

# Neuromagnetic Evidence for the Timing of Lexical Activation: An MEG Component Sensitive to Phonotactic Probability but Not to Neighborhood Density

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Evidence from electrophysiological measures such as ERPs (event-related potentials) and MEG (magnetoencephalography) suggest that the first evoked brain response component sensitive to stimulus properties affecting reaction times in word recognition tasks occurs at 300–400 ms. The present study used the stimulus manipulation of Vitevich and Luce (1999) to investigate whether the M350, an MEG response component peaking at 300–400 ms, reflects lexical or postlexical processing. Stimuli were simultaneously varied in phonotactic probability, which facilitates lexical activation, and in phonological neighborhood density, which inhibits the lexical decision process. The present results indicate that the M350 shows facilitation by phonotactic probability rather than inhibition by neighborhood density. Thus the M350 cannot be a postlexical component. © 2002 Elsevier Science (USA)

*Key Words:* MEG; lexical decision; lexical access; phonotactic probability; neighborhood effects; N400; M350.

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## INTRODUCTION

Despite numerous reaction time (RT) and neuroimaging studies on word recognition, the timing of automatic lexical activation remains controversial. Since reaction times offer only one measure for the multiple mental operations between stimulus onset and response, they are a priori limited in their potential to determine the timing of specific cognitive processes. Behavioral studies have, however, been valuable in categorizing various effects as either lexical or postlexical (see, e.g., discussion in Bradley & Forster, 1987; Forster, 1989, p. 77; and Taft, 1991, pp. 28–32). This makes them an important background for electrophysiological investigations of lexical access, which do provide the additional dependent variables necessary for studying the timing of mental processes in detail. The millisecond-by-millisecond temporal resolution of techniques such as EEG (electroencephalography) and MEG (magnetoencephalography) allows one to search for response components whose properties

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reflect understood effects on RTs. If there is evidence that a given RT effect reflects some stage of lexical processing, e.g., spreading activation of lexical entries or selection of the “winning” candidate (Marslen-Wilson, 1989), and if a response component that shows a parallel effect is identified, it is reasonable to hypothesize that the component indexes the same process to which the RT effect is attributed.

To date, electrophysiological research on lexical processing has centered around the N400 event-related potential (ERP) (Kutas & Hillyard, 1980), which is a response component elicited by all wordlike stimuli (Bentin, McCarthy, & Wood, 1985) and modulated by many of the same stimulus properties that affect RTs. The cognitive process underlying the N400 component has, however, been subject to much debate. Interpretations vary from automatic spreading activation (Van Petten & Kutas, 1991; Fischler & Raney, 1989; Kutas & Hillyard, 1989; Besson & Kutas, 1992) to a high-level “integrative” process (Rugg, 1990; Rugg, Furda, & Lorist, 1988). The main criticism against automatic activation interpretations of the N400 component has been failed attempts to modulate N400 amplitudes with semantic priming in a masked priming paradigm even though robust RT priming is obtained under such conditions (Brown & Hagoort, 1993; Neville, Pratarelli, & Forster, 1989). Significantly, however, two recent studies have succeeded in eliciting semantic priming effects on the N400 even in the masked priming paradigm (Deacon, Hewitt, Yang, & Nagata, 2000; Kiefer & Spitzer, 2000), which strongly supports automatic accounts of the N400 and poses a problem for postlexical interpretations.

So far electrophysiological studies of lexical processing have mainly attempted to correlate effects on event-related response components with effects on reaction times, and the methods for determining which cognitive process a given component indexes have been borrowed directly from behavioral studies. For example, N400 interpretations have been based entirely on whether N400 effects require an SOA of a certain length (Besson & Kutas, 1992; Boddy, 1986; Kiefer & Spitzer, 2000), recognition of the prime (Brown & Hagoort, 1993; Neville et al., 1989; Deacon et al., 2000; Kiefer & Spitzer, 2000), or a certain type of task (e.g., Kutas & Hillyard, 1989). The fine temporal resolution of electrophysiological techniques, however, opens up the possibility for a different approach to the mapping between response components and cognitive processes. Specifically, these techniques permit the simultaneous varying of stimuli along several dimensions affecting distinct levels of processing. One can then study the effects of the different stimulus properties independently of each other. Thus, for example, if stimulus property A has a facilitatory effect on lexical access and stimulus property B an inhibitory effect on postlexical processing, we can determine whether a given response component reflects pre- or postaccess processing by testing whether it shows facilitation or inhibition for a stimulus that has both A and B. The advantages of this type of approach are clear. First, a priming paradigm is not required (unlike in SOA manipulations and masking), which makes it possible to study the effects of variables that are intrinsic to the stimulus (such as frequency). Second, task manipulations are avoided, which obviates the need for detailed models of the tasks involved.

The present study varied stimuli along two different dimensions affecting distinct levels of processing to investigate the time course of lexical processing in MEG. MEG differs from EEG in that it measures the magnetic fields, instead of electric potentials, generated by postsynaptic currents in nerve cells. Unlike electric potentials, magnetic fields are not distorted by the skull. Therefore, localization of the currents underlying the activity measured outside the head is much easier in MEG than in EEG. (For a review of magnetoencephalography, see Hämäläinen, Hari, Ilmoniemi, Knuutila, & Lounasmaa, 1993.)

The specific goal of the present study was to determine whether the M350 MEG

response component reflects automatic lexical activation or subsequent processing. The M350 is a response component in the left temporal cortex peaking at 300–450 ms after the visual presentation of a word or a pronounceable nonword, i.e., slightly earlier than the N400 ERP. M350 latencies and/or amplitudes have been shown to parallel RTs in being sensitive to repetition (Sekiguchi, Koyama, & Kakigi, 2000; Pylkkänen, Stringfellow, Flagg, & Marantz, 2000), frequency (Embick, Hackl, Schaeffer, Kelepir, & Marantz, 2001), and cloze probability (Helenius, Salmelin, Service, & Connolly, 1998, 1999). The cognitive level reflected by the M350 has, however, not yet been directly addressed, the results cited above being compatible both with lexical and postlexical interpretations. For example, M350 latencies could be decreased for frequent and for repeated words because the M350 indexes lexical access, which is facilitated by high frequency and repetition. Alternatively, M350 latencies could show these effects because the latencies of some earlier response do. In other words, it is possible that the studies cited above did not identify a lexical activation component, but rather a postlexical component that only appears to be modulated by stimulus properties affecting lexical activation because the latencies of some earlier response, unidentified in these studies, are. Such secondary effects were found, for example, for developmental dyslexics, who showed a delay in N400-type activity likely attributable to an earlier abnormality (Helenius et al., 1999).

To test the predictions of the lexical and postlexical hypotheses of the M350, we investigated M350 latencies and RTs in a situation where automatic lexical activation is facilitated while postlexical processing is slowed down. To construct such a situation, we based our study on previous results by Vitevich and colleagues (Vitevich & Luce, 1998, 1999; Vitevich, Luce, Charles-Luce, & Kemmerer, 1997), who report task-dependent effects of phonotactic probability (i.e., how frequent the sounds and sound sequences in the word are) and phonological neighborhood density (i.e., how many similar sounding words there are to a stimulus in the language) on RTs in spoken word recognition. Vitevich and Luce show that nonword stimuli with high phonotactic probability are responded to faster than low probability nonwords in tasks such as the same–different task or the speeded single-word shadowing task. In the lexical decision task, however, this facilitatory effect disappears and high probability nonwords are responded to *more slowly* than low probability nonwords. This effect is due to the fact that high probability nonwords necessarily resemble, and hence activate, more actual lexical entries than low probability nonwords and the more competing lexical entries a nonword activates, the longer the time needed for determining that none of them can be selected as the “winner.” Thus, in tasks where the subject is forced to attempt selection, such as the lexical decision task, the competition induced by the dense similarity neighborhood has an inhibitory effect which overrides the earlier facilitation gained by high phonotactic probability. Unsurprisingly, competition effects are task-dependent only for nonwords: for words, selection is automatic and therefore reaction times to words are slowed down by competition both in lexical decision and in the “low-level” same–different and shadowing tasks (Vitevich & Luce, 1999). Thus, for words, the facilitatory effect of phonotactic probability cannot be observed behaviorally in any task in which the subject recognizes the stimulus.

The present study aimed to investigate whether the M350 would show facilitatory effects of phonotactic probability in the lexical decision task, where reaction times to both words and nonwords fail to show such an effect. Specifically, we hypothesized that if the M350 reflects automatic spreading activation prior to selection, stimuli which are high both in phonotactic probability and in phonological neighborhood density should elicit decreased M350 latencies due to facilitation by phonotactic probability and increased RTs due to competition. Such a result would clearly distinguish between lexical and postlexical interpretations of the M350: If the component was

associated with postlexical processing, it should show increased rather than decreased latencies in this type of manipulation.

## MATERIALS AND METHODS

### *Participants*

Eleven right-handed, English-speaking adults with normal or corrected-to-normal vision gave their informed consent to participate in the experiment (three females and eight males ranging in age from 24 to 32, mean age 27). Participants were all graduate students or employees at the Massachusetts Institute of Technology and were paid \$20 for their participation.

### *Stimuli*

Our materials were based on the spoken stimuli of Vitevich and Luce (1999), which were converted into orthographic stimuli to permit direct comparison of the brain responses to those elicited in previous M350 studies from our laboratory. Participants were presented with four categories of 70 stimuli: (i) high probability/density words (BELL, LINE), (ii) low probability/density words (PAGE, DISH), (iii) high probability/density nonwords (MIDE, PAKE), and (iv) low probability/density nonwords (JIZE, YUSH). All stimuli were monosyllabic and the high and the low probability/density words were matched for frequency (Kučera & Francis, 1967). The mean lengths of the different stimulus categories were 3.61 letters (high probability/density words), 3.94 letters (low probability/density words), 4.31 letters (high probability/density nonwords), and 4.7 letters (low probability/density nonwords). Thus, even though the auditory stimuli of Vitevich and Luce (1999) were matched for duration, the written versions of the low probability items were longer than those of the high probability stimuli [words:  $t(1, 138) = -3.28, p < .01$ ; nonwords:  $t(1, 138) = -4.48, p < .001$ ]. Therefore the materials were slightly biased against our hypothesis, i.e., increased RTs for high probability stimuli. The words were the 140 word stimuli used in Vitevich and Luce (1999; Appendix 1) and the 140 nonwords were selected from their list of 240 monosyllabic nonword stimuli in such a way as to achieve the best possible length match between the high and the low probability/density items. The appropriate spellings for the nonwords were determined by having three native speakers of English spell the spoken nonwords of Vitevich and Luce. If a speaker considered several spellings possible, they were asked to judge which one was the most "English like." The list of orthographic nonwords arrived at in this way was further tested with three different native speakers who were asked to read the items out loud. The pronunciations of all three speakers matched those used in Vitevich and Luce (1999).

The measures for phonotactic probability were positional segment frequency and biphone frequency. Similarity neighborhoods were frequency-weighted and phonological neighbors were defined as any item that could be converted to the stimulus by one phoneme substitution, deletion, or addition in any position (for details, see Vitevich & Luce, 1999).

To assess whether the high and the low probability stimuli differed in orthographic probability, which could be a potential confound, total bigram frequency was calculated for each stimulus (Solso & Juel, 1980) and entered into a 2 (Lexicality)  $\times$  2 (Probability/density) ANOVA. High probability stimuli did not differ reliably from low probability stimuli in orthographic probability nor did words differ from nonwords (both  $F_s < 1$ ). Also, there was no reliable interaction between lexicality and probability [ $F(1, 276) = 2.64, p > .1$ ].

### *Procedure*

Stimuli were presented using PsyScope 1.2.5 (Cohen, MacWhinney, Flatt, & Provost, 1993) in a randomized order in two blocks of 140 stimuli. A pause between blocks allowed participants to rest. Each trial consisted of a fixation point (+) which lasted for a 1000 ms followed by the presentation of the stimulus which disappeared at the button press response. The task was continuous lexical decision. In the first block participants made word decisions with the index finger of their left hand and nonword decisions with the middle finger; in the second block the fingers were reversed. The intertrial interval randomly varied between 500 and 1500 ms.

During the experiment, participants lay in a dimly lit magnetically shielded room in the KIT/MIT MEG laboratory. Stimuli were projected onto a screen on the ceiling of the magnetically shielded room approximately 120 cm above the participant's eyes. All letter string stimuli were centered on the fixation point, and were presented in the Courier font. Stimuli subtended approximately 1.2° of visual angle

vertically and 4.8, 6.4, 8.0, or 9.6° of visual angle horizontally (for three-, four-, five-, and six-letter stimuli, respectively).

Neuromagnetic fields were recorded using an axial gradiometer whole-head system (Kanazawa Institute of Technology, Japan). Measurements from the first nine participants were performed using a 64-channel system; 29 additional sensors were then added, offering 93 channels for the last two participants.

For the purposes of source localization, small electromagnetic coils were attached to the participant's head prior to the MEG measurement. Using a 3D digitizer, the locations of these coils were calculated with respect to three anatomical landmarks (the nasion and points just anterior to the participant's ear canals), which established the head coordinate system for each participant. Once the participant was positioned in the MEG instrument, the coils were also localized with respect to the sensors. Thus MEG measurements could be transformed into each participant's individual head coordinate system. Since structural MRIs were not available for any of the participants, the shape of each participant's head was recorded during digitization. The head shapes were later used to estimate a maximally appropriate spherical head model for each participant for the purposes of source localization.

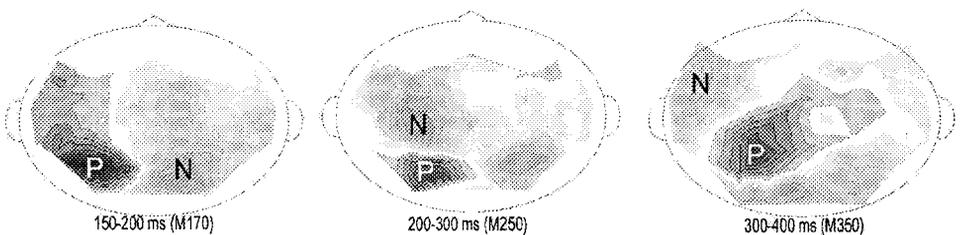
Data were sampled at 500 Hz, with acquisition between 1 and 200 Hz. The recording for each participant lasted approximately 20 min. After the presentation of the word stimuli, responses to 1-kHz tones were recorded in order to identify the participant's auditory cortex, which was used as a functional landmark in source localization. Raw data were noise-reduced to remove environmental artifacts. For the first nine participants' data, external sources of noise were removed via signal-space projection; for the last two participants' data, external noise sources were removed using the Continuously Adjusted Least-Squares Method (CALM; Adachi, Shimogawara, Higuchi, Haruta, & Ochiai, 2001). Responses to stimuli were averaged by stimulus condition. In the averaging, further artifact rejection was performed by excluding all responses to stimuli which contained signals exceeding  $\pm 2.5$  pT in amplitude (if any had survived the noise-reduction algorithms). Following averaging, data were baseline adjusted using a 100 ms prestimulus interval and low pass filtered under 30 Hz.

### Data Analysis

Reaction times were calculated from the onset of the visual stimulus. Incorrect trials and RTs deviating over 3 SD from the mean for the particular participant were excluded from the analysis. This resulted in the exclusion of 5.6% of the data. The same trials were also rejected from the MEG averages. Only MEG averages consisting of more than 50 trials after artifact and error rejection were accepted for further analysis. All participants and all conditions survived this criterion.

In the analysis of the MEG data, averaged signals were first visually inspected to identify dipolar field distributions that showed consistency across experimental conditions and across participants. Such distributions were identified in three time windows: 140–220 ms (M170), 200–300 ms (M250), and 300–420 ms (M350), yielding response components compatible with activity reported in previous MEG studies of visual word recognition (Koyama, Kakigi, Hoshiyama, & Kitamura, 1998; Koyama, Kakigi, & Hoshiyama, 1998; Kuriki, Takeuchi, & Hirata, 1998; Kuriki, Hirata, Fujimaki, & Kobayashi, 1996; Sekiguchi et al., 2000; Helenius et al., 1998, 1999; Pylkkänen et al., 2000; Embick et al., 2001).

As shown in Fig. 1, the M170 was associated with a bilateral field distribution over the occipitotemporal sensors; the M250 with a left-lateralized dipolar pattern oriented along the lateral axis with a posterior positive field (i.e., magnetic flux emerging from the brain) and an anterior negative field (i.e., magnetic flux reentering the brain); and the M350 with a left-lateralized dipolar distribution oriented along the anterior–posterior axis, with the positive field on the right and the negative field on the left. The amplitudes and latencies of these components were recorded by calculating the root mean square (RMS) field



**FIG. 1.** The magnetic field distributions of the M170, M250, and M350 response components at the time of component peak in one representative participant. The letter P indicates the positive field (i.e., the magnetic field emerging from the brain) and the letter N the negative field (i.e., the magnetic field entering the brain) of the magnetic field around the current source.

strength from the sensors that covered the field pattern of the particular component. In some participants, the M250 and/or the M350 showed a bilateral distribution; however, since this did not hold consistently across participants, RMS for these components was calculated from left-hemisphere sensors only. The sensors used for the RMS analysis were selected on the basis of the condition that showed the clearest dipolar distribution and held constant across conditions within a subject. The number of sensors used for RMS analysis varied from 10 to 18 for data collected using the 64 channels and from 22 to 38 for data collected using the 93 channels. In some conditions for some participants, the M350 distribution showed two prominent peaks instead of one. In these cases only the first peak was classified as an M350 and entered into comparisons with M350s that only peaked once. The second peaks of those M350 distributions that peaked twice were considered post-M350 activity and are discussed in the corresponding results section.

One participant did not show the criterial M350 field pattern in any condition and therefore no M350 response latencies could be recorded from this participant. Since the aim of this study was to examine the latencies of the M350 in relation to RTs, data from this participant were excluded from all analyses.

## RESULTS

### Reaction Times

ANOVAs [2 (Lexicality)  $\times$  2 (Probability/density)] were performed for reaction times and for accuracy. As Fig. 2 shows, the behavioral results of Vitevich and Luce (1999) were replicated: high probability/density stimuli were responded to more slowly than low probability stimuli. An ANOVA on reaction times showed a significant overall effect of probability/density [ $F(1, 9) = 103.41, p < .0001$ ], which according to planned comparisons (Scheffe *t* test) was reliable both for words and for nonwords. High probability/density words ( $\bar{x} = 650.6$ ) were responded to more slowly than low probability/density words ( $\bar{x} = 625; p < .01$ ) and high probability/density nonwords ( $\bar{x} = 711.1$ ) more slowly than low probability/density nonwords ( $\bar{x} = 664.1, p < .0005$ ). The main effect of lexicality was also reliable, RTs to nonwords being longer than RTs to words [ $F(1, 9) = 26.81, p < .001$ ]. The interaction between probability/density and lexicality approached significance [ $F(1, 9) = 4.27, p = .07$ ], the slowdown for high probability/density nonwords being more than the slowdown for the high probability/density words.

Analyses of accuracy, where incorrect trials and trials deviating over 3 SD from the mean for the particular participant were counted as errors, revealed that low probability stimuli were responded to more accurately than high probability/density stimuli [ $F(1, 9) = 21.57, p < .005$ ]. Planned comparisons showed this effect to be reliable both for words ( $p < .05$ ) and for nonwords ( $p < .005$ ). This, again, replicates Vite-

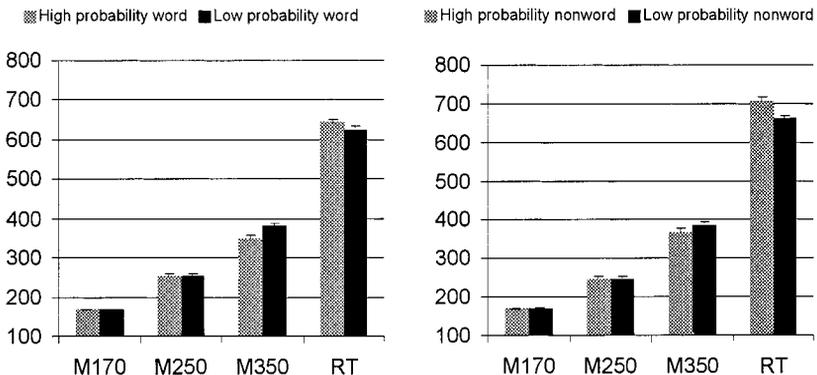
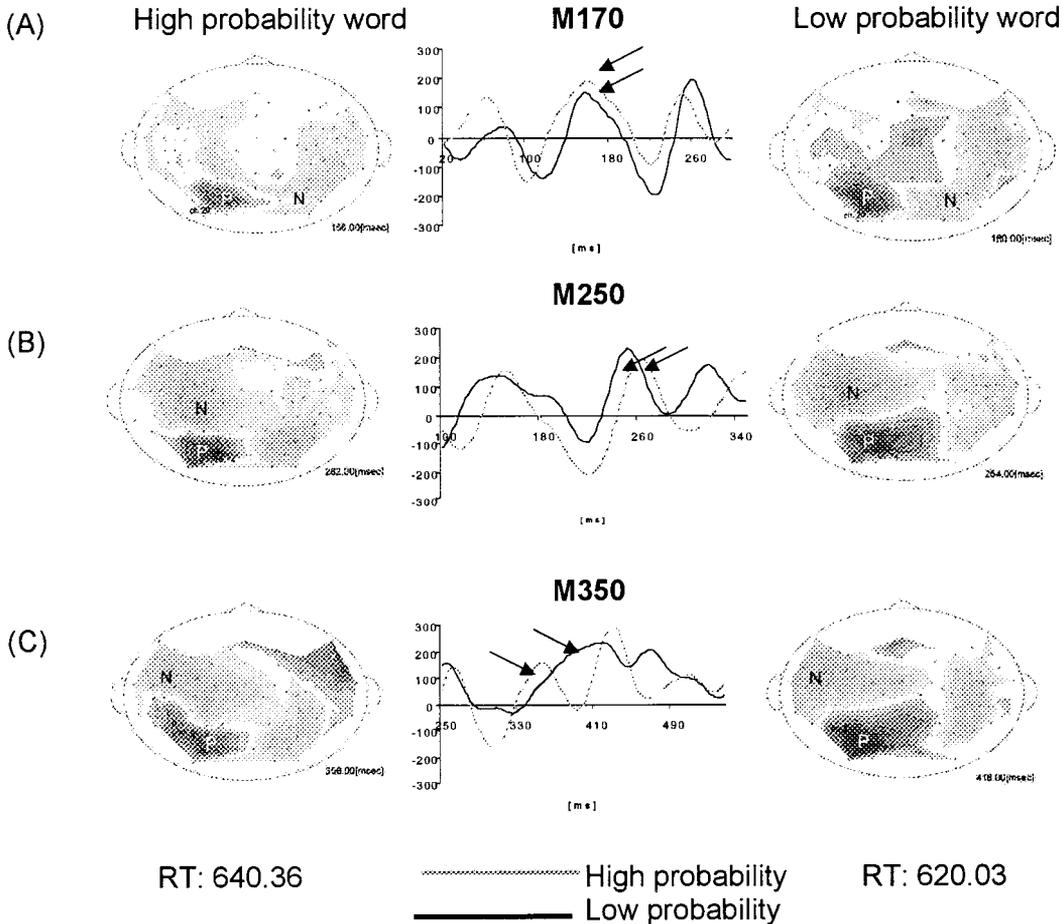


FIG. 2. The mean reaction times and MEG component latencies for high and low probability/density words and nonwords ( $n = 10$ ).

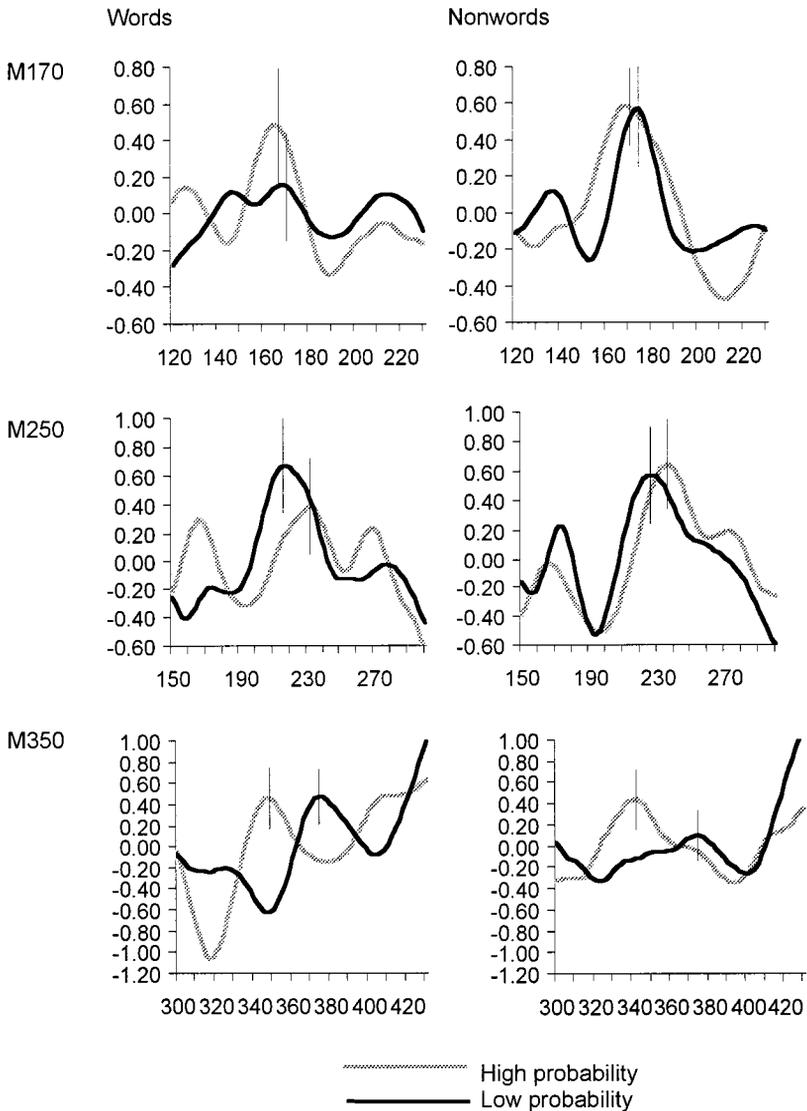
vich and Luce's findings. For accuracy, there was no interaction between lexicality and probability/density [ $F(1, 9) < 1$ ].

### M350

Figure 3 illustrates the averaged MEG responses to high and low probability/density words for a representative participant. Figure 4 shows the grand average standardized RMS waveforms for the M170, M250, and M350 components elicited by high and low probability/density words and nonwords. Counter to the predictions of post-lexical interpretations of the M350 component, M350 latencies were shorter, rather than longer, for high probability/density stimuli than for low probability/density stimuli. Thus M350 latencies showed facilitation by high phonotactic probability/density while response times showed the opposite effect. An ANOVA on M350 latencies (two factors: lexicality and probability/density) revealed a main effect of probability/density [ $F(1, 9) = 19.18, p < .005$ ] which planned comparisons showed to be reliable both for words and for nonwords: high probability/density words elicited shorter



**FIG. 3.** Averaged MEG responses from one participant to high and low probability/density words showing activity from the positive maximum of the M170 (A), the M250 (B), and the M350 (C) response components. The middle column overlays responses to high and low probability/density stimuli, the arrows indicating component peaks. The contour maps on the left and right show the magnetic field distributions for the two stimulus categories at the times of component peaks.



**FIG. 4.** Grand average standardized RMS waveforms for the M170, M250, and M350 response components ( $n = 10$ ).

M350 latencies ( $\bar{x} = 349.4$  ms) than low probability/density words ( $\bar{x} = 382.2$  ms;  $p < .005$ ) and high probability/density nonwords shorter latencies ( $\bar{x} = 368$  ms) than low probability/density words ( $\bar{x} = 385.6$  ms;  $p < .05$ ) (Fig. 2). While the difference between high and low probability stimuli was larger for words (32.8 ms) than for nonwords (17.6 ms), the interaction between lexicality and probability/density was not significant [ $F(1, 9) = 1.1963$ ,  $p = .2$ ].

The M350 latency ANOVA also showed an effect of lexicality, M350 latencies for words ( $\bar{x} = 365.8$  ms) being shorter than those for nonwords ( $\bar{x} = 376.8$  ms) although this effect did not quite reach reliability [ $F(1, 9) = 4.87$ ,  $p = .05$ ].

M350 amplitudes (two factors: lexicality and probability/density) were not modulated by probability/density [ $F(1, 9) = 2.04$ ,  $p = .18$ ] although a trend was observed for words, high probability/density stimuli eliciting decreased M350 amplitudes ( $p = .09$ ).

### *M250 and M170*

In contrast to the M350, neither phonotactic probability/density nor lexicality modulated the latencies of the earlier M250 component (both  $F_s < 1$ ). As regards amplitude, while no significant overall effect of probability/density was found [ $F(1, 9) = 2.57, p = .14$ ], pairwise planned comparisons showed that M250 amplitudes of high probability words were smaller than those of low probability words ( $p < .05$ ).

The M170 component was not sensitive to phonotactic probability/density nor to lexicality either in amplitude or in latency (all  $p$ 's  $> .1$ ).

### *Later Activity*

An obvious question raised by the facilitation seen on the M350 is whether a cortical correlate of the inhibitory effect seen on reaction times could be identified as well. To this end, the magnetic fields following the M350 distribution were inspected to see whether dipolar field patterns showing consistency across participants could be identified for RMS analysis, but the patterns were too variable to justify this.

However, a possible neural correlate of the RT competition effect was identified in M350 activity itself. As mentioned above, the M350 distribution was sometimes associated with two prominent peaks instead of one. An ANOVA on the number of peaks associated with the M350 revealed that high probability stimuli elicited two M350 peaks more often than low probability stimuli [ $F(1, 9) = 6, p < .05$ ]. Thus it is possible that intense competition is indexed by a second M350 peak, while no such peak is elicited when the similarity neighborhood is sparse.

### *M250 and M350 Source Locations*

Finally, in order to take advantage of the spatial accuracy of MEG, the locations of the currents underlying the M250 and M350 response components were estimated using equivalent current dipoles (ECD). The shape of the conducting volume was modeled as a sphere defined on the basis of each participant's head shape data. ECDs were estimated at the times of RMS peaks, using the same sensors as in the RMS analysis. In addition to M250 and M350 localizations, the left-hemisphere source of the auditory M100 component was estimated from each participant's responses to 1 kHz tones to serve as an anatomical landmark. A dipole was considered reliable if it explained  $\geq 80\%$  of the activity in the sensors used for the localization and if it was within 4 cm from the surface of the participant's skull. The latter criterion was used as MEG is best suited for measuring activity in fissural cortex (Hämäläinen et al., 1993), its spatial resolution decreasing considerably for deeper structures.

Figure 5 illustrates typical spatial locations of dipoles explaining the M100, M250, and M350 magnetic field distributions for a single participant: M250 sources are posterior to both M100 and M350 sources, which localize within 2 cm of each other. The M350 source location conforms to previous findings that show activity 300–400 ms post presentation of visual word stimuli localizing to the vicinity of the auditory cortex in superior and middle temporal gyri (Sekiguchi et al., 2000; Helenius et al., 1998, 1999).<sup>1</sup>

<sup>1</sup> An ANOVA on the  $x$ ,  $y$ , and  $z$  coordinates of all M100 ( $n = 7$ ), M250 ( $n = 20$ ), and M350 ( $n = 12$ ) sources meeting our criteria revealed the pattern shown in Fig. 5 to be reliable. In the head-coordinate system, the  $x$  axis runs between the peripheral fiducials (i.e., points right in front of the left and the right ears), the  $y$  axis from the nasion to the back of the head perpendicular to the  $x$  axis, and the  $z$  axis perpendicular both to the  $x$  and the  $y$  axes. The effect of Component was significant both for the  $x$  [ $F(1, 28) = 7.88, p < .005$ ] and the  $y$  [ $F(1, 28) = 11.21, p < .0005$ ] axes but not for the  $z$  axis [ $F(1, 28) = 1.18, p = .3$ ]. Planned pairwise comparisons revealed M250 sources to be more posterior

TABLE 1  
Summary of Pairwise Comparisons of the Mean Coordinates of  
All Reliable M100, M250, and M350 Source Localizations

	M100	M250	Difference	<i>p</i>
<i>x</i>	55.9	38.5	17.4	<.005
<i>y</i>	6.5	29	-22.5	<.01
<i>z</i>	56.4	59.1	-2.7	.9
	M100	M350	Difference	<i>p</i>
<i>x</i>	55.9	48.7	7.2	.4
<i>y</i>	6.5	3.5	3	.9
<i>z</i>	56.1	49.8	6.3	.7
	M250	M350	Difference	<i>p</i>
<i>x</i>	38.5	48.7	-10.2	.7
<i>y</i>	29	3.5	25.5	<.005
<i>z</i>	59.1	49.8	9.3	.3

*Note.* The *x* axis runs between the peripheral fiducials (i.e., points right in front of the left and the right ears), the *y* axis from the nasion to the back of the head perpendicular to the *x* axis, and the *z* axis perpendicular both to the *x* and the *y* axes.

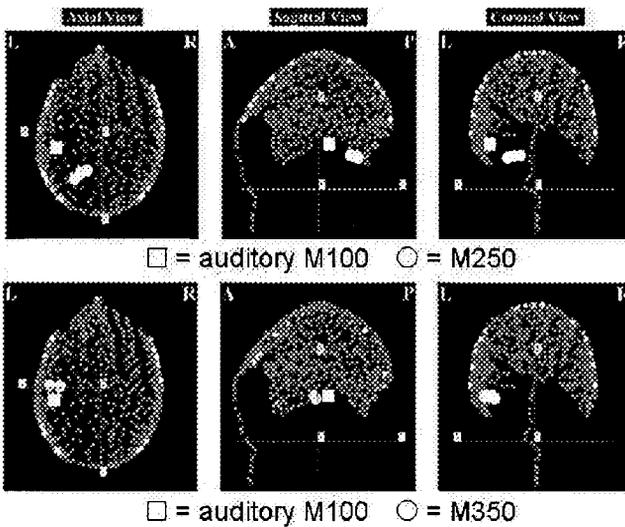


FIG. 5. Source localizations meeting reliability criteria for the M250 (above) and M350 (below) components for one representative participant. The square indicates the location of the auditory M100 response and the circles responses to word stimuli.

(i.e., larger *y* value) than both M100 ( $p < .005$ ) and M350 sources ( $p < .005$ ), which between themselves did not differ in posteriority. M250 sources were also found to be less lateral (i.e., smaller *x* value) than M100 ( $p < .005$ ) and M350 sources, although the latter difference did not reach significance ( $p = .06$ ). M100 and M350 sources did not differ reliably in laterality. The results of the pairwise comparisons are summarized in Table 1.

## DISCUSSION

The present study manipulated two highly correlated stimulus variables, phonotactic probability and phonological neighborhood density, to shed light on the cognitive process underlying the M350 evoked response component. Our results indicate that M350 latencies vary independently from reaction times when stimuli are simultaneously varied along a dimension that affects lexical activation and a dimension that affects selection/decision. This result can only be explained by lexical accounts of the M350; if the M350 reflected postlexical processing, its latency should reflect inhibitory effects of neighborhood density rather than earlier facilitatory effects of phonotactic probability, given the behavioral evidence of Vitevich and Luce (1999). The present study, together with previous results showing that the M350 is the earliest component whose latency and/or amplitude is sensitive to repetition (Sekiguchi et al., 2000; Pylkkänen et al., 2000), to cloze probability (Helenius et al., 1998, 1999) and, in particular, to lexical frequency (Embick et al., 2001) strongly support the hypothesis that the M350 indexes automatic spreading activation across lexical entries.

In addition to the facilitatory effect on M350 latencies, phonotactic probability modulated the amplitudes of the earlier M250 component, although this was reliable only for words. Thus, assuming that decreased latencies and amplitudes both index facilitation, the latency difference seen in the M350 could at least partially be a secondary effect of the earlier amplitude difference. Such a relationship between M250 amplitudes and M350 latencies is in particular suggested by the fact that facilitation for high probability stimuli was larger for words than for nonwords both in M250 amplitudes and in M350 latencies. Whether high phonotactic probability facilitates initial lexical activation, which we hypothesize to be indexed by the first peak of the M350 distribution or some earlier process is irrelevant for our present conclusion (for discussion on cognitive models of the role of phonotactic probability, see Vitevich & Luce 1999). What is important is that high probability/density stimuli do not elicit increased M350 latencies, which they would if the component indexed a process whose timing is sensitive to competition, i.e., selection/decision or any subsequent process leading up to RT.

With respect to the relationship between the M350 and the N400 ERP, the present results are consistent with recent findings by Deacon et al. (2000) and Kiefer and Spitzer (2000), who report N400 priming effects in masked priming, indicating that the N400 cannot be a postrecognition component. Since the M350 peaks somewhat earlier than the N400, these masked priming results predict that the M350 should not be a postlexical component either, which is supported by the present results. However, the M350 peak reported here and the N400 ERP are unlikely to correspond directly, given their latency difference. Rather, the M350 more plausibly corresponds only to an early component of the rather long N400 wave; the M350 distribution never persists for longer than 150 ms while the N400 can persist for up to 500 ms. Another candidate for an electric correspondent of the M350 is negativities in the 250 to 350 ms range found to be sensitive to lexical factors in various ERP word-class studies (e.g., King & Kutas, 1998; Brown, Hagoort, & ter Keurs, 1999).

As regards neuromagnetic predictors of the competition effect on response times, M350 distributions elicited by high probability stimuli were associated with two prominent peaks more often than those elicited by low probability stimuli. This suggests that the number of times the M350 distribution peaks correlates with the amount of competition in a similarity neighborhood. The present results thus support the following hypothesis concerning the dissociation between activation and competition: Activation is indexed by the first peak of the M350 distribution and competition by the presence of a second peak with the same distribution.

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