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MMN and attention: Competition for deviance detection

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Abstract

We addressed the question of whether the mismatch negativity (MMN) event-related potential reflects an attention-independent process. Previous studies have shown that the MMN response to intensity deviation was significantly reduced or even abolished when attention was highly focused on a concurrent sound channel, whereas no conclusive evidence of attentional sensitivity has been obtained for frequency deviation. We tested a new hypothesis suggesting that competition between detection of identical deviations in attended and unattended channels and the biasing of this competition induced by the subject's task account for the observed MMN effects. In a fast-paced dichotic paradigm, we set up competition for frequency MMN and removed it for intensity MMN. We found that frequency MMN was now abolished in the unattended channel, whereas the amplitude of the intensity MMN was unaffected. These results support the competition hypothesis and suggest that selective attention in and of itself does not affect the MMN. Top-down processes can determine what information reaches the deviance-detection process when changes in multiple channels vie for the same MMN resource and one of the competing changes is relevant for the subject's task.

Descriptors: Mismatch negativity, MMN, Attention, ERP, Competition, Deviance detection

The mismatch negativity (MMN) event-related brain potential (ERP) reflects a process of sensory discrimination in the auditory cortex, which is triggered by the detection of a physically deviant sound (e.g., changes in frequency or intensity) within a sequence of repetitive sounds. The question of whether MMN reflects an attention-independent process has not been resolved because attention effects on MMN have been shown to occur under some, but not all, experimental manipulations (Alain & Woods, 1997; Dittmann-Balcar, Thienel, & Schall, 1999; Näätänen, Paavilainen, Tiitinen, Jiang, & Alho, 1993; Paavilainen, Tiitinen, Alho, & Näätänen, 1993; Szymanski, Yund, & Woods, 1999; Trejo, Ryan-Jones, & Kramer, 1995; Woldorff, Hackley & Hillyard, 1991; Woldorff, Hillyard, Gallen, Hampson, & Bloom, 1998). Because MMN is presently the best tool for studying early auditory processing, it is important to understand under what circumstances attention may affect the MMN process.

Näätänen (for a review, see Näätänen, 1990) originally proposed that the MMN was unaffected by attention based on evidence suggesting that the mismatch process between the neural trace of the standard (the repetitive sound) and the incoming deviant sound, which generates the MMN response, was unaffected by various attentional manipulations. This notion was challenged by Woldorff et al. (1991), who hypothesized that the MMN-generating process could be influenced by highly focused auditory selective attention. To test this, they used a dichotic listening paradigm with a rapid stimulus presentation rate and made the difference between the standard and deviant tones difficult to detect ($\sim$70% hit rate). Attended tones were made distinct from the unattended tones by setting a large frequency separation between them. The amplitude of the MMN elicited by the deviant lower-intensity tones in the unattended channel was highly attenuated compared to the MMN elicited by the same lower-intensity deviants in the attended channel. A subsequent study has also shown attention effects on intensity MMN using higher-intensity deviants (Szymanski et al., 1999; cf. Alain & Woods, 1997). Woldorff et al. interpreted their results in terms of the early selection theory of attention, suggesting that the auditory information was gated even before sounds were fully analyzed, preventing further processing of the unattended sound information. Thus, the intensity MMN was attenuated because the memory traces of the partially analyzed unattended sounds were not sufficiently distinct for detecting the loudness differences between them.

Woldorff et al.'s (1991) results, however, did not clarify whether the MMN amplitude difference found between the attended and the unattended channel represented the suppression of information in the unattended channel or the enhancement of the attended difference response. An N2b component, the ERP correlate of target detection (Ritter & Ruchkin, 1992), may have

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overlapped the MMN in the attended channel (as was also the case in Trejo et al., 1995, for frequency MMN). Therefore, Näätänen et al. (1993; see also Paavilainen et al., 1993) replicated Woldorff et al.'s experiment and included a condition in which subjects read a book and were instructed to disregard the sounds. They also added frequency deviants along with the intensity deviants in both channels. Näätänen et al.'s results corroborated those of Woldorff et al. in that the MMN amplitude elicited by unattended intensity deviants in the dichotic listening condition was found to be significantly reduced compared to the amplitude of the intensity MMN elicited when subjects were attending or ignoring the stimuli. However, the amplitude of the frequency MMN was found to be *unaffected* by the direction of attention in Näätänen et al.'s study. Näätänen et al. reasoned that for the frequency MMN to be elicited, stimulus attributes must have been fully analyzed even when the auditory input was unattended. To explain the attenuation of the intensity MMN, they suggested that some part of the intensity-MMN generating system was sensitive to attentional modulation. Subsequent studies testing attention effects on MMN (Szymanski et al., 1999; Woldorff et al., 1998) confirmed these original findings. However, to date, no explanation has been given as to why attention would modulate the amplitude of some feature-deviation MMNs but not others.

In the current study, we propose an alternative hypothesis (the "competition hypothesis") that can account for the results of these previous studies without assuming inconsistent treatment of different features. The competition hypothesis suggests that whenever similar deviants occur in concurrent channels, they compete for deviance detection. In a dichotic listening situation, the competition is biased by selective attention. In the studies described above (Näätänen et al., 1993; Woldorff et al., 1991), the standard and deviant intensity values were identical in both ears. According to the competition hypothesis, the intensity deviants presented in both channels competed for deviance detection by the MMN-generating process. To perform the task, subjects had to suppress detection of intensity deviants in the unattended ear because these deviants had the same intensity as the target deviants and thus could be confused with them. Thus, target selection biased the competition for intensity-deviance detection, which resulted in the attenuation of the intensity-MMN amplitude in the unattended channel. In contrast, because the standard and deviant frequencies differed greatly across the two ears, and there were no frequency-deviant targets, there was either no competition for frequency-MMN generation or the competition was not biased by the subject's goals.

The competition hypothesis assumes that MMN generators can, at least partly, function independently from each other in the elicitation of MMNs based on violations of different feature rules. This explains why competition for MMN generation may occur when the same features vie for MMN output but not when different features do. The findings that partly different neuronal populations generate the MMNs elicited by deviations in different auditory features substantiate this assumption (for a review, see Alho, 1995).

To test the competition hypothesis, we (a) set up competition for frequency MMN by making the frequency of the standards and deviants identical in both ears and by designating attended frequency deviants as targets; and (b) removed competition for intensity MMN by having intensity deviants occur *only* in the unattended channel, and by setting different intensity levels in the two ears. Additionally, a passive condition was run in which subjects ignored the auditory stimuli altogether (reading a book). Support for the competition hypothesis would be found if the amplitude of the *frequency* MMN was attenuated in the unattended channel compared to that in the ignore condition, and the unattended *intensity* MMN had a similar amplitude as the intensity MMN obtained in the ignore condition. Thus, the competition hypothesis predicts an outcome that is separable from both the gating explanation (Woldorff et al., 1991) and the "only intensity MMN is affected by attention" explanation (Näätänen et al., 1993).

Methods

Participants

Twelve adults (4 men) with reportedly normal hearing ranging in age from 23 to 39 years ($M = 31.1$ years) with no history of neurological disorders were paid to participate in the study. Informed consent was obtained after the experimental procedures were explained to them. One participant's data was excluded due to excessive artifacts.

Stimuli and Procedures

Pure tones of 1500 Hz frequency and 30 ms duration (5 ms rise/fall times; 88% of all tones) were dichotically presented through insert earphones with a randomly varying interstimulus interval (ISI; 70–220 ms, rectangular distribution). Frequency deviants, appearing in both ears, were 1590 Hz in frequency (6% overall probability in the left ear, 3% overall probability in the right ear). The intensity of the standard- and deviant-frequency tones was 80 dB SPL in the left ear and 70 dB SPL in the right ear. Intensity deviants (3% overall probability) had the same intensity value of the sounds presented to the left ear (80 dB) and were presented to the right ear only. Intensity deviants had the same frequency value as the standards (1500 Hz). Left and right ear sounds were distributed randomly (50–50% probability) in the sound sequence.

Two conditions (ignore and attend) were conducted. First the ignore condition was run, in which participants were instructed to read a book and ignore all the sounds. After a break, participants received a short practice for the frequency-deviance detection task with only the left ear (to be attended) sounds presented. In the attend condition, sounds were presented to both ears and participants were instructed to press the key for the target, higher-pitched tones occurring in the left ear. For each condition, 8,500 stimuli were presented in 17 separately randomized blocks. An additional 1,000 stimuli were presented (in two "control" blocks) separately for each condition, in which the role of the standard and deviant intensity was exchanged (80 dB for the standard- and frequency-deviant tones in the right ear, 70 dB for right-ear intensity deviants and all left-ear tones). The purpose for this condition was to assess MMN by subtracting between responses elicited by identical tones (see also Data Analysis below).

Data Recording and Analysis

The electroencephalogram (EEG) was recorded from nine electrode sites (Fz, Cz, Pz, F3, F4, C3, C4, LM, and RM), with the common reference electrode placed on the tip of the nose. The horizontal electrooculogram (EOG) was recorded between F7 and F8 and the vertical EOG between FP1 and an electrode placed below the left eye. The EEG was digitized at a rate of 250 Hz (0.05–100 Hz) and off-line filtered (1–15 Hz). Epochs started 100 ms before and ended 500 ms after the stimulus onset. Rejection criteria excluded epochs with EEG or EOG activity exceeding $\pm 50\,\mu V$. ERPs were averaged separately for each stimulus type and condition. Difference waves for frequency deviants were calculated by subtracting the average ERP elicited by the standard tones from that elicited by the frequency-deviant tones, separately for each condition and ear. Difference waves for the intensity deviants were calculated by subtracting from the intensity-deviant (right ear only) response the ERP elicited by the same tone in the control blocks (in which this tone was the frequent one in the right ear), separately for each condition. Thus, in delineating the MMN component, responses to tones of identical intensities and, on the average, equal ISIs were subtracted. This subtraction eliminates those components that are independent of the role of the given stimulus (i.e., standard or deviant) while leaving the MMN, which is elicited only by the deviant, unchanged (Näätänen, 1992), thus avoiding any confound between the MMN response and the obligatory ERP responses associated with different tone intensities.

MMN amplitudes were measured from a 40-ms window centered on the grand-mean MMN peaks and referred to the average amplitude in the prestimulus period. Grand-mean MMN peak latencies were measured at the right mastoid (RM) because it was assumed at the mastoid leads there would not be overlap between MMN and N2b for the attended targets, because N2b does not affect the mastoid traces (Näätänen et al., 1993; Ritter & Ruchkin, 1992). The peaks for frequency MMN were 164 ms for the left attend condition, 156 ms for the left ignore condition, and 164 ms for the right ignore condition. The peak for the right intensity MMN for both the attend and ignore conditions was 120 ms. Thus, the peak MMN latencies were between 120 and 164 ms from stimulus onset and maximally 20–64 ms from the onset of the next stimulus. The shortest ISI was 70 ms, which put the onset of a sound minimally at 100 ms from the onset of the previous sound (i.e., including the 30-ms tone duration). Using the average ISI (145 ms), the onset of the next sound already followed the intensity-MMN peak latency by 50 ms and the frequency-MMN peak latency by 9 ms. Therefore, the MMN peak never overlapped with the N1 of the subsequent tones, not even at the shortest ISIs. Moreover, even the possible overlap with some midlatency components (occurring only at the shortest ISI) was controlled for by subtracting between responses obtained for the different stimulus types (the deviant and the standard or control), which were followed, on average, at the same ISI.

The latency range obtained for the ignore-condition right-ear frequency MMN (144–184 ms) was used to test whether the right-ear frequency deviants in the attend condition elicited MMN, as no negative peak was visible in the possible MMN latency range of the corresponding difference waves. The N2b and P3b amplitudes (elicited by the target left-ear frequency deviants in the attend condition) were measured at Cz and Pz, respectively, around the their respective peaks (252 ms and 464 ms).

Behavioral results were analyzed by calculating hit and false alarm rates and the reaction time (RT) of the responses to the left-ear target frequency deviants in the attend condition. Responses were considered correct if they fell between 200 and 1,300 ms from the target onset.

Three participants could not disregard the tones presented to the right (to be ignored) ear in the attend condition. This was shown by (a) elicitation of target-related ERP components (N2b-P3b) to frequency deviants occurring in the unattended ear, and (b) a considerably greater number of false alarms. Thus, the grand averages and statistical analyses include the 8 remaining participants.

Two-way repeated–measures analysis of variance (ANOVA) with factors of stimulus type (deviant vs. standard) and electrode sites (Fz, F3, F4) were used to test the elicitation of MMN separately for each deviant type, ear, and condition. To test the elicitation of N2b and P3b, factors of stimulus type (standard vs. deviant) and electrode sites (Cz, Pz, C3, and C4) were used in two-way repeated-measures ANOVAs. One-way repeated-measures ANOVAs were used to compare frontal (Fz) MMN amplitudes across conditions. Differences in scalp distribution for N2b and MMN components were assessed using two-way repeated measures ANOVA.

To statistically analyze attention effects on frequency and intensity, separate two-way repeated measures ANOVAs with factors of stimulus type (deviant vs. standard) and attentional state (reading vs. unattended vs. attended for the frequency and reading vs. unattended for the intensity) were calculated. Huyndt–Feldt correction was applied and reported when appropriate.

Results

Subjects, on average, detected 65% of the targets (1% false alarms; RT 511 ± 192 ms) in the attend condition.

Figure 1 displays the grand-averaged ERPs elicited at Fz by the deviant tones, overlain with the ERPs elicited by the corresponding standard (for intensity deviants "control") tones, separately for the attend and the ignore conditions. The difference waveforms are displayed with the frontal (Fz) responses overlain with the RM ones. The overall amplitude of the ERPs was rather small due to the rapid interstimulus interval, but the P1 and N1 waveforms elicited by the standard and deviant tones can still be clearly discerned. Attention-related N2b and P3b components can be seen in the deviant ERP response, peaking about 250 ms for N2b and at about 465 ms for P3b, *only* to the attended targets. The N2b is distinguished from MMN by its scalp topography (Novak, Ritter, & Vaughan, 1992). N2b has its maximal amplitude at centro-parietal scalp sites (Cz), whereas MMN is maximal at frontal sites (Fz). Further, the mastoid inversion distinguishes the MMN from the N2b (which does not invert in polarity at the mastoid) in the difference waveforms at Fz (see Figure 1, upper left panel). The mean amplitude of the N2b elicited by attended targets was largest at the central electrode sites (Cz, C3, C4), whereas the mean amplitude of the MMN elicited by attended targets was largest at the frontal sites (Fz, F3, F4), revealed by a significant interaction between electrode site and component, $F(5,35) = 7.65$, $p = .001$, in the current study. This difference in scalp distribution for MMN and N2b suggest that the generator sources of these components differ.

Neither the frequency nor the intensity deviants elicited P3a in the unattended channel or when ignored altogether (Figure 1, columns 2 and 3) indicating that the deviants were not salient enough to elicit an orienting response.

Attend Condition

MMN was elicited by the target left-ear frequency deviants, $F(1,7) = 6.14$, $p < .045$. Targets also elicited the N2b and P3b components, showing that many of them were consciously detected, $F(1,7) = 8.2$, $p < .02$; $F(1,7) = 15.11$, $p < .01$. No MMN was elicited by the unattended (right-ear) frequency deviants,

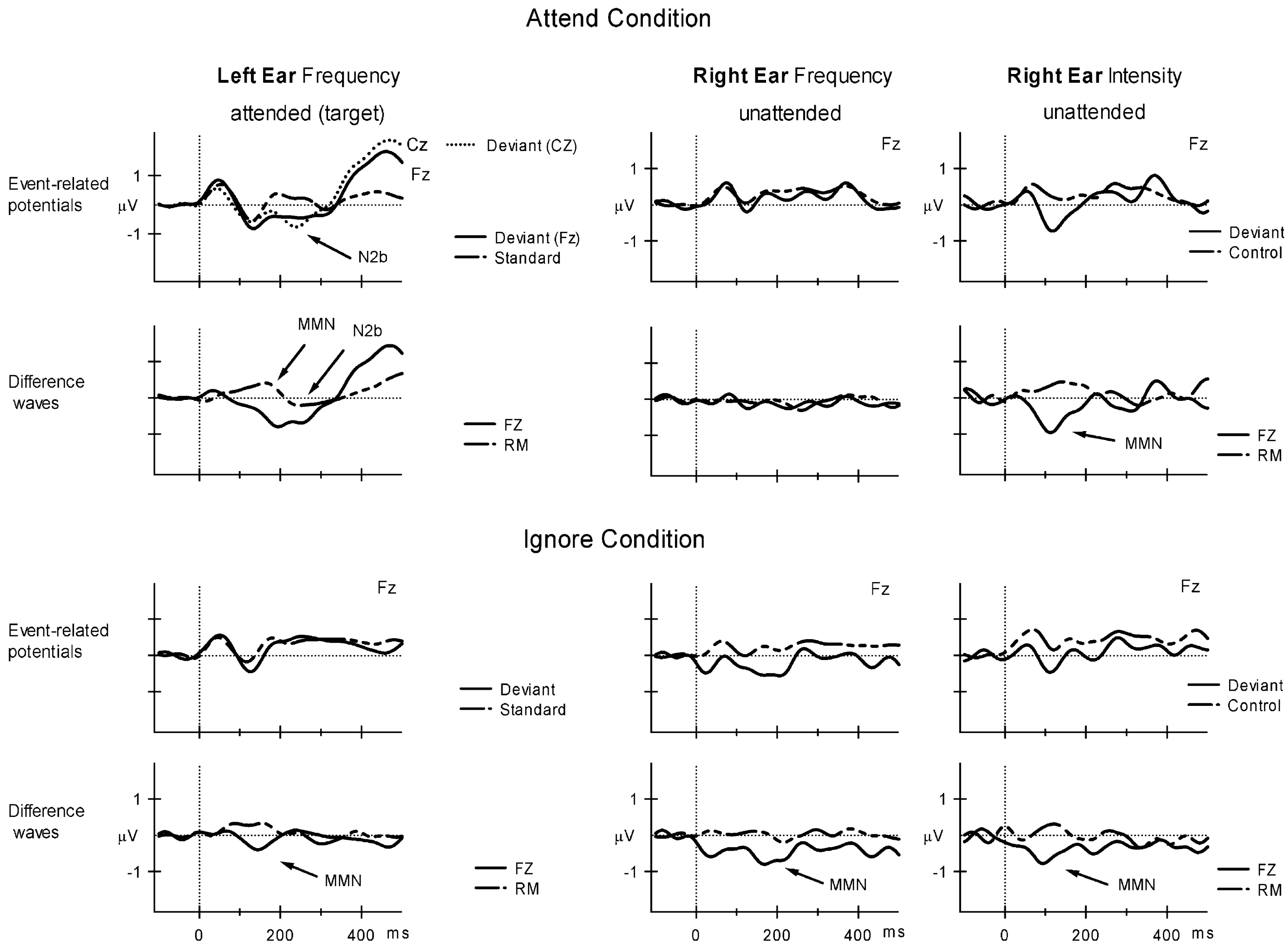

Figure 1. ERPs and difference waveforms. Grand-averaged ERPs elicited at Fz by the deviant tones (solid lines) overlain with the ERPs elicited by the corresponding standard (for intensity deviants, "control"—see Methods) tones (dashed lines) in the attend condition (left attended and right unattended ears; first row) and the ignore condition (third row). The deviant ERP response elicited at the Cz electrode is overlain with the responses to the deviant and standards to show the peak of the N2b. Arrows point to the MMN and N2b. The difference waveforms are displayed for Fz (solid lines) overlain with the right mastoid (RM; dashed lines) in the attend (second row) and ignore (fourth row) conditions.

$F(1,7) < 1$, $p > .70$, whereas it was elicited by the intensity deviants, $F(1,7) = 11.16$, $p < .015$.

Ignore Condition

MMNs were elicited by both right- and left-ear frequency deviants, $F(1,7) = 14.17$, $p < .01$ and $F(1,7) = 9.3$, $p < .02$, respectively, and also by the intensity deviants, $F(1,7) = 8.27$, $p < .025$, right ear only.

No significant difference was found between the intensity-MMN amplitudes measured in the attend and ignore conditions, $F(1,7) = 1.6$, or between the existing frequency MMN amplitudes (left-ear attend and ignore conditions and right-ear ignore condition), $F(1,7) = 2.4$.

An attention effect was found for frequency as revealed by an interaction between stimulus type and attentional state, $F(1,7) = 3.2$, $p < .05$, whereas no effect of attention was found for intensity, $F(1,7) = 1.6$, $p > .20$.

Discussion

Previous studies (Näätänen et al., 1993; Paavilainen et al., 1993; Woldorff et al., 1991, 1998) showed that highly focused attention on sounds occurring in the attended ear attenuated the amplitude of the intensity but not frequency MMN in the unattended ear. In the current study, we showed that frequency MMN may be abolished and intensity MMN amplitude unaffected by highly focused attention (with respect to a passive condition). In addition, we found MMNs of similar amplitude elicited by frequency deviants in the attended ear and in both ears when all sounds were ignored. That is, we demonstrated an effect of attention on the frequency MMN and no effect of attention on the intensity MMN. The contrast between the present and previous results was a consequence of reversing the role of frequency and intensity in the current paradigm as compared with previous studies. In previous studies, tones with a large frequency separation but identical intensity values were presented to the two ears and subjects were required to detect intensity deviants in one ear. In contrast, we presented tones with identical frequency but different intensity values to the two ears and asked subjects to detect frequency deviants in one ear.

The present (as well as those of the previous studies) results are fully compatible with the competition hypothesis. This hypothesis suggests that competition is set up by deviations occurring in more than one channel that require the same MMN resource (the same feature–specific parts of the MMN generator). If the competition is not biased, such as in our ignore condition, deviations are detected in both channels; we found similar amplitude frequency MMNs for both ears in the ignore condition. Conversely, when top–down processes bias the competition for deviance detection, which occurs when one of the competing deviants is the subject's target and the other a distractor, the processes associated with the selected deviation win out. This biasing was demonstrated in the unattended channel of our attend condition, in which the frequency MMN was abolished. Analogously, suppression of the intensity MMN was found in the unattended channels of the previous studies (Näätänen et al., 1993; Woldorff et al., 1991), in which competition and biasing was set up between intensity deviants but not frequency. Furthermore, deviations in different auditory features do not compete with each other for MMN elicitation. This was shown by the elicitation of MMN by unattended intensity deviants in the attend condition and the analogous results of Näätänen et al. (1993) for unattended frequency deviants.

The competition hypothesis also explains the results of Szymanski et al. (1999), whose study used a similar design of dichotic listening in which the conditions of competition were met, although it differed in other design aspects. In Szymanski et al.'s study, phoneme and phoneme-based intensity deviants (15 dB increments) were presented to the two ears and subjects were asked to attend to one ear (while ignoring the other ear) and detect, in separate conditions, either the phoneme or the intensity deviants. They found "task-relevant effects" on the MMN. That is, the attention effects on MMN in the unattended ear were larger for the target than for the nontarget deviant type. When subjects attended the intensity deviants, the attenuation of the intensity-MMN amplitude in the unattended ear was greater than when subjects attended the phoneme deviants and vice versa. The fact that unattended target-type MMNs were not completely abolished (as they were in the current study) is probably due to the considerably longer stimulus duration (250 ms) and ISI (1 s) used by Szymanski et al. The slower stimulus presentation allows more time for the deviance detection system and thus reduces competition.

In other selective attention studies testing effects on the MMN (Alain & Woods, 1997; Alho, Woods, Algazi, & Näätänen, 1992; Dittmann-Balcar et al., 1999; Trejo et al., 1995), the conditions of competition were not met and so these studies cannot be directly compared with the current one. Either there were no competing stimuli with which to assess effects of competition on the MMN elicitation (e.g., Trejo et al.) or in the case of Alain & Woods, in which subjects attended intensity increments in one ear and ignored them in the other (along with alternation deviants occurring in both ears), the overlapping components (of both N1 and N2b) make it problematic to assess the effect of attention on the MMN. Furthermore, it should be noted that as in the current study, these and other selective attention studies also did not find a general effect of attention on the MMN (e.g., Alho et al., 1992; Dittmann-Balcar et al., 1999; Kaukoranta, Sams, Hari, Hamalainen, & Näätänen, 1989; Paavilainen et al., 1993). That is, attention to the attended channel (whether visual or auditory), in and of itself, did not affect the MMN process.

Previously offered explanations (see the introduction) cannot account for the present results. If there were early gating of auditory information, this would prevent *any* MMN from being elicited in an unattended channel. However, MMN was elicited by deviations occurring in an unattended channel in both the present and Näätänen et al.'s (1993) previous studies. Although our results support Näätänen's (1990) view that all incoming sounds undergo full sensory analysis (even when unattended), they do not fit the explanation that intensity would be more sensitive to attentional manipulations than frequency (Näätänen et al., 1993), or that the top-down effects observed in dichotic listening situations act in a feature-dependent manner. In this respect, the competition hypothesis lies closer to Woldorff and colleagues' view suggesting that the observed top-down effects are caused by limited resource-allocating processes (see also Dittmann-Balcar et al., 1999; for a different example of the limitations of MMN resource allocation, see Sussman, Ritter, & Vaughan, 1999). Thus, although the sensory information presented to the two ears may be distinct from each other by separation in frequency or intensity, the two sound streams do not appear to act completely independently of each other. When the target is defined by a feature change common to both streams (e.g., the same intensity or frequency change present in both channels) the MMN based on this feature can be attenuated or abolished in the unattended ear.

The present results shed new light on the question of whether the MMN-generating process can be used to investigate early auditory processes without distortions from top-down processes. We found that highly focused selective attention, in and of itself, does not affect elicitation of the MMN, nor even its amplitude, as no difference was found between the attended and ignored (not the unattended) frequency-MMN amplitudes or between the unattended and ignored intensity-MMN amplitudes. Thus, it is safe to conclude that MMN elicitation does not require attention to be focused on the auditory stimuli. MMN abolishment only occurred when (a) the stimulus paradigm set up a competition for MMN generation by presenting similar deviants in two concurrent channels, and (b) this competition was biased by the subject's goals. In practice, most MMN investigations avoid this combination of experimental design features. This brings us back to the question of whether the deviance detection process, which generates MMN, is sensitive to attentional modulations. The present results are compatible with the view emerging from other studies that suggest that top-down processes can influence the sensory information that reaches the MMN deviance-detection process (Sussman, Ritter, & Vaughan, 1998; Sussman, Winkler, Huotilainen, Ritter, & Näätänen, 2002), but they do not affect the deviance-detection process itself (Rinne, Antila, & Winkler, 2001; Ritter, Sussman, Deacon, Cowan, & Vaughan, 1999; Sussman, Winkler, & Schröger, in press).

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