Word-specific cortical activity as revealed by the mismatch negativity

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Abstract

Neurophysiological brain activity evoked by individual spoken words and pseudowords was recorded and the mismatch negativity (MMN), an automatic index of experience-dependent auditory memory traces, was calculated. Consistent with earlier reported results, the MMN response to word-final syllables was enhanced compared with that elicited by the same syllables placed in a pseudoword context. Here we now demonstrate that the enhancement of the MMN elicited by two individual words showed different scalp topographies. The early word-specific brain activity is consistent with the assumption that the memory traces activated by individual words are carried by large neuronal ensembles that differ in their distributions over the cortex. Current source estimates localized the between-word differences in the right hemisphere and in parieto-occipital left-hemispheric areas. The differential brain responses to individual words appeared as early as ~100 ms after the recognition points of the words, suggesting that their specific memory traces become active almost immediately after the information in the acoustic input is sufficient for word identification.

Descriptors: Acoustics, Language, L2 minimum-norm estimate, Lexical processing, Mismatch negativity (MMN), Phonology, Semantics, Spoken word

Individual words may be represented in the human brain by large but specific cortical neuron ensembles (Freud, 1891), and the cortical distribution of these memory traces may differ between different words (see Pulvermüller, 1999, for a discussion of recent evidence). In this case, two different words could potentially elicit different spatiotemporal patterns of neuronal activity. Support for this view comes from neurophysiological and hemodynamic imaging studies indicating that the processing of words from different categories is accompanied by neuronal activation in distinct sets of cortical areas differing from each other (Kiefer, 2001; Pulvermüller, 2001; Warburton et al., 1996). However, in earlier studies, brain responses to large groups of words from different categories were compared, thus not justifying conclusions on the neurophysiological correlates of individual lexical items. As Humphreys and colleagues (Humphreys & Riddoch, 1987; Humphreys & Forde, 2001) have argued, category differences may be ground in the similarity between the items included into the categories. Items from two category groups might therefore produce different patterns of psychophysiological responses because one stimulus group consists of very similar items and the other one of very different ones, leading to differential priming effects between the items for the two groups. This problem may be avoided by studying single items. If the neural substrates of two categories of words are topographically distinct, so that different areas are differentially involved in their respective processing, the category differences should not only be reflected by studies of word groups, but by probing single items from the categories as well. Psychophysiological investigations of single lexical items are therefore of theoretical importance for two reasons: They may shed further light on the issue of category specificity in the human brain and can directly test the hypothesis that word-related brain circuits differentially involve specific cortical areas.

To record neurophysiological responses to individual words, it is possible to apply an oddball paradigm in which a word is being presented as an infrequent, deviant stimulus among frequent standard stimuli. In recent studies (Korpiilahti, Krause, Holopainen, & Lang, 2001; Pulvermüller, Kujala, et al., 2001; Shtyrov & Pulvermüller, 2002), an oddball paradigm was used to
record the mismatch negativity (MMN) to words. It was found that
the MMN to words was enhanced as compared with that to
meaningless pseudowords, suggesting that the MMN amplitude
can indicate the presence of cortical memory traces for spoken
words. In earlier work, it had been shown that a similar enhance-
ment of the MMN amplitude exists for sounds representing
prototypical members of a phonological category. Prototypical
language sounds of the subjects’ mother tongue elicited enhanced
MMNs compared with sounds that do not correspond to a phoneme in
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that language (Cheour et al., 1998; Dehaene-Lambertz & Baillet,
1998; Näätänen, 2001; Näätänen et al., 1997). These results indicate that the exist-
ence of memory traces for the spoken elements of one’s own
language, including phonemes and words, can be revealed by the
MMN. They provide evidence that the MMN is a general index
of experience-dependent auditory memory traces (Näätänen,
2001; Näätänen & Alho, 1997; Picton, Alain, Otten, Ritter, &
Achim, 2000).

To compare brain responses to individual words with each
other, we recorded the MMN to the second syllable of two
bisyllabic words of Finnish. Both words shared their first syllable
whereas their second syllable differed from each other. To control
for the physical or acoustic differences between the second
syllables distinguishing the words, we also investigated the
MMNs to meaningless pseudowords that ended in the same
syllables as the words. We hypothesized that MMN to words
would not only be greater than those elicited by pseudowords,
but that these MMN enhancements for the two words under
study would differ from each other in their cortical topographies.

Materials and Methods

Participants

The participants were nine right-handers without left-handed
family members whose native language was Finnish. Their age
ranged between 20 and 30 years (average: 24). They reported to
have normal hearing and no history of neurological illness or
drug abuse.

Procedure

The study was designed to investigate possible neurophysiolo-
gical differences between individual spoken words in the absence
of focused attention to these stimuli. Participants were therefore
asked not to attend to the word stimuli, which were delivered
through headphones. To distract them from the language input,
they were shown a silent movie of their own choice that did not
include subtitles. Words and pseudowords necessarily differ in
their physical features. To investigate lexical rather than physical
differences between the stimuli we chose Finnish words and pseudowords
that ended in same syllables. This allowed us to splice identical
copies of the same spoken syllable to the end of words and
pseudowords so that any difference in brain responses to words
and pseudowords could not be explained by physical differences
between the critical final syllables. We chose the Finnish words
lakki (cap) and lakko (labor strike) and the pseudowords vakki
and vakko, which lack a representation in the Finnish mental
lexicon. In condition I (word condition), the words lakki and
lakko were presented as infrequent deviant stimuli, each with a
probability of .06, against the background of the frequent
standard stimulus vakke, which also represents a pseudoword in
Finnish. In condition II (pseudoword condition), the pseudo-
words vakki and vakko were the deviants (p = .06 each) and the
pseudoword vakke the frequent standard stimulus. Note that in
both conditions, the standard stimulus was a pseudoword ending
in the syllable [ke]. In each condition, 160 tokens of each deviant
and 2,720 standards were delivered with a stimulus onset
asynchrony of 1,200 ms. The order of the two conditions was
counterbalanced across participants.

Stimuli

A large sample of syllables [va], [la], [ke], [ki], and [ko] were
spoken in a soundproof room by a female native speaker of
Finnish and recorded on a computer with a sampling rate of
30 kHz. For use in the experiment, we selected exemplars of
the five syllables that were acoustically maximally similar. They
were all normalized to the same peak sound energy. The syllables [va]
and [la], which were used as first or context syllables in the
experiment, had the same fundamental frequency and were
shortened to a length of 250 ms. The second and critical syllables
[ke], [ki], and [ko] had the same fundamental frequency and voice-onset
time of their stop consonant (<3% difference) and
were all adjusted to a length of 230 ms. The five syllables
were cross spliced to yield the items lakki, lakko, lakke, vakki, vakko,
and vakke with 200 ms in between the syllables. This pause is
natural in Finnish, because the words lakki and lakko include a
geminate consonant in the middle that is realized acoustically as a
~200 ms pause followed by an actual [k]. Note, however, that
the pause is an integral part of the geminate, the so-called
“double-k,” which has the status of a phoneme in Finnish, so
that the omission of the pause may change the meaning of a word
(the Finnish laki, e.g., means law). For neurophysiological
experiments, the Finnish stop geminates have the advantage of
allowing for a baseline before a word-final syllable. To determine
the point in time when the word-final syllables could be
identified, a gating study was performed. The first syllables
followed by short fragments of the second critical syllables were
played to four native speakers of Finnish. They were unable to
identify the word lakki and lakko when presented with a 30-ms
fragment of the second syllable but were all capable of identifying
the words when given fragments of 40 ms. This shows that the
word recognition points (Marslen-Wilson & Tyler, 1980) for
both words were around 40 ms after the onset of the critical
syllables. The words were presented with a loudness of 50 dB
above the individual hearing threshold.

EEG Recording

The EEG was recorded with a cap (Virtanen, Rinne, Ilmoniemi,
& Näätänen, 1996) carrying 62 Ag/AgCl electrodes placed at
standard locations of the extended international 10-20 system.
The reference electrode was placed at the tip of the nose. The
horizontal and vertical electrooculograms (EOG) were recorded
through two additional electrode pairs placed close to the eyes.
DC signals (0–100 Hz) were continuously recorded using
SynAmps amplifiers and the Scan 3.0 software (NeuroScan
Labs, El Paso, TX) and sampled at 200 Hz.

Data Analysis

Stimulus-triggered event-related potentials (ERPs), starting
50 ms before the onset of the critical syllables [ke], [ki], and
[ko] and lasting until 550 ms after stimulus onset, were calculated
for each participant, electrode, and stimulus, after rejection of
trials with blinks or eye-movement artifacts (>75 μV). The
MMN was calculated by subtracting the ERP elicited by the
standard stimulus from that of the deviant stimulus. Average
values of the MMN curves in predefined intervals were calculated for each deviant, participant, and recording site and submitted to statistical analysis.

To obtain topographic information about the MMN, an analysis was performed on 16 recording sites located over the brain regions of interest. Four of these electrodes were at fronto-central sites of the midline, corresponding to the sites Fz, FCz, Cz, and CPz of the extended international 10-20 system, where the MMN amplitude usually is largest (Näätänen & Winkler, 1999). In addition, two lines of lateral electrodes were selected: F7, FT7, T7, TP7 and F8, FT8, T8, TP8, which were used for monitoring activity close to the left-hemispheric language areas of Broca and Wernicke, and activity in the homotopic areas of the right hemisphere. Finally, four electrodes placed over the occipital lobes, at recording sites O1, Oz, O2, and OPz, were selected. To avoid the increase of degrees of freedom caused by introducing multilevel factors, the electrodes were grouped in a binary fashion. The factor Centro-Lateral distinguished the two electrode quadruplets at close to the midline from the lateral ones, and the factor Language Area separated those close to language areas from those distant from them. All quadruplets were divided into an anterior and a posterior pair of electrodes (e.g., F and FCz vs. Cz and CPz; factor Anterio-Posterior), and the remaining two electrode pairs were divided by an additional factor called Locus (e.g., Fz and Cz vs. FCz and CPz). A six-way analysis of variance was carried out for each of the three time intervals, with the binary variable Wordness (word context vs. pseudoword context), Syllable ([ki] vs. [ko]), Centro-Lateral, Language Area, Anterio-Posterior, and Locus. Additional analyses of variance were used to further analyze significant interactions. If and only if significant interactions of the topographical variables with the factors Wordness or Syllable were found, z-transformed values were calculated following McCarthy and Wood (1985) to remove possible nonlinear effects of overall source strength on the scalp topography. Significant interactions of the topographical variables are reported for normalized data.

Source Localization

For time intervals during which significant interactions of the variables Syllable and Wordness with one or more of the topographical variables could be found, an attempt at narrowing down the space of cortical generators possibly underlying these effects was made using L2 minimum-norm current estimates. The minimum-norm method reveals the unique constellation of generators that models the recorded potential distribution at a particular point in time with the smallest amount of overall current (Hämäläinen & Ilmoniemi, 1984, 1994; Ilmoniemi, 1993). Among the infinitely many dipole constellations that can explain a given surface potential distribution, there is generally one that does so with the least amount of overall activity. This minimal solution should be preferred for the sake of parsimony. The minimum-norm current estimate is an application of this principle to the inverse problem of localizing neurophysiological current sources in the brain. We used the L2 norm, which minimizes the sum of squares of the amplitudes of the individual current sources, because it is applicable without any a priori assumptions and yields a robust and realistic, although somewhat blurred, constellation of generators (Hämäläinen & Ilmoniemi, 1984, 1994; Ilmoniemi, 1993). Current constellations underlying grand-average ERPs were calculated on the basis of a four-shell model. Current strengths were normalized (maximal dipole = 100%) for each time step and projected on a schematic gray matter surface using the software package BESA 4.2 (MEGIS Software GmbH, Munich). The signal-to-noise ratio (SNR) of the neurophysiological recordings was estimated for each condition and time point by dividing the power over all channels by the average power obtained in the baseline. For the intervals where statistical analysis revealed relevant effects, the minimum-norm current estimate of the underlying constellation of cortical generators was computed using the calculated SNRs. All relevant SNRs were 2.5 or larger.

Results

MMN Morphology

Figure 1 shows MMNs recorded at the central prefrontal electrode FCz to the second, critical, syllables [ki] and [ko] presented in word and pseudoword contexts, respectively. Both syllables elicited a biphasic MMN. The earlier and larger wave started at ~100 ms and peaked at 150–180 ms after the onset of the critical syllable. The later and smaller MMN wave peaked between 300 and 400 ms. The first MMN wave was larger when syllables were part of words compared with their presentation in pseudoword context. The difference curves in Figure 1 illustrate this enhancements of the MMN in word context, as compared with that to the same syllables when they were part of pseudowords.

Figure 1. Top diagram: Event-related potentials elicited by the syllable [ke] in the standard stimulus in the two experimental conditions, after [va] (broken blue lines) and after [la] (continuous red line). Directly below these curves, the acoustic waveforms of the critical syllables [ki] (on the left) and [ko] (right) of the deviant stimuli are shown. After the stimulus waveforms of the critical syllables, the mismatch negativities (MMNs) they elicited are displayed. The MMNs to the syllables placed in word context (continuous red lines) are contrasted with those in pseudoword context (broken blue lines). The diagrams at the bottom illustrate the word-related enhancements of the MMN, that is, the MMN evoked by the critical syllable presented in pseudoword context subtracted from the MMN elicited by the identical syllable presented in word context.
Statistical analyses were performed on data from the MMN rise interval, 100–150 ms after critical-syllable onset, for the MMN peak interval (150–180 ms), and for the interval of the additional, late and smaller negativity at 300–500 ms.

**Early MMN Rise Interval (100–150 ms)**

There were main effects of the topographical variables, Centro-Lateral, and Antero-Posterior, all $F$ values $> 10$, $p$ values < .01, indicating that MMN responses were larger at central sites than at lateral sites, and at anterior sites than at posterior ones. The prominence of the MMN at the fronto-central sites was also reflected by a significant interaction of the factors Centro-Lateral and Language Area, $F(1,8) = 12.0$, $p < .01$. Furthermore, there was a significant triple interaction of the factors Wordness, Centro-Lateral, and Language Area, $F(1,8) = 7.2$, $p < .03$. This interaction was due to the enhancement of the MMN in word context relative to that in pseudoword context. Consistent with the well-known anteriorly predominant topography of the MMN (Näätänen, 1995), the word-related MMN enhancement was the most pronounced at the fronto-central electrodes (planned comparison: $F(1,8) = 8.6$, $p < .02$). In addition, a difference between words and pseudowords could be confirmed statistically for left-lateral electrodes, $F(1,8) = 7.7$, $p < .04$. The significant interaction displayed in Figure 2 (diagram at the top) further confirms the MMN enhancement for words (Korpilahti et al., 2001; Pulvermüller, Kujala, et al., 2001; Shtyrov & Pulvermüller, 2002) and shows that this effect is not necessarily restricted to the midline.

An additional complex interaction indicated that the MMN enhancements elicited by the two critical syllables, [ki] and [ko], differed from each other. This was documented by a significant interaction of the factors Wordness, Syllable, and Language Area, $F(1,8) = 5.5$, $p < .05$. At central recordings, the MMN amplitude difference between the word and pseudoword contexts was clearly visible for both critical syllables at the central recording sites. In contrast, at the right-hemispheric and occipital recording sites, this Wordness effect was also visible for one of the syllables, $F(1,8) = 9.5$, $p < .02$ (Figure 2, diagram at the bottom). Thus, the MMN enhancements for the two words under investigation exhibited topographical differences.

**Early MMN Peak Interval (150–180 ms)**

For the MMN peak, the main effect of the Antero-Posterior factor was still significant, as were all the other main effects related to the topography, all $F$s $> 10$, $p$s $< .01$. Again, an interaction of the factors Centro-Lateral and Language Area indicated stronger signals at the fronto-central sites than lateral sites over the left and right hemispheres, $F(1,8) = 25.9$, $p < .0009$. In this interval, there was a significant main effect of Wordness, $F(1,8) = 7.6$, $p < .02$) and an interaction between Wordness and Centro-Lateral, $F(1,8) = 12.0$, $p < .009$. (Two of these $F$ values have earlier been reported by Pulvermüller, Kujala, et al., 2001, as part of results of their experiment 1.)

Importantly, the factors Wordness and Centro-Lateral were also involved in a triple interaction with the factor Syllable, $F(1,8) = 8.3$, $p < .02$. This interaction was again due to a more widely distributed word-related MMN enhancement for the syllable [ko] than that for the syllable [ki]. Figure 3 presents both significant interactions.

In summary, the MMN peak interval analysis could confirm the two main findings from the rise interval analysis: First, the MMN was larger for words than for pseudowords. Second, this word-related MMN enhancement showed differential scalp topographies for the Finnish words lakki and lakko.

**Late MMN Interval (300–500 ms)**

This analysis indicated no topographical main effects, as they were documented by the analyses of the early MMN, except for an effect of the factor Centro-Lateral, $F(1,8) = 10.5$, $p < .01$. Interestingly, there was a significant complex interaction of both stimulus-related factors, Wordness and Syllable, with both Centro-Lateral and Language Area, $F(1,8) = 13.6$, $p < .006$. However, this late effect was clearly distinct from the one obtained in the earlier MMN intervals analyzed. The Wordness effect was now absent for the syllable [ki], but present for [ko]. The significant interaction indicates that this late MMN-related effect may not be elicited by all words.

**Source Localization**

The L2 minimum-norm current estimates of the cortical sources underlying the statistically significant between-word differences in scalp topographies were performed for the early MMN, including its rise time and peak intervals. Figure 4 shows source current estimates calculated for the word-related MMN enhancement (see Figure 1) projected on a gray matter surface. The time point where the MMN enhancement (measured at FCz) was the most pronounced for the two words (lakki 156 ms, lakko 144 ms, time difference n.s.) were chosen for this analysis, because the SNRs were maximal at these time points and the source estimates therefore led to the most robust results. The estimated sources of the MMN enhancement for the word lakko were strong in both hemispheres, but strongest in the left hemisphere.
temporo-parieto-occipital areas. In contrast, the MMN enhancement elicited by the word lakki was estimated to be primarily due to a set of right-hemispheric parieto-occipital current sources, with additional weaker frontal and occipital sources in the left hemisphere.

Discussion

Following up on earlier studies (Korpilahti et al., 2001; Pulvermüller, Kujala, et al., 2001; Shtyrov & Pulvermüller, 2002), the present data further established that the MMN elicited by spoken words is larger than that elicited by comparable pseudowords. The new result presented here is that the difference between the MMNs to words and pseudowords, that is, the word-related MMN enhancement, exhibited differential topographies for the two individual words under study. We suggest that the word-related MMN enhancement reflects the activation of memory traces for spoken words, and that the present topographical difference in the MMN enhancements between the words can be attributed to the activation of large ensembles of neurons with distinct distributions over the cortex. Thus, neuronal ensembles with different cortical topographies that process relevant information about the words under study could explain the topographical differences in the word-related MMN enhancements observed.

Although the present results indicate that individual word stimuli can elicit different topographical patterns of scalp-recorded ERPs, we do not wish to state that noninvasive neurophysiological recordings with EEG or MEG necessarily distinguish between each and every word pair. Although artificial neural networks can contribute to the classification of the physiological signatures of individual words, not only on the basis of averaged scalp potentials obtained from single subjects (Suppes, Lu, & Han, 1997), but also using single traces of word-evoked MEG signals (Assadollahi & Pulvermüller, 2001b), such classification is far from being error free. Because the classification performance of the network is sometimes above chance, there must be specific information in the single-subject word-evoked potential, and even in the single EEG or MEG trace obtained from individual trials. Still, the claim that every word has its specific cortical EEG signature would, at present, clearly be an overstatement. Most studies have focused on comparing sets of semantically and grammatically very different word categories, reporting ERP differences between abstract and concrete words (Kounios & Holcomb, 1994), nouns and verbs (Pulvermüller, Lutzenberger, & Preissl, 1999), or verbs referring to actions performed with different body parts (Pulvermüller, Hummel, & Härlé, 2001). Conclusions are therefore possible on differences, at the neural level, between word groups that clearly differ in their semantic, syntactic, or lexical properties. The present data now show that neurophysiological differences can even arise between two individual words that clearly fall into different categories. It is but one possibility that these differences reflect the underlying memory traces for words realized as large neuronal ensembles consisting of several thousands up to a million nerve cells. There is reason to assume that scalp-recorded ERPs have the resolving power to accomplish detecting such memory traces if the activation of the neurons included in the large neuronal ensemble occurs near simultaneously (for a discussion, see Pulvermüller, 1999).

The minimum-norm current estimates of the cortical sources underlying the MMN enhancements for words provided additional support for the differential activation of the cortical generators by the two words used. One should, however, avoid overinterpreting the localization suggested by the present analysis. Because there is no unique solution to the Inverse Problem associated with determining the cortical sources from the scalp topography (Hämäläinen, Hari, Ilmoniemi, Knuutila,
Word-specific cortical activity

versus 54 per million for the words Niemikorpi, & Sulkala, 1979), we found word frequencies of 7.
frequency count of Finnish words (Saukkonen, Haipus, & Lounasmaa, 1993; von Helmholtz, 1853), we can only make educated guesses on the basis of these techniques. Still, the differences in scalp topographies between MMN enhancements elicited by two different words prove that these individual lexical items have distinct neurophysiological correlates.

The question where the generators differentiating between words and pseudowords are localized can tentatively be answered as follows. A bilateral though left-hemispherically dominant temporo-parieto-occipital set of generators accounts for the MMN enhancement for the word lakko, whereas the word lukki primarily activated widespread generators in the right hemisphere. These specific generators were activated by the words in addition to the known sources in perisylvian language areas activated by words and pseudowords alike (Pulvermüller, Kujala, et al., 2001). Thus, generators located outside the left-hemispheric core language areas of Broca and Wernicke appear to contribute to the word-related MMN enhancement. This is consistent with the postulate that words are represented in the brain by distributed neuron webs linking phonological information mostly stored in the left-hemispheric language areas to semantic information involving additional cortical areas in both hemispheres (Pulvermüller, 1999). Any two words differ in their physical acoustic make-up. Therefore, differences in brain responses to words can, in principle, be due to these physical differences. For this reason, the experiment was performed with physically identical syllables that were, in one condition, part of words and, in the other condition, pseudowords. The control condition using meaningless pseudoword contexts provided an estimate of the changes of brain responses due to the physical stimulus features. When subtracting the MMN response to the syllables in pseudoword context from that to word-context syllables, the between-word differences in cortical activity patterns became significant. This shows that there are differences in brain activity to words that cannot be explained by physical differences in the acoustic signal. Nor are these neurophysiological differences between words easy to explain by phonological processes. The sequences of language sounds presented in the experiment only included prototypical language sounds of the participants’ mother tongue, Finnish, and all phoneme sequences followed the phonotactic rules of this language. The syllable stimuli that elicited different brain activity were identical sound sequences. The differences in the MMN topography are therefore unlikely to reflect acoustic or phonological properties of the presented spoken words.

One may ask whether the present differential brain responses to two individual words may reflect lexical stimulus properties, the properties of the stored word representation, such as, the frequency with which they are used and heard in everyday language. The words clearly differed in their standardized lexical frequency, which gives an estimate of the frequency with which they are being used by the speakers of the language. In a frequency count of Finnish words (Saukkonen, Haipus, Niemikorpi, & Sulkala, 1979), we found word frequencies of 7 versus 54 per million for the words lukki and lakko, respectively. Thus, one could try to attribute the widespread MMN elicited by lakko to its more frequent use revealed by language statistics. On the basis of earlier research, however, it does not seem likely that the frequency of a word affects the topography of the brain response. Earlier studies (e.g., Polich & Donchin, 1988; Rugg, 1990) revealed more positive-going event-related potentials (ERPs) with higher word frequencies, which was observed for ERP components with longer latencies, in the range of the N400 and P600 components. Furthermore, a recent study (Assadollahi & Pulvermüller, 2001a) also found smaller amplitudes of the early (latency as short as 100 ms) neuromagnetic responses to words with high frequency as compared with infrequent words. However, again, word frequency did not affect the topography of the event-related response. Therefore, we consider it unlikely that the topographical differences of the MMN enhancement seen for the two words resulted from their different word frequencies.

As a further possibility, word meaning, semantics, might underlie the neurophysiological difference between the two words. Several earlier studies report that words with different meanings can elicit ERPs with distinct topographies (e.g., Kiefer, 2001; Kounios & Holcomb, 1994; Pulvermüller et al., 2001; Skrandies, 1998) and, further, that specific cortical areas change their activity with the meaning of the words under processing (e.g., Martin, Wiggs, Ungerleider, & Haxby, 1996; Perani et al., 1999). We therefore consider semantic properties a possible cause of the present between-word differences in the cortical topography of the MMN.

In summary, it seems unlikely that the phonetic or phonological differences between the stimulus words could explain the different topographies of the MMN enhancements. Further, an explanation in terms of the lexical factor word frequency lacks support from the literature. In contrast, a semantic explanation appears feasible.

The temporal dynamics of the MMN enhancement for words may be of theoretical interest. Modular models of language processing postulate a staged or cascaded access to the different types of linguistic information in word perception and comprehension. Accordingly, a word would first be physically analyzed. Then, its phonological pattern would be extracted, which would be followed by lexical access, the lookup of the word form in a mental dictionary. Finally, semantic information associated with the word would be processed. In contrast to these modular theories, it was suggested (Marslen-Wilson & Tyler, 1975), on the basis of behavioral investigation, that phonological, lexical, and semantic information about a word is accessed near simultaneously as soon as the information in the sensory input allows for word identification. The present data speak in favor of the latter view. The ERP differences between the individual critical syllables, [ki] versus [ko], appeared in the same interval as the differences between the word and pseudoword contexts, and these, in turn, were present simultaneously with the differences in the topographies of the MMN enhancements between the two words. Whereas physical stimulus analysis and linguistic processing may be serial (Assadollahi & Pulvermüller, 2001a; 2003; Rinne et al., 1999; Tiitinen, Sivonen, Alku, Virtanen, & Naatanen, 1999), the present physiological data indicate that the linguistic processes of access to phonological and lexical, and possibly also semantic, information about a word occur nearly simultaneously in the brain (Pulvermüller, 2001). The activation of the memory traces for specific spoken words in the brain starts as early as ~100–150 ms after the information in the input is sufficient for word recognition.

Conclusions

The mismatch negativity, an indicator of experience-dependent memory traces in the brain, was enhanced when syllables were parts of words compared with the same syllables presented in pseudoword contexts. This MMN enhancement to words exhi-
bited different topographies for two individual words, thus proving distinct neurophysiological correlates of these words. The distinct word-related MMN enhancements could be related to the activation of memory traces of individual spoken words that differ in their cortical topography. The word-specific neuronal memory traces may start to become active as soon as ~100 ms after the information in the acoustic input allows for unambiguously identifying a word.

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