

Recognizing Spoken Words: Neural Mechanisms of Inhibition

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Abstract

A fundamental issue in spoken word recognition is the mechanism by which one word representation among tens of thousands gets identified as the optimal match to a speech signal. For correct identification, erroneous hypotheses must be inhibited. Competition among lexical hypotheses is evidenced by delayed reaction times to words that are preceded by similar sounding words. However, these inhibitory effects are ambiguous as to the processing level inhibited. We used magnetoencephalography (MEG) to investigate the neural mechanisms of inhibition and found that the cognitive level of similarity-induced inhibition depends on the type of phonological similarity that holds between the correct and incorrect lexical hypotheses: onset-matching similarity leads to inhibited activation of the target representation while non-onset-matching similarity leads to inhibited recognition. Our results suggest that the speech recognition system has a mechanism of complete suppression of activation targeting mismatching representations that initially constitute perfect matches to an incoming signal.

Spoken word recognition involves matching incoming acoustic information to a single lexical representation in a person's mental dictionary. People's vocabularies generally consist of tens of thousands of entries. In contrast, most human languages have only 30 to 40 distinctive sound units, i.e. phonemes¹. It is thus obvious that the sound representations of words are not highly distinctive. Nevertheless, humans are able to perform this computationally demanding matching task effortlessly and extremely rapidly. The average speaking rate in continuous speech has been estimated to be around five syllables per second². Given that many words consist of only one syllable, this implies it must not take humans more than a few hundred milliseconds to map acoustic input to lexical representations.

Although we recognize spoken words extremely rapidly, there is abundant evidence that any given speech signal activates a wide range of lexical representations that are, in fact, incorrect matches to the input³⁻⁹. For example, an input such as *beaker* activates not only the lexical representation BEAKER but also representations that match in onset with the input, such as BEETLE, and representations that rhyme with the input, such as SPEAKER⁸. Clearly, the more erroneous hypotheses the speech processor entertains, the more taxing the recognition process becomes. Given the evidence that large-scale excitation of erroneous hypotheses does occur, a key problem in word recognition research is the mechanism by which incorrect lexical hypotheses are inhibited from identification.

In this study we used magnetoencephalography (MEG) to investigate the neural bases of behavioural inhibitory effects in word recognition. In behavioural paradigms, inhibition is evidenced by delayed reaction times to words that are similar to a previously heard word^{5, 9}. Most current models agree that such inhibitory effects arise from competition among activated lexical representations^{10, 11, 12}. However, these reaction time effects are ambiguous as to the processing stage that is affected by

competition. One possible source of similarity-induced behavioural delay is inhibited target activation (henceforth *the inhibited activation hypothesis* (Fig 1A)). On this hypothesis, an input such as *spinach* suppresses an incorrect match such as SPIN under its resting level of activation, which should lead to delayed activation of SPIN on a subsequent trial. Alternatively, the cognitive source of the behavioural delay could be in inhibited target *recognition* (henceforth *the inhibited recognition hypothesis* (Fig 1B)). In other words, even if target activation is not delayed, target recognition could still be delayed due to intense competition between the target representation and a previously activated, highly similar, representation. Thus, although behavioural reaction time data can tell us that inhibition of incorrect matches occurs, behavioural measures alone are limited in their potential to elucidate the precise mechanisms by which the speech processor rejects erroneous lexical hypotheses.

Here we took advantage of the millisecond-resolution of magnetoencephalography (MEG) to distinguish between the inhibited activation and recognition hypotheses. Even though the two hypotheses predict similar delayed behavioural responses, they make distinct predictions at an earlier processing stage, i.e. at the stage of initial lexical activation. The inhibited activation hypothesis quite obviously predicts delayed target activation. In contrast, the inhibited recognition hypothesis predicts facilitated lexical activation. This is because the inhibited recognition hypothesis does not assume suppression of incorrect matches under their resting level of activation. Without suppression, the activation level of incorrect matches should remain elevated for some time after stimulus presentation, which should consequently lead to faster activation for such an item if it is presented as the target before this residual activation decays.

We have previously identified an MEG correlate of initial lexical activation, precisely the processing stage at which the inhibited activation and recognition hypotheses make distinct predictions. This makes MEG particularly well-suited for distinguishing between the two hypotheses. Our prior results suggest that the initial excitation of the mental lexicon is indexed by the M350, an MEG component generated in the left superior temporal cortex^{13, 14} peaking at approximately 350ms post-stimulus onset (Fig. 2). We have found the M350 to be the first MEG component that is sensitive to lexical frequency¹⁵ but not to the level of competition between lexical hypotheses¹³. The only interpretation of the M350 that explains this pattern of results is that the M350 indexes initial excitation of lexical representations, prior to competition. Thus the M350 offers a promising tool for investigating the nature of inhibition in word recognition. If inhibition is suppression of competitors (inhibited activation hypothesis), M350 latencies should be increased for phonologically related targets. In contrast, if inhibition effects arise purely from post activation competition (inhibited recognition hypothesis), M350 latencies of phonologically related targets should show facilitation (Fig. 1).

In order to test these predictions, the MEG responses of twenty-three healthy native English speakers were recorded while they made word/nonword decisions to visual targets preceded by phonologically related auditory primes. Previous MEG studies on lexical processing have concentrated on visual word recognition¹³⁻¹⁸. Our crossmodal paradigm allowed us to investigate inhibition in the processing of spoken primes by measuring the effects of inhibition on well-established response components elicited by visual targets.

The effects of two different types of phonological similarity were investigated. In one type the prime and target matched in onset, as in *spinach-spin*, while in the other the prime and target were phonologically similar without onset-matching, as in *teacher-reach*. These experimental conditions were contrasted to control trials with the same

targets and unrelated primes (e.g. *muffler-spin* and *teacher-reach*) (see Methods: Stimuli).

In addition to the M350, the amplitudes and latencies of two earlier components elicited by visual word stimuli were examined. The first, the M170, follows the visual M100 and peaks at 150-220ms^{15, 13, 19, 20}. The second component, the M250, peaks at 200-300ms and has a left-hemisphere source which is somewhat more posterior than the source of the M350^{15, 13}. In previous studies, the M170 and the M250 have not shown sensitivity to lexical factors^{15, 13}; if the M350 indexes initial activation of lexical entries, neither the M170 nor the M250 should vary across conditions in this experiment either. Out of the twenty-three subjects that participated in the study, two subjects were excluded from the analysis since no M350 component could be identified from their data.

Results

The predicted behavioural inhibition was obtained both for onset-matching and for non-onset-matching similarity. Response times to targets of phonologically related non-onset-matching pairs (*teacher-reach*, $\bar{x} = 685$) were significantly slower than responses to their unrelated controls (*ocean-reach*, $\bar{x} = 666$), $t(20) = 2.25$, $p < 0.05$. Similarly, targets of onset-matching pairs (*spinach-spin*, $\bar{x} = 705$) were responded to more slowly than targets of their unrelated controls (*muffler-spin*, $\bar{x} = 672$), $t(20) = 2.76$, $p < 0.05$. The phonologically related conditions also elicited more incorrect or timed-out responses than their unrelated controls. 9.2% of onset-matching targets were responded to incorrectly or too slowly while their unrelated controls elicited an error-rate of only 6.8%, $t(20) = 2.02$, $p < 0.05$. Similarly, phonologically related non-onset-matching targets elicited more incorrect or timed-out responses (5.2%) than their unrelated controls (3.9%), $t(20) = -1.78$, $p < 0.05$.

In the MEG data, neither the latencies nor the amplitudes of the early M170 and M250 components were modulated by phonological similarity, as predicted. The M350, on the other hand, did show sensitivity to phonological relatedness. Surprisingly, however, even though onset-matching and non-onset-matching phonological relatedness elicited a similar type of behavioural delay, these two types of phonological similarity had strikingly different effects on the M350, as shown by the individual subject data in Fig.3A and by the grand-averaged data in Fig.3B. The M350 latencies of targets in *teacher-reach* type pairs ($\bar{x}=332.8$) were shorter than their controls' ($\bar{x}=345.7$, $t(20) = -3.33$, $p < 0.005$), supporting the inhibited recognition hypothesis. In contrast, the M350s elicited by the targets of *spinach-spin* type pairs ($\bar{x} = 349.7$) were delayed in comparison to their controls' ($\bar{x}=334.6$), $t(20) = 2.8$, $p < 0.05$), a pattern conforming to the inhibited activation hypothesis. Amplitude results patterned similarly: the amplitudes of the M350s elicited by phonologically related non-onset-matching targets were smaller than their controls ($t(20) = -2.6$, $p < 0.05$), while the amplitudes of the M350s elicited by onset-matching targets were larger than their controls, although the latter effect was only marginal ($t(20) = 2$, $p = 0.06$).

Discussion

Our results reveal that the cognitive source of similarity-induced behavioural inhibition in word recognition depends on the type of phonological similarity that holds between the competing lexical hypotheses. *Spinach-spin* type prime-target pairs were associated with increased M350 latencies and amplitudes, indicating that target activation was inhibited. The opposite effect was found for targets in the *teacher-reach* condition: M350 latencies and amplitudes were decreased, which suggests facilitated activation. Clearly then, the behavioural delay of targets in *teacher-reach* type pairs

must have originated after initial activation, i.e., in the competition between the highly active prime representation TEACHER and the target representation REACH, leading to inhibited recognition of REACH.

Since in most current models of word recognition a speech signal activates numerous lexical representations that bear some resemblance to the acoustic input, the main computational problem in word recognition research is how to limit the search space. Our results provide neurophysiological evidence that, as the speech signal unfolds, some incorrect matches to the input undergo complete suppression of activation, thus eliminating them from the recognition process. This result then raises the intriguing question of precisely which erroneous lexical hypotheses undergo this type of suppression. Does the input *spinach* trigger the suppression of SPIN because SPIN matches the input at the onset, or because SPIN is actually an embedded word in *spinach*, neither of which is the case for *teacher* and REACH? The present results underdetermine this, but only the former hypothesis is compatible with recent behavioural results showing that in French, final embedded words (such as CAR in *branCARD*) can semantically prime related words while onset-embedded words (such as CAR in *CARgo*) cannot²¹. These results are straightforwardly predicted by the proposal that the activation of onset-matching incorrect hypotheses is suppressed, while the activation of non-onset-matching competitors is not. Thus, assuming that word recognition mechanisms are the same for English and French speakers, these semantic priming data provide an argument for the hypothesis that in the present study, *spinach* suppresses SPIN because SPIN is an onset-matching incorrect hypothesis, not because SPIN is a simple word embedded in *spinach*.

The claim that word onsets play a special role in lexical access is not new; rather, it was the very essence of the first influential model of spoken word recognition, the Cohort-model²². In the Cohort model, only representations that matched the beginning

of the acoustic input were activated. Then, when mismatch occurred, a candidate was dropped out of this onset-matching “cohort” of candidates and recognition occurred at the point when only one representation was left in the cohort. The Cohort-model was computationally attractive as it had a clear mechanism of delimiting the search space. However, it did not successfully model the impressive capacity of the human speech recognition system to recover from mispronunciations and other disruptions in the input. For example, while humans effortlessly recover from word-initial mispronunciations such as *shigarette*, the Cohort-model was unable to consider CIGARETTE a possible match to *shigarette*. To address this, alternative models have been proposed where the speech signal continuously activates lexical representations and where recognition is determined not by a sequential narrowing down of the cohort but by over-all goodness of fit^{11, 12}.

The present study clearly supports continuous activation as M350 priming was obtained for the non-onset-matching prime-target pairs. However, our results also show an asymmetry between the activation of onset-matching and non-onset-matching representations: onset-matching hypotheses that later on mismatch with the input are suppressed below their resting level, while non-onset-matching representations remain active for at least a few hundred milliseconds. This result is relevant to a recent revision to the Cohort-model, according to which non-onset-matching representations are activated, but only for repair purposes²³. In other words, the mispronounced *potato* is hypothesized to activate *tomato* but only to the extent that it is possible for the listener to recognize, in second-pass processing, what the intended word should be. The actual set of lexical hypotheses is still assumed to be strictly onset-based. Thus it is possible that in the present study the suppression of SPIN by *spinach* is a reflection of SPIN being an actual hypothesis for the acoustic input *spinach*, and the lack of suppression of REACH by *teacher* an indication that REACH was never a hypothesis for *teacher*, but was rather only activated by *teacher* in case this acoustic input would have turned out to

be a mispronunciation of REACH. Clearly, the present study is only an initial step towards understanding how the brain rapidly maps acoustic input to stored mental representations. However, the neuromagnetic evidence obtained here about the processing of erroneous lexical hypotheses offers a promising starting point for using brain measurements not only to investigate the timing and anatomical location of mental events such as word recognition, but also to elucidate the actual mechanisms underlying human cognition.

Methods

Subjects. Twenty-three right-handed, English-speaking adults with normal or corrected-to-normal vision gave their informed consent to participate in the experiment (7 females and 16 males). Participants were all students or employees at the Massachusetts Institute of Technology and were paid \$30 for their participation.

Stimuli. The present experimental conditions were part of a larger study that investigated the effects of phonological, semantic and morphological relatedness on MEG and behavioural lexical decision responses. The stimulus materials were derived from the cross-modal behavioural study of L. Gonnerman²⁴, although phonologically related, non-onset-matching word and non-word targets were added to her original materials in order to block a response strategy where subjects tended to judge the target as a word every time the target constituted the first syllable of the prime. All auditory primes were prepared by Gonnerman.

Four categories of word stimuli served to test the inhibited recognition and activation hypotheses: phonologically related onset-matching pairs (*spinach-spin*, n=28) with their controls (*muffler-spin*, n=28) and phonologically related non-onset-matching pairs (*teacher-reach*, n=56) with their controls (*ocean-reach*, n=56). The number of

non-onset-matching pairs was larger than the number of onset-matching pairs as their original purpose was to balance the design, rather than to function as test stimuli. This imbalance should not affect the conclusions of this study as the two conditions are not compared directly in the statistical analysis.

In addition to these materials, participants made lexical decisions to 290 other word-targets, which served to test other hypotheses. Of these additional targets, 84 were phonologically related to their primes. This relationship was either a fully transparent morphological relation (*teacher-teach*, $n=28$), a somewhat opaque morphological relation (*dresser-dress*, $n=28$) or a pseudo-affix relation (*corner-corn*, $n=28$). The rest of the word targets were phonologically unrelated. Nonword stimuli consisted of 170 targets of which 50 were onset-matching to their primes (*lecture-lect*), 50 were phonologically related without onset-matching (*mundane-tund*) and 70 were phonologically unrelated (*biscuit-cobe*). To balance the ratio of words to nonwords, all the nonword stimuli were presented twice. As a result, the overall experiment consisted of 458 word targets and 340 non-word targets. The percentage of phonologically related items was somewhat lower for words (36%) than for non-words (58%), thus biasing the materials somewhat towards ‘no’ responses for phonologically related targets. But it is unlikely that subjects engaged in this type of a strategy as both the *teacher-teach* and *dresser-dress* types of similarity elicited faster, rather than slower, reaction times than their unrelated controls, although for the latter the difference was only numerical (teacher-teach: $\bar{x} = 619$, ocean-teach: $\bar{x} = 656$, $t(20) = -2.8$, $p < 0.05$); dresser-dress: $\bar{x} = 639$, soda-dress: $\bar{x} = 651$, $t(20) = -1.5$, $p = 0.14$).

Procedure. During the experiment, participants lay in a dimly lit magnetically shielded room in the KIT/MIT MEG laboratory while auditory prime and visual target stimuli were presented to them. Participants were instructed to make word/nonword decisions as quickly and as accurately as possible to the visual targets only. In addition to the

lexical decision task, participants were occasionally asked to pronounce out loud the last auditory stimulus they had heard. This guaranteed that the subjects were paying attention to the auditory primes even though no task was performed on them. Auditory primes were presented binaurally via airtube earphones, and visual targets were projected onto a ground glass screen. The visual targets were presented immediately at the offset of the auditory primes (i.e. SOA = prime duration) and they remained visible until the subjects' button press response. Target stimuli were presented in nonproportional Courier font, and subtended approximately 1.2° of visual angle vertically and 1.2° per character horizontally (the length of target stimuli varied from 4 to 10 letters).

MEG recording. Neuromagnetic fields were recorded using a 93-channel axial gradiometer whole-head system (Kanazawa Institute of Technology, Kanazawa, Japan). Data were acquired in a band between 1Hz and 200Hz, at a 500Hz sampling frequency. External sources of noise were removed online using an active compensation coil system (Vacuumshmelze, Hanau, Germany). Offline noise reduction using three orthogonally-oriented reference sensors was also performed (CALM algorithm)²⁵.

Data analysis. For the averaging of the MEG data, an epoch length of 900ms, plus a 100ms baseline period, was used. Trials where the subject responded incorrectly or responded more than 3SD faster or slower than his/her mean were eliminated from both from MEG averages and the analysis of the behavioural data. This resulted in the rejection of 5.7 % of the trials. Artefact rejection excluded all trials to stimuli that contained signals exceeding $\pm 2\text{pT}$ in amplitude and resulted in the exclusion of an additional 7.5 % of the trials. The MEG averages for the *spinach-spin* condition and its unrelated control contained on the average 24 trials (SD = 2) and the MEG averages for the *teacher-reach* condition and its unrelated control contained on the average 49 trials,

(SD = 3). Averaged files were low-pass filtered at 30Hz, and baseline adjusted using the 100ms pre-stimulus interval.

The latencies and amplitudes of three MEG components elicited by visual word stimuli were examined: the M170 (150-200ms), the M250 (200-300ms) and the M350 (300-420ms). For all three components, peak latencies and amplitudes were determined individually for each participant by calculating the root mean square (RMS) field strength of the sensors that covered the appropriate field pattern (Fig 2). The characteristic field distributions of the M170, M250, and M350 components are shown in Fig. 2. RMS for the M350 was calculated from all 44 left hemisphere sensors (excluding midline sensors) as its distribution often covers all of the left hemisphere. The source of the M250 is somewhat more posterior than the source of the M350; therefore RMS for the M250 was taken from a set of left hemisphere sensors that excluded the most anterior ones (n=21). Finally, the occipitotemporal distribution of the M170 was captured by including all occipitotemporal sensors (n=37) (bilaterally arrayed) in the RMS. The sensors used for RMS were held constant across experimental conditions and participants. Two participants' data did not show the characteristic distribution of the M350; these participants were excluded from all analyses.

The M350 distribution often persists for over a 100 ms and commonly peaks more than once. Our previous results indicate that it is the first peak of the M350 distribution that is sensitive to lexical factors but insensitive to competition¹³, not the onset of the distribution, or the largest peak. Therefore, the present study focussed on the first M350 peak only, since, given our prior results, this was the dependent measure that correlated with initial lexical activation.

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Competing interests statement

The authors declare that they have no competing financial interests.

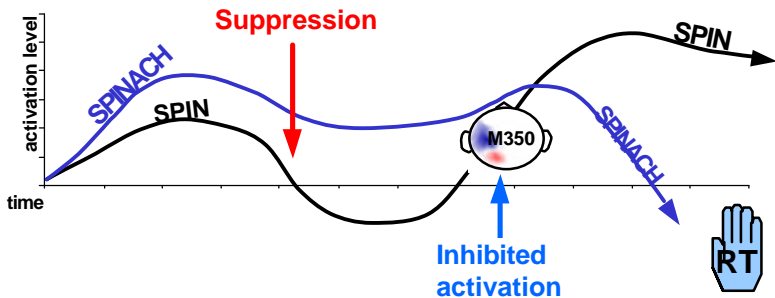
Fig. 1. Changes in lexical activation levels predicted by the inhibited activation and inhibited recognition hypotheses. Inhibited activation attributes behavioural inhibitory effects to suppression of lexical activation **(A)** while the inhibited recognition hypothesis locates the source of response delay in intense competition in target recognition **(B)**. The two hypotheses make different predictions about the timing of target activation, measured here with the M350.

Fig. 2. Magnetic field distributions corresponding to the M170, M250 and M350 response components.

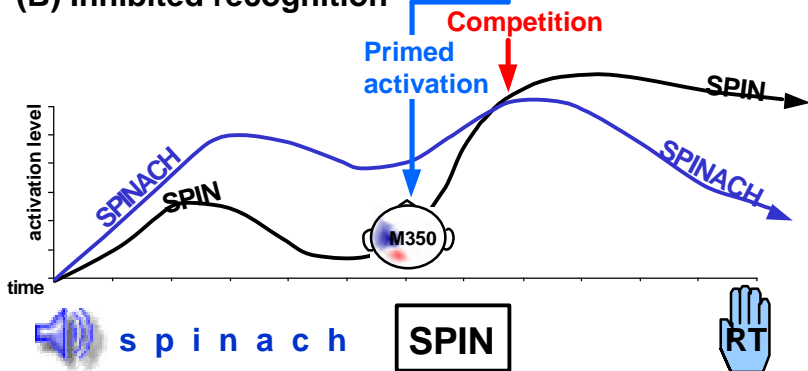
Fig. 3. (A) Averaged MEG responses from one representative subject illustrating that the M350 of onset-matching targets peaks later than the M350 of their unrelated controls, while the M350 of non-onset-matching targets peaks earlier than the M350 of their unrelated controls. Activity on the left shows the time course of activation of the M350 positive maximum, indicated by a square on the contour map on the right (here the same sensor also yields the positive maximum of the M170). The contour maps on the right show the distribution of the magnetic field at the times of M350 maxima for all stimulus categories. **(B)** Grandaverage waveforms for the onset-matching and non-onset-matching comparisons ($n = 21$). The maximum sensor of the M350 outgoing field is shown. Due to variance across subjects in M350 latency, only the differences in M350 amplitude are visible in these grandaverages. The small latency differences between the test and control conditions can only be detected by inspecting individual subject data (Fig. 3A).

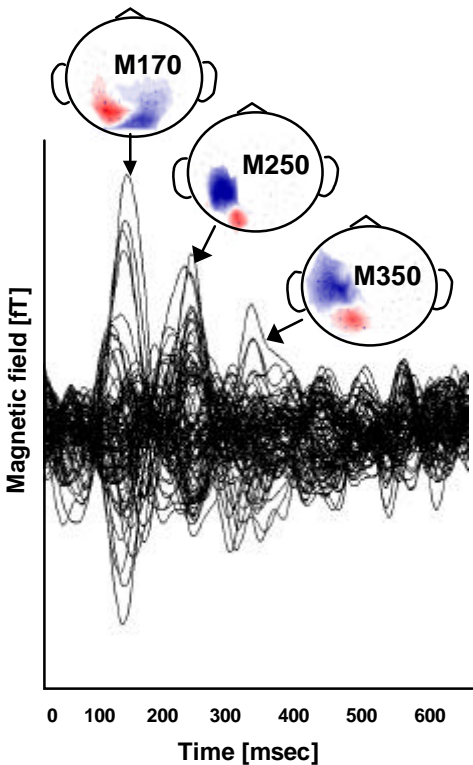
Fig. 4. Priming in reaction time (RT), M350 latency and M350 amplitude for onset-matching (*spinach-spin*) and non-onset-matching (*teacher-reach*) targets as compared to their unrelated controls.

(A) Inhibited activation



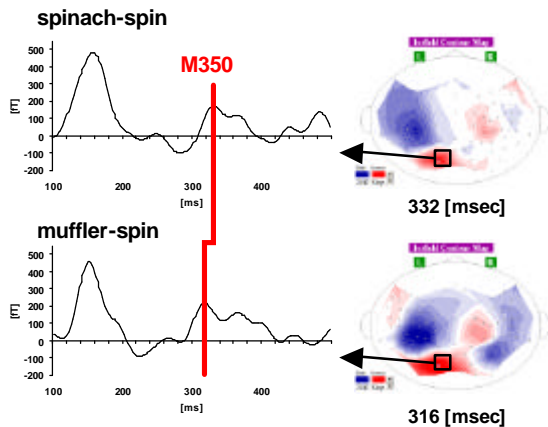
(B) Inhibited recognition





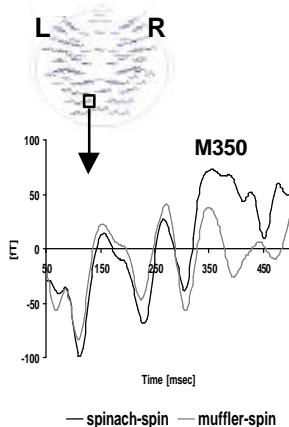
(A) S1

Onset-matching

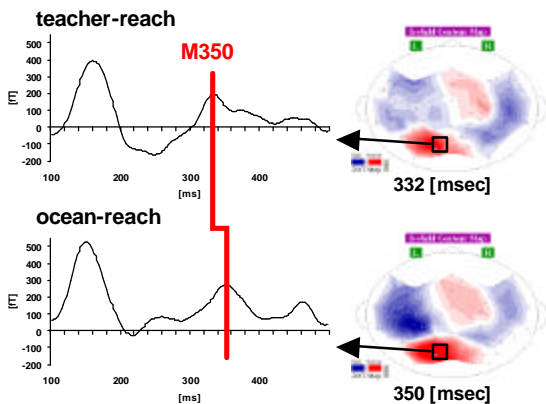


(B) $N = 21$

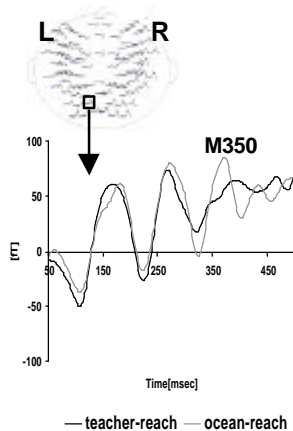
Onset-matching



Non-onset-matching



Non-onset-matching



□ RT ■ M350-latency ■ M350-amplitude

