available at www.sciencedirect.com
ScienceDirect
www.elsevier.com/locate/brainres
BRAIN RESEARCH

Research Report

Neurophysiological evidence of delayed segmentation in a foreign language

Tineke M. Snijders[a], *Valesca Kooijman*[a,b], *Anne Cutler*[b,c,d], *Peter Hagoort*[a,b,c,*]

[a]F.C. Donders Centre for Cognitive Neuroimaging, Radboud University Nijmegen, Box 9101, 6500 HB Nijmegen, The Netherlands
[b]Max Planck Institute for Psycholinguistics, Box 310, 6500 AH Nijmegen, The Netherlands
[c]Nijmegen Institute for Cognition and Information, Radboud University Nijmegen, Box 9104, 6500 HE, Nijmegen, The Netherlands
[d]MARCS Auditory Laboratories, University of Western Sydney, NSW 1797, Australia

ARTICLE INFO

Article history:
Accepted 17 July 2007
Available online 17 August 2007

Keywords:
Language
L1
L2
Segmentation
Event-related brain potential (ERP)

ABSTRACT

Previous studies have shown that segmentation skills are language-specific, making it difficult to segment continuous speech in an unfamiliar language into its component words. Here we present the first study capturing the delay in segmentation and recognition in the foreign listener using ERPs. We compared the ability of Dutch adults and of English adults without knowledge of Dutch ('foreign listeners') to segment familiarized words from continuous Dutch speech. We used the known effect of repetition on the event-related potential (ERP) as an index of recognition of words in continuous speech. Our results show that word repetitions in isolation are recognized with equivalent facility by native and foreign listeners, but word repetitions in continuous speech are not. First, words familiarized in isolation are recognized faster by native than by foreign listeners when they are repeated in continuous speech. Second, when words that have previously been heard only in a continuous-speech context re-occur in continuous speech, the repetition is detected by native listeners, but is not detected by foreign listeners. A preceding speech context facilitates word recognition for native listeners, but delays or even inhibits word recognition for foreign listeners. We propose that the apparent difference in segmentation rate between native and foreign listeners is grounded in the difference in language-specific skills available to the listeners.

1. Introduction

"Parlez plus lentement, s'il vous plaît", "Bitte, sprechen Sie langsamer","Hable más despacio, por favor": Such utterances are the common resource of listeners attempting to understand an unfamiliar language: "Please, speak more slowly". Continuous speech contains no silences between words analogous to the spaces in written text. But while the continuity of spoken utterances is hardly noticeable in the native language, so that we effortlessly interpret each utterance as a sequence of individual words, the process of resolving continuous speech into words is markedly harder in a foreign language. This may explain why speech in foreign languages often seems unnervingly fast (Pfitzinger and Tamashima, 2006).

The difficulty of segmenting foreign speech lies in part in the language-specificity of the procedures by which listeners segment speech into words (Cutler et al., 1983, 1986, 1989; Dumay et al., 2002; Kolinksy et al., 1995; Otake et al., 1993;

* *Corresponding author.* F.C. Donders Centre for Cognitive Neuroimaging, Radboud University Nijmegen, Box 9101, 6500 HB Nijmegen, The Netherlands. Fax: +31 24 3610989.
E-mail address: peter.hagoort@fcdonders.ru.nl (P. Hagoort).

0006-8993/$ – see front matter
doi:10.1016/j.brainres.2007.07.080

Suomi et al., 1997). Native listeners efficiently combine the prosodic, phonotactic, and lexical cues and statistical regularities in the language to extract words from speech. The non-native listener, however, may be unable to call on the strategies of this kind which native listeners find to be effective. In part segmenting foreign speech is also difficult because native segmentation procedures may be applied to other languages irrespective of whether they are appropriate (Cutler, 2000–2001; Cutler et al., 1986; Cutler and Otake, 1994; Otake et al., 1993; Vroomen et al., 1998). And finally, the native listener's ability to exploit syntactic and discourse information for rapid disambiguation will far outstrip that of the non-native listener. All these factors might combine to slow the segmentation process for non-native listeners.

However, it is currently unknown how great the difference in segmentation ability is. In this study, we addressed this issue via on-line electrophysiological measures. We tested 12 native Dutch-speaking adults, and 12 native English-speaking adults without knowledge of Dutch, on segmentation of Dutch. We will refer to the latter group as the foreign listeners. Foreign listeners cannot call on any of the language-specific sources of knowledge that the Dutch listeners command. They have, in effect, as little working knowledge of the language as infant listeners, who are known to develop the ability to extract word forms from continuous speech before they start to learn word meanings (Jusczyk, 1999; Jusczyk and Aslin, 1995; Kooijman et al., 2005). Note, however, that the foreign listeners can in this case use partly similar segmentation procedures, as Dutch resembles English in the metrical structure called upon in segmentation (Cutler and Butterfield, 1992; Cutler and Norris, 1988; Vroomen et al., 1996). Our comparison thus allows us to focus on the effect of knowledge of the language on the ability to extract word forms from continuous speech.

Our study exploited the known effect of repetition on event-related brain potentials (ERPs): the ERP to a later presentation of a word is typically more positive than the ERP to the first presentation of the same word (Rugg, 1985; Rugg and Doyle, 1994; Rugg et al., 1995). Participants received 20 trials, each made up of two phases: Familiarization plus Test. In each Familiarization phase, 10 tokens of a low-frequency Dutch word were presented in isolation. The words were all bisyllabic words with stress on the first syllable (e.g., *hommel*, 'bumble bee'). This type of word form is extremely common in both English (Cutler and Carter, 1987) and Dutch (Vroomen et al., 1996), and with one exception, the words conformed to English constraints on permissible syllable structures. In Familiarization, comparison of ERPs to the first vs. the second token tests for a repetition effect for isolated words.

In each following Test phase, participants heard eight short sentences, of which half contained the familiarized word, and half a matched novel word. Table 1 shows an example of an experimental Test block (*hommel*, with its matched control *mammoet*, 'mammoth'). Familiarized status of the word tokens was counterbalanced across participants. The recognition of familiarized words in continuous speech was assessed by comparing the difference between ERPs to the first occurrence of the familiarized and the first occurrence of the unfamiliarized word in the sentences. In addition, ERPs to the first and the second presentation of the unfamiliarized word in continuous speech were compared to examine repetition effects to words that had previously been heard only in a sentence context (novel word repetition within the Test phase).

Table 1 – Example of one experimental block

hommel	hommel	hommel	hommel	hommel
hommel	hommel	hommel	hommel	hommel

1. Die kleine *mammoet*[1] zwemt in de rivier.
   (That little mammoth swims in the river.)
2. De *hommel*[2] vliegt van bloem naar bloem.
   (The bumblebee flies from flower to flower.)
3. Er is een oude *mammoet*[3] in het museum.
   (There is an old mammoth in the museum.)
4. De *mammoet* is al lang geleden uitgestorven.
   (The mammoth became extinct long ago.)
5. Vaak kan een *hommel* erg hard zoemen.
   (Often a bumblebee can buzz very hard.)
6. Het is een oude *hommel* met gele strepen.
   (It is an old bumblebee with yellow stripes.)
7. Daar is een *mammoet* met veel vriendjes.
   (Over there is a mammoth with many friends.)
8. Een kleine *hommel* zit op het gordijn.
   (A little bumblebee is sitting on the curtain.)

Materials were in Dutch.
[1] First unfamiliarized control word.
[2] First familiarized word.
[3] Second unfamiliarized word.

To control for possible differences in memory load between the two groups, we conducted a second experiment, differing from Experiment 1 only in that pauses of 100 ms were inserted between the words in the sentences. This manipulation reduced the speech segmentation load, while the working memory load was kept constant. Since the familiarization phase was identical in the two experiments, we collapsed the familiarization results of both experiments.

2. Results and discussion

2.1. Familiarization phase

The results showed a similar ERP response in the Familiarization phase for both the native and the foreign listeners: a positive repetition effect with a central-posterior distribution (see Fig. 1). In the 400–900 ms "time-window, there was a significant effect of repetition ($F_{rep}(1,44)=74.42$, $p<0.001$) that was larger over posterior sites ($F_{rep\times quadrant}(3,132)=33.30$, $p<0.001$), and did not differ for the two groups ($F_{rep\times group}(1,44)=1.22$, $p=0.276$, Supporting Table 2a). Onset analysis showed that the Repetition effect started at 240 ms (see Supporting Table 2b). Thus both participant groups were equally able to recognize that the string of isolated tokens (e.g., *hommel, hommel, hommel…*) consisted of repetitions of the same word type. Prior knowledge of the language in which the words are spoken makes no difference to the nature of this response. This is consistent with previous research observing the same ERP repetition effect not only with words but also with pseudowords (Rugg et al., 1995), suggesting that no lexical knowledge is required for the appearance of this effect.

2.2. Experiment 1: Test phase

In the Test phase of Experiment 1, however, ERP responses for the native and foreign listeners differed. Fig. 2 shows ERPs to the first familiarized word and the first and second presentation of the unfamiliarized word in the sentences, for each group separately. It can be seen that *native* listeners (Fig. 2A) showed a repetition effect both to the familiarized words encountered in sentences ($F_{\text{rep native}}(1,11) = 23.95$, $p < 0.001$), and to novel word repetition within the Test phase ($F_{\text{rep native}}(1,11) = 11.05$, $p = 0.007$, Supporting Table 3). The *foreign* listeners (Fig. 2B) detected the occurrence of the familiarized word in the sentences ($F_{\text{rep foreign}}(1,11) = 18.98$, $p = 0.001$), although their ERP repetition effect was reduced and substantially delayed (starting at 515 ms) compared to that of the native listeners (which started at 115 ms, Supporting Table 4). However, foreign listeners showed no repetition effect at all ($F_{\text{rep foreign}} < 1$) in the comparison of first and second presentation of the *un*familiarized word in continuous speech (novel word repetition within the Test phase). Detecting word forms in continuous speech was thus exceptionally difficult for foreign listeners.

We observed that the native listeners achieved segmentation from the preceding context and launched the recognition response rapidly—well within the time-span of the word's delivery. The mean duration of the two-syllable words in the sentences was 721 ms, and yet for familiarized words the native listeners initiated the segmentation and recognition process already at 115 ms. Thus the process began well before the end of the first (stressed) syllable. Since the effect in continuous speech started slightly earlier than when the same words were presented in isolation (115 vs. 240 ms), contextual cues might have been assisting native listeners to detect the repetitions in continuous speech. These contextual cues can presumably be similarly exploited whenever adult listeners segment their native language. As the example in Table 1 illustrates, our materials in general afforded no semantic or lexical cues which would have enabled the native listeners to anticipate the upcoming word. Thus the cues in question could involve word-to-word coarticulation, syntactic structure, and rhythmic and prosodic predictability. The consequence of the native listeners' efficient use of this information is that as soon as the initial sounds of the familiarized word were heard, segmentation could take place, allowing word recognition to be initiated.

Consistent with this suggestion of rapid response to word-initial sounds is a finding of Sanders and Neville, who measured ERPs evoked in native listeners by different syllables in continuous speech; their experiments revealed a larger early sensory component (N100) for word-initial than for word-medial sounds (Sanders and Neville, 2003a,b; Sanders et al., 2002). In our experiment, the familiarized words were strongly primed (subjects had already heard 10 tokens of the familiarized word) and were expected to occur in the sentences, facilitating both the segmentation and the recognition process.

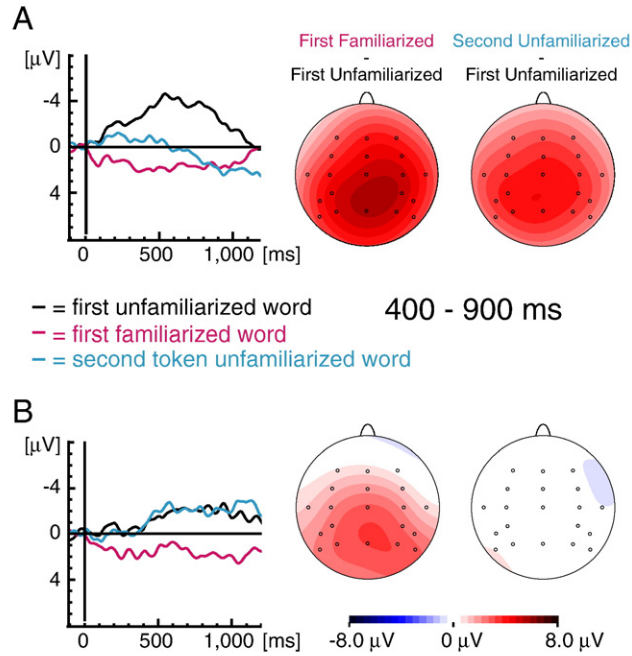

Fig. 2 – Experiment 1: Repetition effect in the Test phase for native (A) and foreign listeners (B). Left: Event-related potential (ERP) from the first familiarized word, and the first and the second occurrence of the unfamiliarized control word in the sentences at a representative electrode site (Pz). Negativity is plotted upwards. Middle and Right: Topographic iso-voltage maps of the different repetition effects in the 400–900 ms latency range. Middle: Recognition of familiarized words in continuous speech: familiarized–unfamiliarized. Right: Repetition effects within continuous speech: second unfamiliarized–first unfamiliarized.

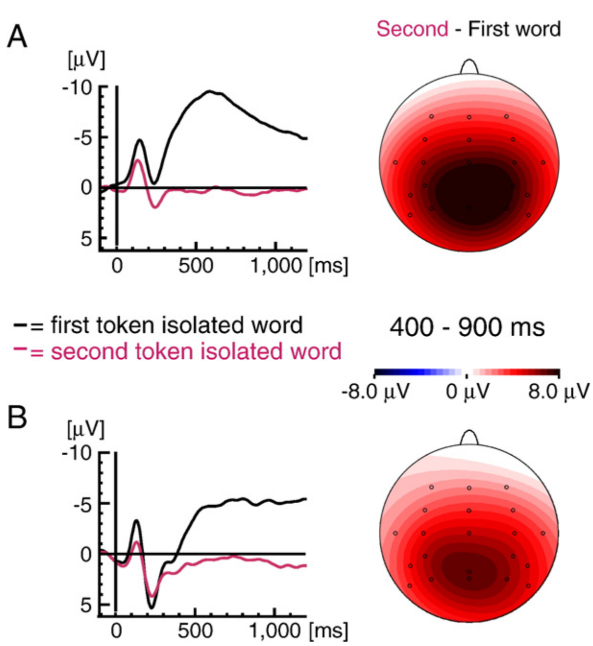

Fig. 1 – Repetition effect in the Familiarization phase for native (A) and foreign listeners (B). Left: Event-related potential (ERP) from the first and the second token of the word at a representative electrode site (Cz). Negativity is plotted upwards. Right: Topographic iso-voltage maps of the single word repetition effect in the 400–900 ms latency range.

Note that for novel word repetition within the Test phase, the repetition effect started only at 420 ms for native listeners; here the continuous speech context did not facilitate segmentation and recognition.

The pattern that we observed for foreign listeners in the Test phase differed from the native pattern. For familiarized words repeated in continuous speech, a repetition effect occurred, but only from 515 ms. Novel word repetition in continuous speech, however, was not detected by these listeners. Thus with sufficient familiarization, foreign listeners could segment and recognize words in the sentence (although the repetition effect was delayed compared to that of native listeners); but without familiarization, segmentation and recognition did not occur at all. In other words, a preceding speech context helps native listeners but appears to hinder foreign listeners.

2.3. *Speech segmentation vs. memory load*

The results from Experiment 1 suggest that foreign listeners have difficulties recognizing words in continuous speech. Is this due to the segmentation difficulties they encounter, or to a larger working memory load (compared to the native listeners)? Native listeners can chunk the different words of the meaningful sentences into larger units, whereas foreign listeners can only store the unknown word forms individually. To investigate the possibility that our results in Experiment 1 were due to differences between the two groups in memory load rather than in segmentation capacities, we conducted a second experiment. In this experiment, we used the same materials as in Experiment 1. However, in Experiment 2, the sentences for the Sentence Test phase were constructed from words spoken in isolation and concatenated, with 100 ms pauses between words. In this way, segmentation is rendered unnecessary, while working memory load stays the same as in Experiment 1. If the effects we found in Experiment 1 were entirely due to differences in working memory load, the results of Experiment 2 should be the same as those of Experiment 1. If, however, the smaller and delayed repetition effect in continuous speech shown by the foreign listeners is mainly due to their segmentation difficulties, the difference in repetition effect between native and non-native listeners should be reduced in the second experiment.

2.4. *Experiment 2: Test phase*

For the Sentence Test phase, Fig. 3 shows the ERPs to the first familiarized word and the first and second presentation of the unfamiliarized word in the sentences, for the two groups separately. Comparison of Fig. 3 with Fig. 2 reveals that the repetition effect size in Experiment 2 is somewhat reduced and delayed compared with Experiment 1. Importantly, however, in Experiment 2, the size of the repetition effect for familiarized words in continuous speech did not differ between native and foreign listeners. In contrast to Experiment 1, in this experiment, there was *no Repetition by Group interaction* in the 400–900 ms time window for the repetition effect to the familiarized words encountered in continuous speech ($F_{rep \times group}(1,22)=2.65$, $p=0.118$, Supporting Table 5a). A main effect of Repetition was observed ($F_{rep}(1,22)=13.57$, $p=0.001$).

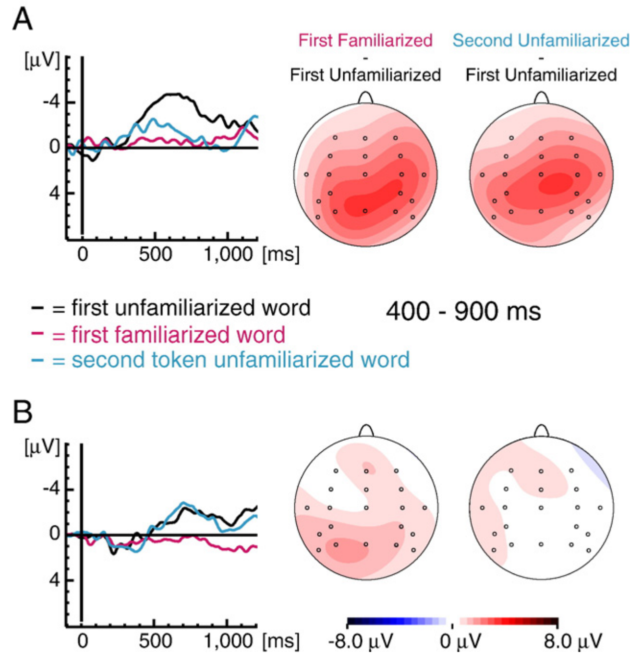

Fig. 3 – Experiment 2: Repetition effect in the Sentence Test phase for native (A) and foreign listeners (B). Left: Event-related potential (ERP) from the first familiarized word, and the first and the second occurrence of the unfamiliarized control word in the sentences at a representative electrode site (Pz). Negativity is plotted upwards. Middle and Right: Topographic iso-voltage maps of the different repetition effects in the 400–900 ms latency range. Middle: Recognition of familiarized words in continuous speech: familiarized–unfamiliarized. Right: Repetition effects within continuous speech: second unfamiliarized–first unfamiliarized.

The Repetition effect lasted from 465 to 910 ms (Supporting Table 6a). An analysis in this time window (465–910 ms) again failed to show a significant *Repetition by Group* interaction ($F_{rep \times group}(1,22)=1.67$, $p=0.210$).

For novel word repetition within the Test phase (second unfamiliarized–first unfamiliarized), there was no Repetition by Group interaction in the 400–900 ms time window ($F_{rep \times group}(1,22)=2.51$, $p=0.128$, Supporting Table 5b). However, results of the onset and duration analysis using cluster randomization indicated a Repetition by Group interaction from 600–795 ms (Supporting Table 6b). The Repetition effect lasted from 600 to 1090 ms for native listeners, while there was no significant cluster for the foreign listeners.

In contrast to Experiment 1, in Experiment 2 the ERP repetition response to familiarized words repeated in sentences did not differ significantly for native and foreign listeners. This suggests that a foreign listener's difficulty in detecting familiarized word forms in the continuous speech signal of an unfamiliar language is indeed at least in part due to segmentation difficulties, and not just to a difference in working memory load induced by foreign rather than native input. However, for novel words repeated in continuous speech, the difference in repetition effect between the native and foreign listeners was not abolished. The 100 ms pauses between words were not enough for the foreign listeners to detect the novel word repetition within the Test phase. Thus, the speech segmentation difficulties that foreign listeners encounter cannot be the only reason for the absence of a repetition effect for words repeated within continuous speech. For the familiarized words, a memory trace is formed, resulting in successful recognition when word boundaries are made clearer. But the novel unfamiliarized words will have to compete for a place in short term memory with all other words in the sentence (none of them evoking a lexical response). This makes the recognition process extremely difficult for foreign listeners even if the segmentation process is facilitated by inserting pauses between words.

The smaller size and the shorter duration of the repetition effects in Experiment 2 (compared to Experiment 1, see Supporting Tables 4 and 6) might have multiple origins. One possibility might be that the adding of pauses causes this attenuation. However, if anything, we would expect that to have the opposite effect, since silence is the clearest marker of word boundaries. The side effects of adding pauses, though, could well be responsible for the attenuated repetition effects. First, the absence of coarticulation in Experiment 2 might explain why the repetition effect in this experiment started much later (for natives) than in Experiment 1. Second, the smaller effect sizes in both groups might be the result of an overall signal-to-noise reduction in Experiment 2, due to the absence of a normal intonation contour. Because the materials were constructed by concatenating words recorded in isolation, the sentences lacked a normal intonation contour, and, presumably showed compared to words spoken as part of a sentence, an abnormal phonological variability. As a result, the intelligibility of the speech is likely to have been somewhat reduced. This would make it more difficult for both native and foreign listeners to recognize the repeated words, resulting in later (for natives) and smaller (for both groups) repetition effects. In this way the advantage of the short 100 ms pauses, making segmentation easy (or even redundant), could have been partly counteracted by a loss of intelligibility due to the absence of a normal intonation contour. Nevertheless the differential effect of Familiarization for native and foreign listeners was less pronounced in Experiment 2 than in Experiment 1, and failed to reach significance. This argues against any claim that the effect in Experiment 1 was solely due to a difference in working memory load in native vs. foreign listening.

3. Conclusions

The ERP repetition effect for words that are repeated in continuous speech is quite different for native and foreign listeners. Even though Dutch and English are highly similar languages, the neurophysiological evidence presented here shows fast segmentation and recognition by Dutch adults, but a reduced and delayed response for English adults. That is, only the native listeners are able to perform fast segmentation of Dutch sentences. Segmentation of continuous speech is a process which listeners have optimized for application to their native language, with the result that this process becomes a demanding one for foreign listeners. Foreign listeners also cannot call on lexical knowledge (in memory) to find boundaries in the speech stream. The resulting speech segmentation difficulty forms an important part of why understanding a spoken foreign language can be so problematic. The frequently reported subjective impression that speakers of other languages talk extremely fast may be grounded in the brain response delays which we have observed here.

4. Experimental procedures

4.1. *Experiment 1*

4.1.1. *Subjects*

Native language participants were 12 right-handed native speakers of Dutch (7 female, mean age 22, range 18–28 years). Foreign language participants were 12 right-handed native speakers of English (7 female, mean age 22, range 19–27). Six of them spoke British English and six American English. At the time of testing, these subjects had been in the Netherlands for on average 2.4 months (range 1–7 months). They were unable to speak or understand Dutch. The answers of the English subjects on a Dutch lexical decision task did not differ from chance ($t=1.97$, $p=0.074$, mean=54% correct, SD=7.5%). They could translate on average not more than 3.3 of 72 English monosyllabic words (e.g., *rope, sweep*) into Dutch. None of the participants had any neurological impairment or had experienced any neurological trauma according to their responses on a questionnaire. All subjects gave written informed consent.

4.1.2. *Materials*

Forty low frequency, two-syllable nouns with a strong/weak stress pattern were selected from the CELEX Dutch lexical database. These were arbitrarily formed into twenty pairs. For each of the 40 nouns, a set of four sentences containing the noun was constructed (see Appendix A for a complete list of stimulus materials). The position of the critical noun in the sentence and the word preceding it were matched within pairs. The sentences were short and contained, prior to the occurrence of each critical word, no semantic information that could have enabled native listeners to predict the word. Words and sentences were recorded in a sound-attenuating booth onto digital audiotape by a female native Dutch speaker, sampled at 16 kHz mono to disk, and edited using a speech waveform editor. The 10 tokens of each word were acoustically highly variable. The mean duration of the words was 710 ms (range: 365–1270 ms) in isolation, 720 ms (range: 225–1045 ms) in sentence context. The mean sentence duration was 4080 ms (range: 2700–5840 ms).

4.2. *Experiment 2*

4.2.1. *Subjects*

Native language participants were 12 right-handed native speakers of Dutch (7 female, mean age 21, range 18–25 years). Foreign language participants were 12 right-handed native speakers of English (8 female, mean age 23, range 19–27). Five of them spoke British English and seven American English. At the time of testing, these subjects had been in the Netherlands for on average 2.3 months (range 1 week–8 months). They were unable to speak or understand Dutch. The answers of the English subjects on a Dutch lexical decision task did not differ from chance ($t=0.28$, $p=0.785$, mean = 50.5% correct, SD = 6.5%). They could translate on average not more than 1.7 of the same 72 English monosyllabic words into Dutch. None of the participants had any neurological impairment or had experienced any neurological trauma according to their responses on a questionnaire. None of the subjects had participated in Experiment 1. All subjects gave written informed consent.

4.2.2. *Materials*

The materials were identical to the materials of Experiment 1. However, in Experiment 2, the words that made up the sentences were recorded separately, and the original sentences were reconstructed by concatenating these words, with 100 ms silence between adjacent words.

The mean duration of the words was 710 ms (range: 365–1270 ms) in isolation, 800 ms (range: 450–1190 ms) in sentence context. The mean sentence duration was 6030 ms (range: 4200–8170 ms).

4.3. *Procedure*

The procedure in both experiments was the same. The experimental trials were presented in 20 experimental blocks, each consisting of 10 different tokens of the same word (familiarization stimuli) followed by eight randomized sentences (test stimuli). Four of these contained the familiarized word (repetition condition), the other four contained the paired word, which had not been familiarized (non-repetition condition). Table 1 shows an example of an experimental block. Each block lasted approximately 1.6 min. There were short breaks between the blocks. In the Familiarization phase, the different tokens of the same noun were separated by a silent interval of 2500 ms. In the Test phase, there was a silent interval between sentences of 4200 ms. Four versions of the experiment were constructed, such that the same nouns (and sentences) appeared in both the familiarized and the unfamiliarized conditions, and the presentation order of the blocks was counterbalanced. Thus in the Table 1 example, for half the listeners *hommel* was familiarized and *mammoet* was not, while for the other half *mammoet* was familiarized and *hommel* was not. EEG was measured during both the Familiarization and the Test phase. During EEG measurement, the subjects were seated in a comfortable chair in front of a computer screen, in a dimly illuminated sound-attenuating booth. The subjects listened to the stimuli via a loudspeaker set, placed approximately 1.5 m in front of them. On the computer screen, a fixation asterisk was presented during the auditory presentation of the words and the sentences. The subjects were asked to avoid eye and other movements during stimulus presentation. No additional task demands were imposed.

4.4. *EEG recordings*

EEG was measured using a BrainCap with 27 sintered Ag/AgCl electrodes. Twenty-one electrodes were placed according to the 10% standard system of the American Electroencephalographic Society (midline: Fz, FCz, Cz, Pz, Oz; frontal: F7, F8, F3, F4; fronto-temporal: FT7, FT8; fronto-central: FC3, FC4; central: C3, C4; centro-parietal: CP3, CP4; parietal: P3, P4; and occipital: PO7, PO8). Another six electrodes were placed bilaterally on non-standard intermediate positions. A temporal pair (LT and RT) was placed 33% of the interaural distance lateral to Cz, while a temporo-parietal pair (LTP and RTP) was placed 30% of the interaural distance lateral to Cz and 13% of the inion–nasion distance posterior to Cz, and a parietal pair (LP and RP) was placed midway between LTP/RTP and PO7/PO8. All electrodes were referenced to the left mastoid online. The EEG electrodes were re-referenced offline to linked mastoids. Electro-oculogram (EOG) was recorded from electrodes above and below the eye, and at the outer canthi of the eyes. EEG and EOG data were recorded with a BrainAmp AC EEG amplifier using a high cut-off of 30 Hz and a time constant of 10 s. Impedances were typically kept below 3 kΩ for the EEG recordings and below 5 kΩ for the EOG recordings. The EEG and EOG signals were digitized online with a sample frequency of 200 Hz.

4.5. *Data analyses*

Individual trials were time-locked to the acoustic onset of the critical words. All trials were screened for eye movements, electrode drifting, amplifier blocking, and EMG artifacts, in a time window ranging from 200 ms before onset of the critical word to 1200 ms after the critical word. Trials containing artifacts were rejected. The mean number of rejected trials per condition was 2.2 for native and 3.3 for foreign listeners in Experiment 1, and 1.7 for native and 2.6 for foreign listeners in Experiment 2). For the remaining trials a baseline correction was applied, in which the waveforms were normalized relative to a 100 ms stimulus-preceding epoch. Subsequently, averaged waveforms were computed. Statistical analyses of the repetition effects consisted of repeated measures analyses of variance (ANOVAs), using mean amplitude values for the 400–900 ms latency window computed for each subject, condition, and electrode site. To investigate the topographical distribution of the ERP-effects, different subsets of electrodes were grouped together (Anterior Left (AL): F7, F3, FT7, FC3, LT; Anterior Right (AR): F4, F8, FC4, FT8, RT; Posterior Left (PL): LTP, CP3, LP, P3, PO7; Posterior Right (PR): CP4, RTP, P4, RP, PO8). Omnibus $2\times2\times4$ repeated measures ANOVAs on mean ERP amplitude (in μV) for the 400–900 ms time window were carried out first, with Group (native language, foreign language) as between-subject factor and Repetition (repetition/no-repetition) and Quadrant (AL, AR, PL, PR) as within-subject factors. When significant Repetition by Group interactions were found, separate ANOVAs were performed for the different groups. Where interactions between Repetition and Quadrant were significant, ANOVAs on the 4 quadrants were carried out separately. For the Familiarization phase, ERPs of Experiment 1 and the Experiment 2 were analyzed together, with Experiment as an additional between-subjects factor, as this phase was identical for both experiments (confirmed by absent Repetition by Experiment interactions, see Supporting Table 2). For the Test phase, ERPs of the two experiments were analyzed separately. For evaluation of effects with more than one degree of freedom in the numerator, the Greenhouse–Geisser correction was used. The original degrees of freedom and adjusted p-values are reported.

To establish onset and duration of the repetition effect, cluster randomization analyses were performed using Fieldtrip, an open source toolbox for EEG and MEG analysis developed at the F.C. Donders Centre for Cognitive Neuroimaging (http://www.ru.nl/fcdonders/fieldtrip). The cluster randomization method that Fieldtrip uses is an improved version of the method described in Maris (2004) (Maris, 2004; Takashima et al., 2006). This test effectively controls the Type-1 error rate in a situation involving multiple comparisons (i.e., 27 electrodes × 240 time points). Briefly, the method works as follows: In a first step, all (electrode, time point) pairs are identified for which the *t*-statistics for the difference between conditions (e.g., familiarized vs. unfamiliarized) exceed some prior threshold. The selected (electrode, time point) pairs are then grouped into a number of clusters in such a way that, within every cluster, the (electrode, time point) pairs form a set that is connected spatially and/or temporally. Each cluster is assigned a cluster-level test statistic whose value equals the sum of the (electrode, time point) specific test statistics. Thus, the cluster-level test statistic depends on both the extent of the cluster and the size of the (electrode, time) specific *t*-statistics that belong to this cluster. The Type-I error rate for the complete spatio-temporal data matrix is controlled by evaluating the cluster-level test statistic under the randomization null distribution of the maximum cluster-level test statistic. This randomization null distribution is obtained by randomizing the order of the data (e.g., familiarized and unfamiliarized trials) within every participant. By creating a reference distribution from 1000 random draws, the *p*-value may be estimated by the proportion from this randomization null distribution in which the maximum cluster-level test statistic exceeds the observed cluster-level test statistic (this proportion is called a Monte Carlo *p*-value in the statistics literature). With this number of 1000 random draws, our Monte Carlo p-value is an accurate estimate of the true *p*-value. In brief, the cluster randomization *p*-value denotes the chance that such a large summed cluster-level statistic will be observed when there is actually no effect. In this way, significant clusters extending both over time and over electrodes can be identified, providing a measure both of the timing and of the distribution of the effect.

First, cluster randomization tests were performed to check for Repetition by Group interactions, comparing the size of the repetition effect for the native and the foreign listeners. Where interactions between Repetition and Group were significant, cluster randomization analyses to test the Repetition effect were carried out for native and foreign listeners separately. When no significant Repetition by Group interaction was found, both groups were analyzed together.

For illustrative purposes only, the grand-average ERPs were smoothed off-line using a 5-Hz low pass filter.

Acknowledgments

We thank Miriam Kos, Nienke Weder, Eric Maris, Carolien van den Hazelkamp, Walter van Heuven, and Marlies Wassenaar for their help. This research was supported by the Spinoza grant “Native and Non-Native Listening” from the Netherlands Organization for Scientific Research (NWO) to A. Cutler and by NWO grant 051.04.031 to P. Hagoort.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.brainres.2007.07.080.

REFERENCES

Cutler, A., 2000–2001. Listening to a second language through the ears of a first. Interpreting. 5, 1–23.
Cutler, A., Butterfield, S., 1992. Rhythmic cues to speech segmentation: evidence from juncture misperception. J. Mem. Lang. 31, 218–236.
Cutler, A., Carter, D.M., 1987. The predominance of strong initial syllables in the English vocabulary. Comput. Speech Lang. 2, 133–142.
Cutler, A., Norris, D.G., 1988. The role of strong syllables in segmentation for lexical access. J. Exp. Psychol. Hum. Percept. Perform. 14, 113–121.
Cutler, A., Otake, T., 1994. Mora or phoneme—further evidence for language-specific listening. J. Mem. Lang. 33, 824–844.
Cutler, A., Mehler, J., Norris, D., Segui, J., 1983. A language specific comprehension strategy. Nature 304, 159–160.
Cutler, A., Mehler, J., Norris, D., Segui, J., 1986. The syllable’s differing role in the segmentation of French and English. J. Mem. Lang. 25, 385–400.
Cutler, A., Mehler, J., Norris, D., Segui, J., 1989. Limits on bilingualism. Nature 340, 229–230.
Dumay, N., Frauenfelder, U.H., Content, A., 2002. The role of the syllable in lexical segmentation in French: word-spotting data. Brain Lang. 81, 144–161.
Jusczyk, P.W., 1999. How infants begin to extract words from fluent speech. Trends Cogn. Sci. 3, 323–328.
Jusczyk, P.W., Aslin, R.N., 1995. Infants’ detection of the sound patterns of words in fluent speech. Cogn. Psychol. 29, 1–23.
Kolinksy, R., Morais, J., Cluytens, M., 1995. Intermediate representations in spoken word recognition: evidence from word illusions. J. Mem. Lang. 34, 19–40.
Kooijman, V., Hagoort, P., Cutler, A., 2005. Electrophysiological evidence for prelinguistic infants’ word recognition in continuous speech. Cogn. Brain Res. 24, 109–116.
Maris, E., 2004. Randomization tests for ERP-topographies and whole spatiotemporal data matrices. Psychophysiology 41, 142–151.
Otake, T., Hatano, G., Cutler, A., Mehler, J., 1993. Mora or syllable? Speech segmentation in Japanese. J. Mem. Lang. 32, 258–278.
Pfitzinger, H.R., Tamashima, M., 2006. Comparing perceptual local speech rate of German and Japanese speech. Proc. of the 3rd Int. Conf. on Speech Prosody, vol. 1. TUD Press, Dresden, pp. 105–108.
Rugg, M.D., 1985. The effects of semantic priming and word repetition on event-related potentials. Psychophysiology 22, 642–647.
Rugg, M.D., Doyle, M.C., 1994. Event-related potentials and stimulus repetition in direct and indirect tests of memory. In: Heinze, H.-J., et al. (Ed.), Cognitive Electrophysiology. Birkhäuser, Boston, pp. 124–148.
Rugg, M.D., Doyle, M.C., Wells, T., 1995. Word and nonword repetition within-modality and across-modality—an event-related potential study. J. Cogn. Neurosci. 7, 209–227.
Sanders, L.D., Neville, H.J., 2003a. An ERP study of continuous speech processing: I. Segmentation, semantics, and syntax in native speakers. Cogn. Brain Res. 15, 228–240.
Sanders, L.D., Neville, H.J., 2003b. An ERP study of continuous speech processing: II. Segmentation, semantics, and syntax in non-native speakers. Cogn. Brain Res. 15, 214–227.

Sanders, L.D., Newport, E.L., Neville, H.J., 2002. Segmenting nonsense: an event related potential index of perceived onsets in continuous speech. Nat. Neurosci. 5, 700–703.
Suomi, K., McQueen, J.M., Cutler, A., 1997. Vowel harmony and speech segmentation in Finnish. J. Mem. Lang. 36, 422–444.
Takashima, A., Jensen, O., Oostenveld, R., Maris, E., van de Coevering, M., Fernandez, G., 2006. Successful declarative memory formation is associated with ongoing activity during encoding in a distributed neocortical network related to working memory: a magnetoencephalography study Neuroscience 139, 291–297.
Vroomen, J., Tuomainen, J., de Gelder, B., 1998. The roles of word stress and vowel harmony in speech segmentation. J. Mem. Lang. 38, 133–149.
Vroomen, J., van Zon, M., de Gelder, B., 1996. Cues to speech segmentation: evidence from juncture misperceptions and word spotting. Mem. Cogn. 24, 744–755.