked to detect target words that could appear in either the initial or the final syllable of the stimuli. A possible explanation of the observed effect could be that the high-probability word-final contexts before the final targets were suggestive of the presence of an initial target, thus slowing down the detection of the actual finally embedded target word. This hypothesis is further supported by the error data. Listeners made almost twice as many errors in that con-

Table 3
Mean Reaction Times (in Milliseconds) and Error Rates (Percentages), Experiment 1

Target Position	Sequential Probability	Reaction Time		Error Rate		Dutch Example
		<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	
Initial	low	593	22.8	12.4	0.02	<i>boom</i> (tree) in <i>boom-douf</i>
	high	567	23.0	11.3	0.01	<i>boom</i> (tree) in <i>boom-dif</i>
Final	low	393	15.9	12.6	0.01	<i>veer</i> (feather) in <i>buul-veer</i>
	high	475	21.6	21.9	0.02	<i>veer</i> (feather) in <i>beel-veer</i>

dition as in the other three conditions. The highly probable VC sequences activate many lexical candidates in the initial position. These candidates all compete with each other for recognition but are more suggestive of an initial target than are the fewer lexical candidates activated by the lower probability VC sequences. Detection of the final target is thus delayed in the high-probability condition. This explanation is in line with findings by Luce et al. on the role of similarity neighborhood frequencies⁶ in spoken word recognition (e.g., Cluff & Luce, 1990; Goldinger, Luce, & Pisoni, 1989; Luce & Pisoni, 1998; Luce, Pisoni, & Goldinger, 1990). Furthermore, Vitevitch and Luce (1998, 1999) have shown that, depending on the nature of the processing environment and the task demands, sequential probability manipulations can have opposite effects on word recognition performance: inhibitory lexical competition effects and facilitatory sequential probability effects. The finding that high-probability contexts made detection of final targets harder could thus be a lexical competition effect, one that was emphasized by task-level competition between initial and final targets.

The absence of such a competition effect for initial targets can be explained by the sequential nature of spoken word recognition: The later incoming information of the following-target context is too late to interfere with the detection of the initial target. The effects of the following-target context on word-spotting performance have been shown to be weak (McQueen, 1998) or even absent (Suomi et al., 1997).

To explore these issues, two experiments were carried out with subsets of the materials in Experiment 1. In these experiments, the subjects monitored for target words in only one position. In a series of word-spotting experiments, McQueen et al. (1994) have shown that blocked target location can attenuate lexical effects. It was therefore predicted that if the listener could attend to a single location, the beginning or the end of a nonsense bisyllable, response-level competition with lexical candidates in the other position would decrease. The subjects were asked to listen only for initially embedded words in Experiment 2 and only for finally embedded words in Experiment 3.

EXPERIMENT 2

Method

Materials. All 80 initial target-bearing nonsense bisyllables from Experiment 1 were mixed with 80 appropriate fillers. Again, the two different target-context pairs for every target were counterbalanced across two different versions of the experiment, so that both versions contained a different context for each particular target word. Each version therefore contained a total of 40 initial target-bearing bisyllables (20 for each probability condition) and a set of 80 fillers (64 CVC-CVC, 16 CVC-CVCC) with no embedded words.

Subjects. Forty subjects participated in Experiment 2.

Results and Discussion

The subjects were, on average, 25 msec faster in spotting targets that were followed by a high-probability boundary CV (see Table 4). This difference, however, was not completely reliable. The analyses of RTs (6.4% of the data

Table 4
Mean Reaction Times (in Milliseconds) and Error Rates (Percentages), Experiments 2 and 3

Target Position	Sequential Probability	Reaction Time		Error Rate		Dutch Example
		<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	
Experiment 2						
Initial	low	506	22.8	6.6	0.01	<i>boom</i> (tree) in <i>boom-douf</i>
	high	481	24.4	6.1	0.01	<i>boom</i> (tree) in <i>boom-dif</i>
Experiment 3						
Final	low	363	17.6	8.9	0.01	<i>veer</i> (feather) in <i>buul-veer</i>
	high	373	18.5	8.3	0.01	<i>veer</i> (feather) in <i>beel-veer</i>

discarded) revealed a significant effect of boundary probability in the subjects analysis [$F_1(1,38) = 7.29$, $MS_e = 1,728$, $p < .05$], but this effect did not reach significance in the items analysis [$F_2(1,78) = 1.88$, $MS_e = 5,292$, $p > .1$]. No reliable differences in listeners' performance were found in the error analyses.

The results of Experiment 2 are in line with the results for the initial targets of Experiment 1. Listeners responded faster to words that were followed by a very likely word onset sequence, but not reliably so. No differences were found in the error rates. Although these results are suggestive of the predicted facilitatory effect of a common following-target context, they do not provide strong evidence that position-specific sequential probabilities are used by the listener in this situation.

EXPERIMENT 3

Method

Materials. The 80 final target-bearing nonsense bisyllables from Experiment 1 were combined with 80 appropriate fillers in two different versions. The design was identical to that in Experiment 2.

Subjects. Forty subjects participated in Experiment 3.

Results and Discussion

The subjects were, on average, 10 msec faster in detecting embedded words that were preceded by a low-probability boundary VC (see Table 4). This difference, however, was not statistically reliable. Both in RTs (8.6% missing responses) and in error rates, no reliable differences ($p > .1$) were found between the two probability conditions.

In Experiment 1, in which the subjects were asked to listen for words that were embedded either at the beginnings or at the ends of the bisyllabic nonsense items, it was harder for listeners to detect words that were preceded by a probable word-final context than to detect words that were preceded by an improbable word-final context. In the present experiment, the subjects were monitoring exclusively for final embedded words in a set of materials that did not contain any initial embedded words. Under these circumstances, it was equally hard to detect a target in a common preceding context as in an uncommon pre-

ceding context. This is in line with the prediction that the attentional focus on a single location (i.e., the end of the stimulus) would diminish the effects of competition with candidates in the other location (i.e., the beginning of the stimulus).

Nevertheless, no actual reversal of the lexical competition effect was observed. This is not surprising. To a large extent, competition is an automatic feature of spoken word recognition (see also McQueen et al., 1994). The high-probability sequences still will have activated many lexical candidates, causing a weaker competition effect, even when the possibility of embedded words in the initial position was not emphasized by the task or the materials. This lexical competition effect still may have canceled out any facilitatory segmentation effect of sequential probability. A second series of experiments was therefore planned in which sequential likelihoods were manipulated *within* the embedded words. In order to avoid effects that could be caused by the intermixing of initial and final targets, these effects were investigated in two separate word-spotting experiments with initial and final embeddings, respectively.

EXPERIMENT 4

In Experiment 4, listeners were asked to listen for embedded words at the beginnings of bisyllabic nonsense items. Hearing a combination of sounds that often occurs immediately before a syllable or word boundary (e.g., [ap] in Dutch) may facilitate recognition of a target word that ends with that combination of sounds. Conversely, hearing a combination of sounds that seldom occurs as the end of a syllable or word (e.g., [ø:p] in Dutch) may interfere with the recognition of a word that ends with that sequence. It was hypothesized that it would be easier to detect *kap* (cap) in *kap-juif* than to detect *heup* (hip) in *heup-juik*.

Method

Materials. A slightly different procedure was used for the construction of materials from the sets of CV and VC segments. First, a list was generated that consisted of all the monosyllabic words of Dutch that end in one of the VC nucleus+coda pairs from the low sequential probability set. Second, a similar list was constructed for the high-probability set. The words from these lists were matched on their syllabic structure, the manner of articulation of the final consonant, and as far as possible, on the place of articulation of the final consonant. The two sets of words were also matched, as far as possible, on the frequencies of occurrence of the words in the CELEX database and on the variance of these frequencies.⁷ This resulted in two sets of 15 words, 9 CCVC and 6 CVC, with a mean log frequency of 2.14 ($SD = 0.50$) for the high-probability set and a mean log frequency of 2.16 ($SD = 0.49$) for the low-probability set. Two sets of 15 nonsense syllables without embedded words were constructed, using 15 CV segments with normal positional segment probabilities (i.e., segments selected from within the second and third quarters of the ranked CV and VC sequential probability lists), that were all paired with two different coda consonants (see also Table 2). These 15 pairs of nonsense syllables were placed in the final context of the target words in such a way that the two target words that were matched on their final consonant were combined with a context that started with the same CV segment. The experiment therefore con-

tained a total of 30 target-bearing bisyllables (15 for each probability condition) and a set of 60 fillers (24 CVC-CVC and 36 CCVC-CVC) with no embedded words. The target-bearing items are listed in Appendix B.

Subjects. Twenty-one subjects participated in Experiment 4.

Results and Discussion

The results suggest that it is easier to detect words with a common VC offset. The listeners were faster and made fewer mistakes when the embedded words ended with a very likely sequence (such as [ap] rather than [ø:p]).

The subjects were, on average, 49 msec faster in spotting targets that ended in a high-probability boundary VC (see Table 5). The RT analyses (12.4% missing) revealed a significant effect of boundary probability in the subjects analysis [$F_1(1,21) = 5.77$, $MS_e = 4,397$, $p < .05$], but not in the items analysis [$F_2(1,28) = 2.87$, $MS_e = 13,090$, $p > .1$]. In the analysis of the errors, more reliable differences in listeners' performance were found between the probability conditions. The listeners made, on average, 14% more errors in spotting targets that ended in a low-probability boundary VC. This effect was significant both by subjects [$F_1(1,21) = 48.58$, $MS_e = 0.001$, $p < .01$] and by items [$F_2(1,28) = 7.00$, $MS_e = 0.02$, $p < .05$].

Because different items were used in the two probability conditions, additional analyses were performed for Experiments 4–7 to investigate possible effects of the specific items that were used. Correlation analyses and analyses of covariance (ANCOVAs) are reported for target duration and/or target frequency only if those differences indeed had an effect (as revealed by a significant correlation).

Although an attempt was made to control for differences in target frequency and variation, targets in the high-probability set had, on average, a slightly smaller log frequency than did the words in the low-probability set. A significant negative correlation of target log frequency and RT was found [$r(30) = -.41$, $p < .05$]. An ANCOVA with target frequency as covariate showed that the effect of probability was more reliable than was shown in the items ANOVA, but it remained only marginally significant [$F_2(1,27) = 3.67$, $MS_e = 11,005$, $p < .1$]. The correlation between target duration and RT was not reliable.

Table 5
Mean Reaction Times (in Milliseconds) and Error Rates (Percentages), Experiments 4 and 5

Target Position	Sequential Probability	Reaction Time		Error Rate		Dutch Example
		<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	
Experiment 4						
Initial	low	669	46.7	19.7	0.02	<i>heup</i> (hip) in <i>heup-juik</i>
	high	620	32.1	5.2	0.01	<i>kap</i> (cap) in <i>kap-juif</i>
Experiment 5						
Final	low	492	29.8	8.9	0.02	<i>geur</i> (smell) in <i>pien-geur</i>
	high	444	22.4	7.4	0.02	<i>galg</i> (gallows) in <i>hien-galg</i>

EXPERIMENT 5

In Experiment 5, the listeners were asked to listen exclusively for embedded words at the ends of bisyllabic nonsense items. Hearing a combination of sounds that often occurs immediately after a syllable or word boundary—for instance, [xa] in Dutch—may facilitate recognition of a target word that begins with that combination of sounds; hearing a combination of sounds that seldom occurs as the beginning of a syllable or word—for example, [xø:] in Dutch—may interfere with the recognition of a word that begins with that sequence. It was hypothesized that it would be harder to spot *geur* (smell) in *pien-geur* than to spot *galg* (gallows) in *hien-galg*.

Method

Materials. The materials for this experiment were constructed in a similar way to those in Experiment 4. This resulted in two sets of 21 words, 4 CVCC and 17 CVC, with a mean log frequency of 2.30 ($SD = 0.56$) for the high-probability set and a mean log frequency of 2.28 ($SD = 0.54$) for the low-probability set. Two sets of 21 nonsense syllables without embedded words were constructed, using 21 VC segments with normal positional segment probabilities, that were all paired with two different onset consonants. These 21 pairs of nonsense syllables were placed in the initial context of the target words in such a way that the two target words that were matched on their initial consonant were combined with a context that ended with the same VC segment (see also Table 2). The experiment therefore contained a total of 42 target-bearing bisyllables (21 for each probability condition) and a set of 84 fillers (16 CVC-CVCC and 68 CVC-CVC) with no words embedded in them. The target-bearing items are listed in Appendix B.

Subjects. Twenty-one subjects participated in Experiment 5.

Results

The subjects were, on average, 48 msec faster in spotting targets that started with a high-probability boundary CV (see Table 5). The RT analyses (8.1% missing values) revealed a highly significant effect of boundary probability by subjects [$F_1(1,21) = 10.58, MS_e = 2,357, p < .01$], but not by items [$F_2(1,40) = 1.90, MS_e = 12,145, p > .1$]. The listeners made just as many errors in spotting targets that began with a common CV as in spotting targets with an uncommon CV onset (F_1 and F_2 , n.s.).

Targets in the high-probability set were shorter than targets in the low-probability set (low probability, 497 msec; high probability, 454 msec), and the targets in the high-probability set had, on average, a slightly higher log frequency than did the words in the low-probability set. Further analyses showed a significant negative correlation of target duration and RT [$r(42) = -.42, p < .01$] and a significant negative correlation of target frequency and RT [$r(42) = -.41, p < .01$].

Discussion

These findings are consistent with results from previous word-spotting studies. Subjects have been shown to respond faster to longer embedded targets (McQueen, 1998). The present results, however, cannot be explained by durational differences between the two probability conditions. In fact, the target duration effect is working against

the sequential probability effect, since the items in the high-probability set were shorter than those in the low-probability set. It has also been shown that listeners are faster and more accurate in detecting high-frequency than low-frequency words (Freedman, 1992). In the present study, the items from the high-probability set were slightly more frequent than the items from the low-probability set. Thus, part of the processing advantage for high-probability items might be explained by this difference in frequency. Frequency and duration were therefore both entered as covariates in an ANCOVA of the RTs by items. The effect of probability was now significant [$F_2(1,38) = 6.63, MS_e = 8,207, p < .05$]. This suggests that differences in duration and frequency between the high-probability and the low-probability items were partly neutralizing the effect of positional probability. Similar analyses were performed for the errors. Both duration [$r(42) = -.51, p < .01$] and frequency [$r(42) = -.49, p < .01$] were significantly correlated with the error rates. An ANCOVA showed no significant differences between the two probability conditions.

These results suggest that the faster detection latencies for words that began with a common CV onset cannot be explained by durational differences or frequency differences between the high- and the low-probability sets. But since different targets were used in these two probability sets, it was necessary to make a closer examination of the possibility that differences other than the probability of the initial CV segments between the two sets were responsible for this effect. As control experiments, lexical decision experiments were used to investigate the possibility that differences other than the segment probabilities of the target words made it easier to spot words that ended (Experiment 4) or started (Experiment 5) with common segments. In order to keep the experiments as closely related as possible to the earlier experiments, separate control experiments were carried out for the embedded words from Experiments 4 and 5.

EXPERIMENT 6

If the different effects for the low- versus the high-probability target words from the word-spotting experiments are due to the relative ease of segmentation that is caused by the manipulated probabilistic cues to the location of the syllable boundary, these differences should not be found if the target words are presented in isolation. It is assumed that when monosyllabic words and non-words are presented in isolation—that is, when the beginnings and ends of the words are unambiguously cued by silence—no effects of sequential probability will arise, because there is no need for segmentation in this situation. But if the relative ease of spotting targets from the high-probability set was caused by some other difference that was not directly related to the ease of segmentation (e.g., an acoustic difference between the items in the high- and the low-probability sets), the same pattern of results should be found in the lexical decision task.

In Experiment 6, all of the initially embedded target words from Experiment 4 were cut out from the original bisyllabic nonsense items. Nonsense monosyllables were constructed by cutting out the first syllables from the Experiment 4 bisyllabic fillers. All the items were presented to the listener in the same order as that used in Experiment 4, and they were asked to respond only when they heard a real word by pressing the response button and to say aloud the real word that they heard. This go/no-go lexical decision task is a fairly standard control for word-spotting experiments (McQueen, 1996).

Method

Materials. The items were all constructed from the items that were used in Experiment 4. Target words were constructed by excising the first syllables from the target-bearing bisyllables; the first syllables from the original filler items were cut out to serve as non-word fillers. The items were excised at zero-crossings on the basis of visual and auditory inspection of the waveform, under the constraint that this point was consistent across the two probability conditions. For this purpose, the Xwaves speech editor was used. The order of presentation was the same as that in Experiment 4.

Subjects and Procedure. Twenty-four subjects participated. Subjects that had already participated in Experiment 4 or 5 were excluded. The procedure was similar to the procedure used in the word-spotting experiments. The only difference was that the subjects were now instructed to respond whenever they heard a real word. As before, the subjects were asked to name the word they recognized after the manual response.

Results and Discussion

The listeners were, on average, 23 msec faster in detecting targets that ended in a high-probability boundary VC (see Table 6), but this difference was not significant (12.8% missing; both $ps > .1$). In the analysis of the errors, a more reliable difference was found in the listeners' performance. Listeners made 10% more errors in detecting targets that ended in a low-probability boundary VC. This effect was highly significant by subjects [$F_1(1,23) = 30.19, MS_e < 0.01, p < .001$] and marginally significant by items [$F_2(1,28) = 3.65, MS_e = 0.02, p > .05$].

Additional correlation analyses were performed in order to quantify the relationship between these results

and the word-spotting results. Lexical decision and word-spotting latencies were highly correlated [$r(30) = .60, p < .001$], and the error rates also showed a robust correlation [$r(30) = .64, p < .001$]. As a final control, the RT data and the error data from the lexical decision experiment were entered as covariates in ANCOVAs of the word-spotting responses of Experiment 4. These analyses showed that when the effects of the specific target items used were filtered out, no reliable differences were left between the detection of embedded words that ended with a likely VC offset and the detection of embedded words that ended with an unlikely VC offset [RTs, $F_2(1,27) = 2.30, MS_e = 8,797, p > .1$; errors, $F_2(1,27) = 3.04, MS_e = 0.02, p > .05$].

EXPERIMENT 7

In Experiment 7, all of the finally embedded target words from Experiment 5 were cut out from the original bisyllabic nonsense items. Nonsense monosyllables were constructed by cutting out the second syllables from the Experiment 5 fillers.

Method

Materials. The items were all constructed from the items that were used in Experiment 5, in the same way as in Experiment 6.

Subjects and Procedure. Twenty-four subjects participated. Subjects that had already participated in Experiment 4, 5, or 6 were excluded. The procedure was the same as that in Experiment 6.

Results and Discussion

The listeners were, on average, 24 msec slower in detecting words that started with a high-probability boundary CV (see Table 6). This difference was not significant (F_1 and $F_2, p > .1$). The subjects never recognized words other than the intended targets, but the error rate was much higher than in the original word-spotting experiment (25.2% vs. 8.1%). There is a simple acoustic explanation for this increase in errors. Because the finally embedded target words were excised from their original context, many of the beginnings of the items were not very clear, owing to residual coarticulatory information from

Table 6
Mean Reaction Times (in Milliseconds) and
Error Rates (Percentages), Experiments 6 and 7

Target Position	Sequential Probability	Reaction Time		Error Rate		Dutch Example
		<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	
Initial		Experiment 6				
	low	506	22.4	18.1	0.02	<i>heup</i> (hip) excised from <i>heup-juik</i>
	high	483	25.2	7.5	0.02	<i>kap</i> (cap) excised from <i>kap-juif</i>
		Experiment 7				
Final	low	463	24.6	24.2	0.03	<i>geur</i> (smell) excised from <i>pien-geur</i>
	high	487	19.9	26.2	0.03	<i>galg</i> (gallows) excised from <i>hien-galg</i>

the offset of the first syllable. However, this affected the items in both probability sets equally. In the analysis of the errors also, no reliable differences were found (both $ps > .1$).

Lexical decision and word-spotting latencies were again highly correlated [$r(42) = .63, p < .001$], and the error rates from both tasks again showed a robust correlation [$r(42) = .51, p < .001$]. The ANCOVA of the word-spotting errors, with the lexical decision errors as covariate, yielded no reliable differences between the two probability conditions. The ANCOVA of the word-spotting RTs, with the lexical decision RTs as covariate, confirmed the earlier findings that it was easier for the listener to detect words that began with a common onset than words that began with an uncommon onset [$F_2(1,39) = 5.33, MS_e = 6,964, p < .05$]. It is therefore unlikely that the observed effect for the common onsets in Experiment 5 was due to the use of particular target items in the two probability sets.

GENERAL DISCUSSION

In these experiments, the influence of sequential probabilities on the segmentation of speech has been systematically examined. In Experiment 1 and the control Experiments 2 and 3, it was demonstrated that the listeners' sensitivity to sequential likelihoods could be obscured by higher order effects, owing to competition between lexical candidates. When targets could occur in both initial and final positions (Experiment 1), the sequences of segments in the context activated lexical candidates to the extent that they interfered with detection of the intended target word. In line with McQueen et al. (1994, Experiment 2), this competition effect was shown to be in part task specific. In Experiments 2 and 3, in which target words occurred in a single position, the lexical competition effect was no longer observed. This is also consistent with the results of recent studies by Vitevitch and Luce (1998, 1999). They demonstrated that the processing of speech is a function of both facilitatory effects associated with sequential probabilities and inhibitory effects associated with lexical competitors. In particular, they showed that the task environment can differentially emphasize lexical and sublexical levels of processing.

In the second series of experiments, sequential probability was manipulated within the target words. The results of Experiments 4 and 6 provide no reliable support for the hypothesis that listeners use the likelihood of a word's *offset* as a boundary cue when this boundary is also marked by a phonotactically mandatory boundary. Experiment 5 and the control lexical decision Experiment 7, however, demonstrated that the listener can exploit the likelihood of a word's *onset* in combination with a phonotactic boundary in the segmentation of speech. Common sequences at the onset of a word made it easier for the listeners to detect these words in a word-spotting task; however, they did not affect performance in the lexical decision task. These findings provide converging evidence that sublexical levels of processing operate in the

recognition of spoken stimuli, even for words. In line with previous research (Vitevitch & Luce, 1999), it has been demonstrated that sublexical sequential probability effects manifest themselves when effects of lexical competition are minimized. In Experiments 4 and 5 of the present study, this was established by manipulating sequential probabilities within the target words and by blocking target position.

The likelihood of a word's onset seems to be more important than the likelihood of a word's offset. Many studies have confirmed the intuitive notion that the beginnings of words are particularly important for the fast recognition of words in continuous speech. Gating studies (Grosjean, 1980; Tyler & Wessels, 1983, 1985) have shown that words can be recognized reliably before their offset, at the point at which they become unique with respect to all other words in the language (the *uniqueness point*). Other evidence from phoneme monitoring (Marslen-Wilson, 1984), auditory lexical decision (Taft, 1986), mispronunciation detection (Cole, 1973; Marslen-Wilson & Welsh, 1978), and cross-modal priming (Marslen-Wilson, 1987; Marslen-Wilson & Zwitserlood, 1989; Zwitserlood, 1989) also suggests that word-initial information is crucial for efficient word recognition. In the present study, there is a confound between increases in word-spotting latency and the position of the target word. The RTs for initial target words in Experiment 4 were much longer than the RTs for final targets in Experiment 5. Two issues are relevant with respect to this difference. First, statistical power may have been reduced by the higher variance associated with longer RTs. Second, if effects of sequential probability are short-lived, one might argue that the subjects responded too late for probability effects to be observed. Therefore, no strong conclusions on the positional specificity of the sequential probability effect can be drawn on the basis of these results.

In Experiments 4 and 5, words with high-probability sequences by definition come from a high-density similarity neighborhood. Similarly, words with low-probability sequences come from a low-density neighborhood. Therefore, the findings in Experiments 6 and 7 could be interpreted as a failure to replicate the results of Luce and Pisoni (1998), whose neighborhood activation model predicts that words in dense lexical neighborhoods should take longer to recognize than words in sparse neighborhoods. However, as was also shown by Vitevitch and Luce (1999, Experiment 2), lexical effects can be substantially attenuated by the task demands and processing environment. In the present experiments, this attenuation of lexical effects was most likely due to the fact that the words were excised from a bisyllabic context.

These findings provide further evidence that listeners have access to information regarding the probability that a particular sequence of phonemes occurs at a certain position within a syllable or word. More important, the results also show that listeners exploit this kind of information in the segmentation of words from longer sequences. Current implementations of models of spoken word recognition—for instance, the Shortlist model (Nor-

ris et al., 1997)—lack a mechanism to account for these findings. Such a mechanism would incorporate some kind of prelexical analysis of the speech signal that would result in the accumulation and storage of distributional information. A different approach is taken by Vitevitch and Luce (1999). In recent work, they proposed an adaptive resonance framework (Grossberg, Boardman, & Cohen, 1997) to account for both the lexical and the sublexical levels of the processing of speech. In this approach, the two levels of processing are modeled by a single mechanism (rather than by a prelexical and a lexical mechanism). Resonant states between chunks in short-term memory and items in working memory constitute the speech percept. If sublexical chunks (corresponding to units smaller than words) in short-term memory are the most predictive (for instance, in the case of a non-word input), the model reflects sublexical processing. If lexical chunks are consistent with the item in working memory (for instance, when the input is a word), they will dominate processing, since they represent a larger stretch of the input. In this case, the model reflects a lexical level of processing (see also Vitevitch & Luce, 1999).

A final point to note about these results is that the use of sequential probability information as a cue to segmentation has been investigated only in conjunction with one other cue to the location of word boundaries—namely, those that are marked by phonotactics. The different findings for adults (McQueen, 1998) and infants (Mattys et al., 1999) on the integration of prosodic and phonotactic boundary markers show that the operation of an explicit boundary cue can vary enormously, depending on the situation. Future research should therefore include experiments on the interaction of sequential probability information before and after the boundary, the interaction with other boundary cues, and the use of sequential probability cues in the absence of other explicit boundary cues.

In summary, two limitations were observed in the use of sequential probabilities as a cue for segmentation. The probability of a sound sequence influenced segmentation more when the sequence occurred within the target words (Experiments 4–7 vs. Experiments 1–3). Furthermore, the effects were stronger when the sequences occurred in onset position (Experiments 1, 2, 5, and 7 vs. Experiments 1, 3, 4, and 6). It has been argued that these limitations may only be artifacts that are introduced by the task environment and, therefore, the issue of whether these are genuine limitations of the use of sequential probabilities in segmentation is still unresolved. Nevertheless, at least in these conditions, position-specific sequential probabilities appear to be used to direct the segmentation of speech by adult listeners.

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NOTES

1. The strongest facilitatory effect in segmentation might be expected for strings that are frequent at word edges and infrequent word-internally (John Kingston, personal communication, April 24, 1999).
2. Onset, nucleus, and coda are used to describe the structure of syllables in phonology (e.g., Booij, 1995). Each syllable consists of an obligatory vocalic part (the nucleus), preceded by zero or more consonants (the onset) and followed by zero or more consonants (the coda).
3. At present, there is no corpus of spoken Dutch available for the direct computation of frequencies of occurrence of diphones in speech. Instead, digraph frequencies from the CELEX corpus of written language were computed, using the phonological transcription of each word and the written word frequency. Correlation analyses between the non-zero digraph probabilities taken from the English CELEX lexicon and those taken from the MARSEC corpus of spoken English (Roach, Knowles, Varadi, & Arnfield, 1993) have shown that the CELEX digraph frequencies are reasonable estimates of spoken frequencies [$r(1,237) = .74, p < .001$].
4. Typically, both by type and token, syllable and word position-specific frequencies of CV and VC strings are highly correlated. Furthermore, instances in which word and syllable frequencies diverge tend to have a specific linguistic status. High syllable frequencies combined with low word frequencies are typical for CV strings that are common final syllables, such as plural inflections in Dutch. Conversely, low syllable frequencies with high word frequencies are typical for CV strings that are common first syllables—for instance, the past participle prefix /xə/. Asymmetries between type and token counts are mostly caused by CV and VC segments that form function words in Dutch, such as /də/. The use of the intersection of the four sets, rather than the use of a single frequency measure, was motivated by this observation. Since the main aim was to investigate the role of sequential probabilities, confounds with higher level linguistic information—for instance, the potential role of function words and morphemes in segmentation—were avoided.

5. A full list of the diphone sequences used in the experiments, together with their frequencies of occurrence, is available from the author on request.

6. This is also supported by the lexical neighborhood characteristics of the materials that were used in Experiments 1–3. The average frequency-weighted lexical neighborhood density measures (see Newman, Sawusch, & Luce, 1997, for the complete procedure) were calculated per condition for both the nonword contexts (high-probability preceding context, 36.6 [$SD = 20.0$]; low-probability preceding context, 15.9 [$SD = 5.6$]; high-probability following-target context, 24.6 [$SD = 14.6$]; low-

probability following-target context, 15.9 [$SD = 9.5$]) and the target words (initial, 42.8 [$SD = 15.2$]; final, 44.5 [$SD = 16.9$]).

7. At a later stage, subjective frequency ratings (on a scale from 1 to 7) were collected from 30 subjects for all the target words that were used in Experiments 4, 5, 6, and 7. These ratings were reasonably correlated with the CELEX frequencies [$r(72) = .60, p < .001$], and, more important, the targets were well balanced in each experiment (Experiments 4+6, high-probability mean rating = 4.4 [$SD = 1.4$], low-probability mean rating = 4.5 [$SD = 1.3$]; Experiments 5+7, high-probability mean rating = 4.5 [$SD = 1.1$], low-probability mean rating = 4.3 [$SD = 1.1$]).

APPENDIX A Target-Bearing Stimuli Used in Experiments 1, 2, and 3

Initial Targets, Experiment 1+2			Final Targets, Experiment 1+3		
High	Low	Translation	High	Low	Translation
bok-dif	bok-dous	goat	beel-deuk	buul-deuk	dent
ham-dil	ham-douf	ham	seel-douche	suul-douche	shower
kap-dirm	kap-doum	cap	kweel-rib	wuul-rib	rib
long-dir	long-doup	lung	vreel-rang	muul-rang	rank
zaag-dils	zaag-douk	saw	breel-teug	tuul-teug	sip
big-moof	big-nuif	piglet	gan-ram	goum-ram	ram
duif-mool	duif-nuim	pigeon	lan-riem	loun-riem	belt
pet-moon	pet-nuip	hat	tan-lap	toun-lap	rag
gif-moop	gif-nuik	poison	stan-leus	woun-leus	slogan
juf-mools	juf-nuig	nanny	nan-lood	noun-lood	lead
kiem-vam	kiem-guum	seed	fag-pauw	feug-pauw	peacock
duim-varf	duim-guuf	thumb	kag-put	veug-put	well
dam-vap	dam-guup	dam	tag-kuif	peug-kuif	forelock
rum-vag	rum-guug	rum	zwag-kus	neug-kus	kiss
kam-vams	kam-guun	comb	knag-mug	weug-mug	mosquito
boon-waam	boon-wuim	bean	kaat-goot	gouk-goot	gutter
deun-waaf	deun-wuig	tune	taat-geul	louk-geul	gully
map-waamt	map-wuip	folder	zwaat-mus	wouk-mus	sparrow
nul-waaft	nul-wuik	zero	knaat-non	stouk-non	nun
tor-waapt	tor-wuin	beetle	snaat-gips	nouk-gips	plaster
bil-wam	bil-zeuk	buttock	get-fuik	stuup-fuik	fyke
bon-wap	bon-zeut	receipt	ket-mouw	duup-mouw	sleeve
duin-wan	duin-zeun	dune	tet-mol	puup-mol	mole
pap-wamt	pap-zeus	mash	klet-nut	luup-nut	utility
lam-waps	lam-zeunt	lamb	stet-nok	muup-nok	ridge
peuk-wif	peuk-guif	butt	tat-kok	deup-kok	cook
pil-wing	pil-guik	pill	snat-kies	geup-kies	molar
lol-wimt	lol-guip	fun	brat-cape	leup-cape	cape
jeuk-wift	jeuk-guin	itch	grat-nis	meup-nis	niche
sap-wifs	sap-guim	juice	smat-jack	neup-jack	jacket
sein-voof	sein-veur	signal	fon-lus	duun-lus	loop
tang-vook	tang-veus	pliers	gon-loep	buun-loep	lens
mam-vool	mam-veul	mom	lon-rit	kuun-rit	ride
ring-voom	ring-veuk	ring	mon-lek	muun-lek	leak
loon-voon	loon-veut	wages	kron-roos	vuun-roos	rose
pol-vof	pol-feur	clump	stein-rek	deum-rek	rack
tol-vom	tol-feul	toll	nein-wol	geum-wol	wool
zang-von	zang-feuk	song	slein-wok	leum-wok	wok
lak-voft	lak-feus	varnish	smein-doeck	meum-doeck	towel
kuip-voms	kuip-feukt	barrel	krein-bek	neum-bek	snout

APPENDIX B
Target-Bearing Stimuli Used in Experiments 4 and 5

High Probability	Target Translation	Low Probability	Target Translation
Initial Targets, Experiment 4			
drum-baaf	drum	creme-baag	cream
dief-beem	thief	sleuf-beep	groove
pus-bif	pus	hasj-bim	hash
spies-bouf	skewer	creche-boug	daycare
kroos-daaf	duckweed	gleuf-daam	slot
pluis-deup	fluff	vleug-deut	breath
vlas-doum	flax	teug-dous	sip
slag-duip	beat	spuug-duis	spit
speen-fiek	teat	clown-fiet	clown
k Luis-foek	safe	douche-foes	shower
pauw-gam	peacock	kieuw-gan	gills
koek-heem	cake	truc-heeg	trick
kap-juif	cap	heup-juik	hip
muis-ruuf	mouse	zeug-ruus	sow
kwaal-suun	disease	beul-suun	hangman
Final Targets, Experiment 5			
kaaf-zeem	chammy	taaf-zeur	nag
baam-dis	dish	daam-jazz	jazz
beeg-dok	dock	peeg-junk	junkie
jeel-vaas	vase	weel-vouw	fold
beem-dot	dowry	deem-dauw	dew
deep-wees	orphan	heep-woud	forest
teuf-wig	wedge	veuf-jicht	gout
peum-vaat	dishes	veum-fout	error
meun-zeef	sieve	veup-fohn	hairdryer
deus-wal	shore	meus-jack	jacket
fiem-gal	gall	siem-geul	gully
hien-galg	gallows	pien-geur	smell
bif-dam	dam	tif-jeans	jeans
goem-vat	barrel	loem-fuik	fyke
boof-gans	goose	toof-shirt	shirt
bouk-ven	puddle	fouk-cheque	check
boum-vork	fork	foum-zeug	sow
kuuf-gast	guest	puuf-sjeik	sheik
guuk-zeep	soap	suuk-chef	boss
buum-vel	skin	puum-saus	sauce

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