

available at www.sciencedirect.comwww.elsevier.com/locate/brainres

**BRAIN
RESEARCH**

Research Report

Effects of spatial separation and stimulus probability on the event-related potentials elicited by occasional changes in sound location

Ranil R. Sonnadara^a, Claude Alain^{b,c}, Laurel J. Trainor^{a,b,*}

^aDepartment of Psychology, McMaster University, Hamilton, Ontario, Canada L8S 4K1

^bRotman Research Institute, Toronto, Ontario, Canada

^cDepartment of Psychology, University of Toronto, Ontario, Canada

ARTICLE INFO
Article history:

Accepted 30 November 2005

Available online 9 January 2006

Keywords:

Mismatch negativity

MMN

Event-related potential

ERPs

Sound localization

N1

P2

Auditory

ABSTRACT

The ability to extract information about the spatial location of sounds plays an important role in auditory scene analysis. The present study examined the effects of spatial separation and stimulus probability on auditory event-related potentials (ERPs) to changes in sound location. In Experiment 1, we found that difference waves between ERPs elicited by standard and deviant stimuli showed a biphasic negative-positive response peaking around 126 and 226 ms after deviant onset. The amplitude of both responses increased with decreasing deviant stimulus probability, and increasing stimulus deviance. When the same stimuli were presented with equal probability for all locations (Experiment 2), there were no significant differences in the ERP amplitude and latency. These results suggest that the data reported in Experiment 1 are the result of contextual changes, rather than changes in simple acoustic features. Brain electrical source analyses are consistent with generators located in auditory cortices posterior to Heschel's gyrus. Although occasional changes in sound location elicit earlier peaks than the mismatch negativity (MMN) response reported for other types of deviation, their topographical distribution and behavior are consistent with MMN. The early latency of MMN for changes in sound location is interpreted in the context of an early-warning system to alert the organism to new sound sources in the environment.

© 2005 Elsevier B.V. All rights reserved.

1. Introduction

Spatial information is key to the formation of auditory objects (Bregman, 1990); it alerts us to potential sources of danger; it allows us to selectively listen to relevant auditory input whilst filtering out extraneous noise (Hawley et al., 2004; Haykin and Chen, 2005; Trainor et al., 2004). The ability to extract spatial information from incoming sounds is also essential for the

cross-modal integration necessary for building up accurate representations of our environment.

Several studies have looked at the extent to which sound localization is an automatic process. Most of these have used mismatch negativity (MMN) as the dependent measure. MMN is a component in the event-related potential (ERP) which is thought to be an index of auditory discrimination (Picton et al., 2000a). MMN is elicited by

* Corresponding author. Department of Psychology, McMaster University, Hamilton, Ontario, Canada L8S 4K1. Fax: +1 905 529 6225. E-mail address: ljt@trainor.ca (L.J. Trainor).

occasional changes in a stream of repeating stimuli: if participants are able to discriminate between the repeating (standard) stimulus and the occasionally changing (deviant) stimulus, the ERPs elicited by the deviant stimuli are more negative in the range between about 100 and 250 ms after stimulus onset.

Initially, MMN was thought to reflect the activation of a pre-attentive change detection mechanism (Naatanen, 1992). Although, some studies suggest that MMN can, in fact, be modulated by attention (Naatanen, 1991; Picton et al., 2000a; Woldorff et al., 1991; Woods et al., 1992), it remains unclear whether it is the MMN itself or the representations of the incoming stimulus entering the MMN system which are modulated by attention. Recent evidence suggests that there may, in fact, be several change detection mechanisms which work in parallel. Deouell and Bentin (1998) showed that occasional changes across different acoustic dimensions elicit MMN which peaks at different latencies, and with different amplitudes, depending on the dimension that is changed. Giard et al. (1995) showed that MMN elicited by different acoustic features had at least partially distinct neural generators, suggesting that there may in fact be more than one neural process involved in the generation of MMN.

The literature on MMN elicited by changes in the location of a sound is not entirely consistent. Some studies report MMN peaks as early as 105 ms (Ruusuvirta, 1999), whereas others report MMN peaks later than 200 ms (Stekelenburg et al., 2004). In some studies, the MMN amplitude increases with increasing spatial separation between standard and deviant stimuli (Nager et al., 2003; Paavilainen et al., 1989), whereas other studies suggest that MMN elicited by changes in location is 'all or nothing' (Colin et al., 2002; Shestakova et al., 2002). In addition to MMN, occasional changes in sound location can also elicit an N1 and P2 waves (Butler, 1972; McEvoy et al., 1990, 1991; Naatanen et al., 1988; Picton et al., 1991). Whereas the MMN response is driven by contextual changes in the incoming stimulus, the N1 response (Martin and Boothroyd, 1999; Naatanen and Picton, 1987) is driven by changes to the acoustic features of the incoming stimulus. This response typically peaks between 50 and 150 ms after stimulus onset (Naatanen and Picton, 1987) and N1 peaks to changes in sound location have been reported as late as 136 ms (McEvoy et al., 1990). There is often much overlap between the N1 and MMN components, and it is possible that some studies which report early MMN components could actually be reporting a combination of N1 and MMN, which have very similar distributions across the scalp.

The aim of the present study is to systematically examine neural correlates of change detection for sound location by varying two parameters known to influence the amplitude of the MMN in an effort to understand some of the inconsistencies in the existing literature. Specifically, we examine the amplitude, latency and source of the evoked response across a number of stimulus locations and probability conditions. If the response behaves like 'classic' MMN, we expect to see larger responses as the probability of deviant stimuli decreases, and also as the distance between standard and deviant stimuli is increased. We also test whether at this

stage of processing, responses are larger contralateral to the stimulus.

2. General discussion

The data from Experiment 1 demonstrate that ERP waveforms elicited by occasional changes in location of a sound are dominated by two components—a negative peak (at frontal sites) between 100 and 145 ms after stimulus onset, and a subsequent positive peak between 200 and 260 ms, with the polarities of the peaks reversing towards the back of the head. For both components, there was a significant effect of probability, with less probable deviants eliciting larger negative and positive peaks. Peaks were largest contralateral to the side of presentation of the deviant stimuli. There was also a significant effect of the location of the deviant stimulus, with those presented at 90° eliciting larger peaks than those presented at 30°, and those presented at 90° showing a different scalp distribution than those presented at 30°. Source analysis suggests generators located in the posterior portion of the superior temporal plane, and that the laterality effect may be accounted for by different weighting of the left and right generators for stimuli presented from different locations, although it is also possible that the data are indicative of somewhat different neural generators.

The latency of our negative peak is earlier than is typically reported for MMN elicited by other sound features (Picton et al., 2000a), although it is not atypical for localization. In fact, there is considerable variability in the literature with regard to MMN elicited by occasional changes in spatial location of a sound, both in terms of the latency of the MMN response, and also in the responsiveness of MMN amplitude to the degree of location change. Some studies report MMN present as early as 105 ms (Ruusuvirta, 1999), whereas others report significant MMN later than 200 ms (Stekelenburg et al., 2004). Some studies report no differentiation between the amplitude of MMN elicited by deviants from different locations (Colin et al., 2002; Shestakova et al., 2002), whereas other studies report smaller MMN amplitudes to deviants which are spatially closer to the standard stimulus compared with those that are farther from it (Nager et al., 2003; Paavilainen et al., 1989).

The variability in the effect of degree of change on the MMN amplitude could, at least in part, be explained by differences in signal to noise ratio between the different studies. Higher noise levels could mask subtle changes in the recorded waveforms that are revealed in recordings with a higher signal to noise ratio. However, it is difficult to see how differences in signal to noise ratio could explain the great variability in MMN peak latency that is present across studies.

One possibility for this variability is that there are several MMN processes involved in detecting changes in sound location, and that different studies are measuring somewhat different processes. There is certainly evidence for separate MMN processes for different sound features (Alain et al., 1999; Deouell and Bentin, 1998; Giard et al., 1995). Doeller et al. (2003) showed that two separate MMN windows, operating at slightly different time-points, could be manipulated independently using occasional changes in pitch and spatial location. Schroger and colleagues (Schroger, 1996; Schroger et al.,

1997) showed that occasional changes in the location of a sound when location was set using interaural timing differences (ITD), elicited MMN with different latency and distribution compared with when the location was set using interaural level differences (ILD). They also showed that MMN elicited when location is set using both ITD and ILD is larger than the sum of MMN elicited by the two separate processes (Schroger et al., 1997), and that occasional changes in pitch elicited later MMN than occasional changes in location (Schroger and Wolff, 1997). Deouell and Bentin (1998) showed that occasional changes in different physical stimulus dimensions such as frequency, intensity and location all elicited MMN at different latencies and with different distributions. Giard et al. (1995) used dipole-model analyses to show that scalp topographies of MMN elicited by different physical stimulus features involved at least partially distinct neural populations. There is also developmental literature which suggests that MMN to different physical dimensions of a stimulus develops at different ages (Trainor, 2005; Trainor et al., 2003), and evidence showing that as ‘standard’ and ‘deviant’ stimuli become harder to define (such as when they require integration of different features or integration over time) the elicited MMN becomes more susceptible to attention than is the case for simpler stimuli (Alain and Woods, 1997; Alain et al., 1994). It is possible that differences in the latency of MMN reported across studies (ranging from 105 to 250 ms) arise because there are different MMN processes related to detecting changes in sound location at different stages of processing. However, the very large range in reported MMN latency, combined with the absence of studies reporting more than one MMN peak in response to changes in location makes it unlikely that the possible existence of different MMN processes related to location change could fully account for the latency differences reported.

Another possibility is that this variability arises as a result of overlapping components. There are many components elicited when a stimulus is presented to the auditory system, and several researchers have shown that these components can interact with each other, affecting what is seen at the scalp (see Naatanen, 1992, for a review on the effects of component superimposition). Prominent components in the 105–250 ms time window include N1, P2, and N2. As mentioned previously, several studies have shown a robust N1 response, followed by a positive P2 response, to changes in the location of a stimulus. Attention to a change in auditory input can also elicit an N2b response at around 240 ms after stimulus onset (Pritchard et al., 1991; Ritter et al., 1992; Tervaniemi et al., 2004).

In Experiment 1, we used a paradigm with a very short stimulus onset asynchrony that was specifically designed to maximize signal to noise ratio for the MMN. Difference waveforms elicited a robust negative component around 120 ms followed by a positive component around 230 ms. Although the similarities in distribution between the N1 and MMN components and the notion that N1 is elicited to all state-changes in the auditory environment (Naatanen and Picton, 1987; Picton et al., 2000a) make it difficult to categorically state that there is no N1 component contributing to our data, the paradigm we used in Experiment 1, coupled with our results from Experiment 2, make it unlikely that our waveforms are solely reflecting the N1–P2 complex. We found no

other significant components present in our data when all locations were presented with equal probability (removing the context required for generating MMN). Thus, we are fairly confident in interpreting the negative peak from Experiment 1 as MMN, reflecting the automatic detection of a change in an auditory stimulus (Picton et al., 2000a), and the subsequent positive peak as a P3a-like component, reflecting the inadvertent capture of attention by occasional stimuli (Roeber et al., 2003; Shestakova et al., 2002).

The question remains then as to why some studies report MMN much later than other studies. One possibility is that this late-reported MMN largely reflects activity from the N2b component. Interestingly, studies which report earlier MMN tend to be ones in which participants’ capacity to focus on the location of the auditory stimuli is minimized, either through the use of rapid rates of presentation, or through the use of secondary tasks which place a heavy attentional load on participants: Al’tman et al. (2004) presented 200 ms sequences of 100 μ s square wave impulses from different locations and reported MMN peaking as early as 126 ms; Ruusuvirta (1999) had participants perform a counting task whilst short 1000 Hz pure tones were presented from different locations, and reported MMN to deviant stimuli starting as early as 105 ms; Roeber et al. (2003) had participants perform a two-alternative forced choice auditory discrimination task whilst occasional 200 ms noise bursts from different locations were interleaved into procedure, and reported MMN deflections from 140 ms. On the other hand, studies which rely on more passive listening tasks tend to report later MMN: Schroger and Wolff (1996) had participants read a book whilst presenting pure tone stimuli from different locations and also reported MMN peaking around 200 ms. Given that attention was not tightly controlled in this latter group of studies, it is possible that N2b may have contributed to the waveforms which were recorded at the scalp. Indeed, it is possible that at least some of the variability in the reported latency of the MMN could be explained in terms of interactions between the N2b and MMN components of the ERP. If the slightly later N2b component were superimposed on the earlier MMN component, then the resulting waveform might be expected to reveal a single peak whose latency would depend on the relative contributions of the MMN and N2b. Such an explanation could be tested through source analysis and by manipulating the attentional load of participants across a series of studies and examining the effect of this manipulation on the latency of MMN.

We conclude that MMN to sound location occurs very early in the processing stream. Schroger and Wolff (1997) suggest that early MMN to location is “based on faster preattentive processing of location relative to frequency information”. Why might this be so? Sound localization is key to our survival: it is used in the formation of auditory objects (McDonald and Alain, 2005); it is used to steer our visual field; it is used to allocate attentional resources (McDonald et al., 2000). Perhaps, most importantly from an evolutionary standpoint, sound localization can warn us of potential sources of danger which are outside of our visual and attentional foci. In order to maximize the efficacy of such a warning system, one might expect relatively early processing for spatial information, perhaps in parallel with the processing of information regarding the nature of the sound source, in order to give us as much time as

possible to evaluate and react to auditory objects which appear from unexpected locations. Indeed, there is emerging evidence for distinct pathways for what and where information from relatively peripheral levels in the auditory system (Alain et al., 2001; Arnott et al., 2004; Eggermont, 2001; Weeks et al., 1999) and that information regarding the location of a sound is available below the level of auditory cortex (Eggermont, 2001; McAlpine et al., 2001). In Experiment 1, we used very short stimulus onset asynchronies (SOAs) in order to maximize MMN. A by-product of such a fast SOA was that our 'standard' stimuli formed a very strong perceptual stream, that is, produced a strong impression of a single object emitting the sound, making the deviant stimuli especially salient (see Alain and Arnott, 2000; Bregman, 1990) for a discussion on auditory streaming). This is exactly the scenario for which such a warning system might be designed: a new auditory object suddenly appearing from an unexpected location needs to trigger further processing as quickly as possible. Thus, we conclude that sound localization is processed early, and we predict that the stronger the auditory stream formed by the standard stimulus, the easier it will be to detect the change in location, and the earlier the measured MMN.

3. Experimental procedures

3.1. Experiment 1

3.1.1. Participants

Eight paid volunteers (mean age = 25; 2 males, 6 females) participated in this study. All were right handed, and none reported any hearing problems.

3.1.2. Apparatus, stimuli and recordings

Stimuli were generated using a Tucker Davis Technologies RP-2 real-time processor, and were presented via a Tucker Davis Technologies HB-7 headphone buffer and Sennheiser HD-265 headphones at a level of approximately 65 dB (C) across the ears. The experiment was run using Matlab software on a PC computer, and was conducted in a sound-attenuating chamber (Industrial Acoustics Company). All tones were 1000 Hz pure tones of 50 ms duration including 5 ms cosine ramps. Locations of tones were specified by applying Head Related Transfer Function (HRTF) coefficients taken from the Tucker Davis Technologies library to the tones prior to sending them to the headphone buffer (see Wenzel et al., 1993; Wightman and Kistler, 1989a,b for a detailed description and behavioral validation of the HRTF co-efficients used).

Continuous EEG was recorded with Neuroscan software using a Synamps neural amplifier and 64-channel tin electrode caps (Electro-Cap International), with electrodes placed according to the 10–20 system (Jasper, 1958). EEG recordings were made at a sample rate of 500 Hz, using a CZ reference. The continuous EEG recordings were filtered on line between 0.1 and 30 Hz.

3.1.3. Procedure

In order to find the most suitable HRTF co-efficients, each participant initially completed a behavioral calibration task which required them to identify (by pointing) the locations of several tones which were presented over headphones using a variety of HRTF coefficients. The co-efficients which resulted in the most accurate responses were then determined and used for the remainder of the experiment. Although we did not record individual HRTFs for each participant, previous work shows that this standardized library is very effective for tasks involving localization on the horizontal plane (Wenzel et al., 1991, 1993).

Whilst the use of HRTFs sometimes results in tones being perceived as coming from 'inside the head', of the 6 participants interrogated, all reported hearing tones 'outside' the head, as might be predicted from previous studies. After the calibration procedure, participants were then fitted with the electrode cap.

The experiment consisted of three blocks, each with 5000 trials. For each block, an oddball paradigm was used, with standard trials consisting of single tones coming from straight ahead (0°), and oddball trials consisting of single tones coming from either 30 or 90° to the left (−30°, −90°) or right (+30°, +90°). All tones were presented in the horizontal plane. All trials were presented with a stimulus onset asynchrony of 104 ms in random order, constrained so that at least 2 standard trials succeeded each oddball. The probability of receiving a standard stimulus varied across the three blocks (70%, 80% or 90%) which made the probability of each oddball type 7.5, 5 or 2.5%, respectively. Blocks were presented in random order across participants who were offered short breaks between blocks as required.

During the experiment, participants watched a silent (captioned) DVD film of their choosing. Participants were instructed to focus their attention on the film they were watching, rather than on the sounds being presented, and were told that they would later be asked questions about the film.

3.1.4. Data analysis

The continuous EEG files were segmented into 700 ms epochs including a 100 ms pre-stimulus window. These epochs were then re-referenced to a common-average reference, and baseline corrected over the pre-stimulus window¹. All epochs on which the measured activity at any electrode exceeded $\pm 100 \mu\text{V}$ were rejected as containing movement/blink artifact. Remaining epochs were then sorted and averaged so that for each participant, each presentation location under each probability had its own average. Across participants, the number of included oddball trials varied between 88 and 376 (mean = 234 trials). Finally, all averages were then linear detrended to remove drift, filtered between 0.5 and 20 Hz and baseline corrected again.

Difference waves for each deviant presentation location (−90°, −30°, 30°, 90°) by probability (70%, 80%, 90%) were calculated by subtracting standard waveforms from oddball waveforms. For each participant at each electrode, the amplitude and latency for the most negative (frontal sites) or most positive (parietal, occipital and mastoidal sites) peak in the difference wave between 95 and 145 ms were measured. The amplitude and latency of the following positivity (frontal sites) or negativity (parietal, occipital and mastoidal sites) between 186 and 272 ms were also measured.

Two-tailed *t* tests were employed to determine the portions of the difference waves that were significantly different from 0 across participants. The effects of stimulus probability, angle, and side of stimulus presentation on peak amplitude and latency data and their distribution across the scalp were examined with analyses of variance.

3.2. Results and discussion

For each condition [angle (30°, 90°) × probability (70%, 80%, 90%) × side of presentation (left, right)], difference waves were dominated by a negative peak between 100 and 170 ms after stimulus onset, and a following positive peak between 200 and 260 ms (see Fig. 1). The polarities of the peaks reversed towards the back of the head. Analyses were centered around these time windows.

¹ The data were also analyzed using Nz as a reference. We did not see any significant differences in the results of the two analyses, and preferred to report data analyzed using a common average reference because we feel it offers a better approximation of the zero voltage (Picton et al., 2000b).

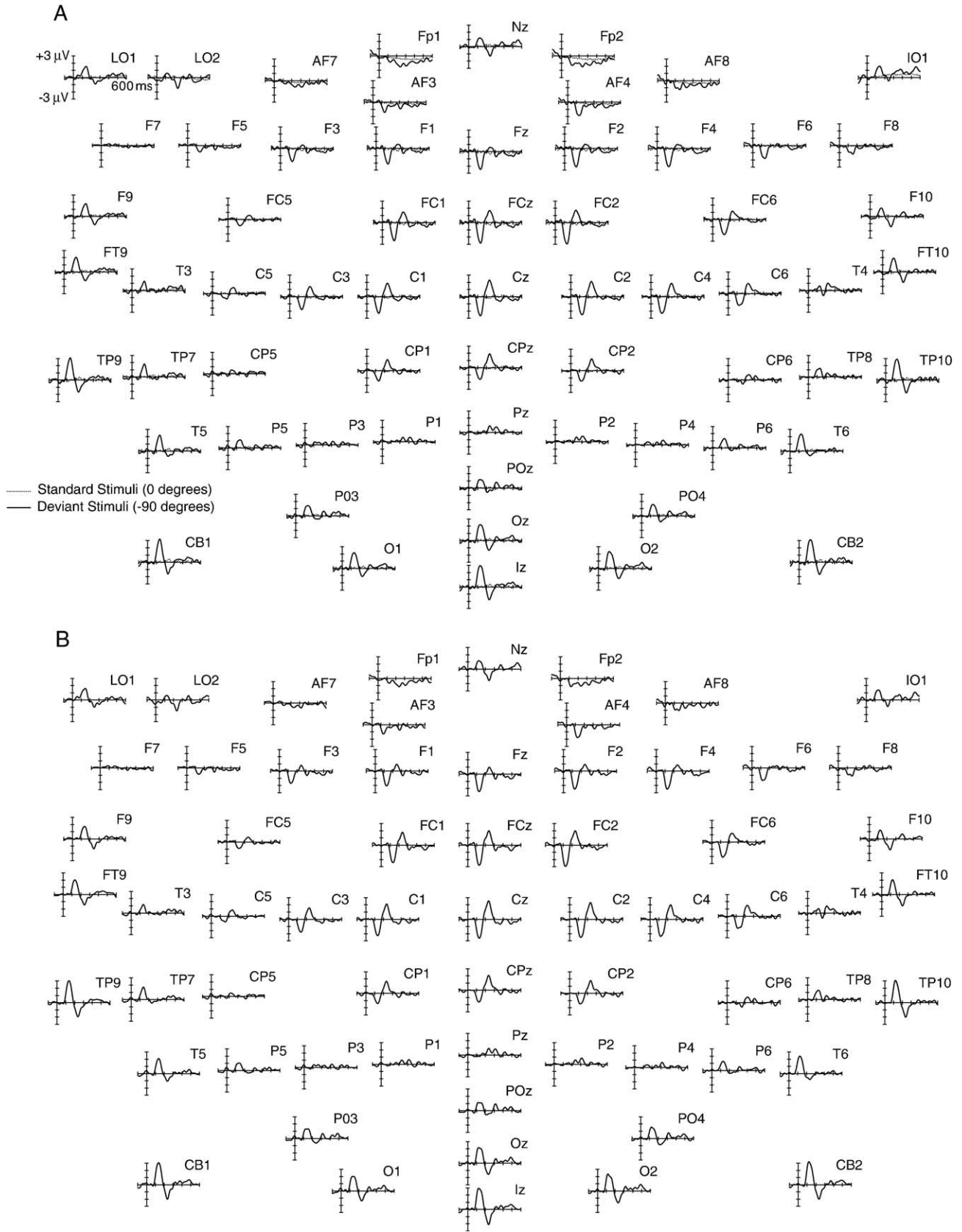


Fig. 1 – A whole-head montage (using a common average reference) showing standard and deviant ERPs (A) and difference waves (B) from Experiment 1. There is a significant negative peak around 120 ms, and a subsequent positivity around 230 ms.

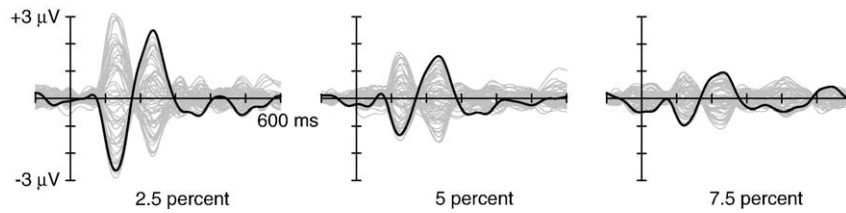


Fig. 2 – A butterfly plot showing difference waves from Experiment 1. For deviant stimuli presented from 90° to the left of participants, less probable deviant stimuli elicit larger peaks than more probable deviant stimuli. The highlighted trace shows data recorded from Cz.

3.2.1. Negative peak

Single sample *t* tests comparing observed voltages with the expected mean under the null hypothesis (0 μ V) revealed windows of significance around latencies of 105–130 ms for frontal sites (negative voltages), and mastoidal and occipital sites (positive voltages).

To examine the effects of angle, probability, and side of presentation on the distribution of the difference waves, peak amplitude and latency data were separately averaged into four clusters of electrodes representing left anterior (FP1, FC1, F3), right anterior (FP2, FC2, F4), left posterior (CB1, TP9), and right posterior (CB2, TP10) areas. Two ANOVAs were conducted, one on absolute peak amplitude and one on peak latency data. Each had five within-subjects factors: probability of the standard (70, 80 or 90%); side of stimulus presentation (left or right); angle of stimulus presentation (30 or 90°); anterior/posterior electrode cluster (front, back), and side of electrode cluster (left or right).

Peak amplitudes increased as the probability of deviant stimuli decreased [$F(2, 14) = 13.197, P < 0.01$], and as spatial separation

between standard and deviant stimuli increased [$F(1, 7) = 17.349, P < 0.01$] (see Figs. 2 and 3). In addition, peak amplitude was larger at posterior compared with anterior electrode clusters [$F(1,7) = 15.691, P < 0.01$] (see Fig. 1B and Table 1).

There were also a number of interactions. Importantly, there was an interaction between angle of presentation and side of electrode cluster, $F(1,7) = 6.731, P < 0.036$, suggesting that the difference waves had a slightly different scalp distribution for the 90° and 30° angles, and were therefore elicited by somewhat different generator locations or by differences in the weighting of the left and right generators. Head maps of isovoltage contours illustrating these differences are shown in Fig. 3b. There was also an expected interaction between side of presentation and side of electrode cluster, with larger peaks in the hemisphere opposite to the side of presentation, $F(1, 7) = 11.15, P < .05$. In addition, rarer deviants generated larger amplitude differences across locations than did less rare deviants [probability \times angle interaction, $F(2,14) = 7.213, P < 0.01$] and larger differences between front and back electrodes [probability \times anterior/posterior electrode

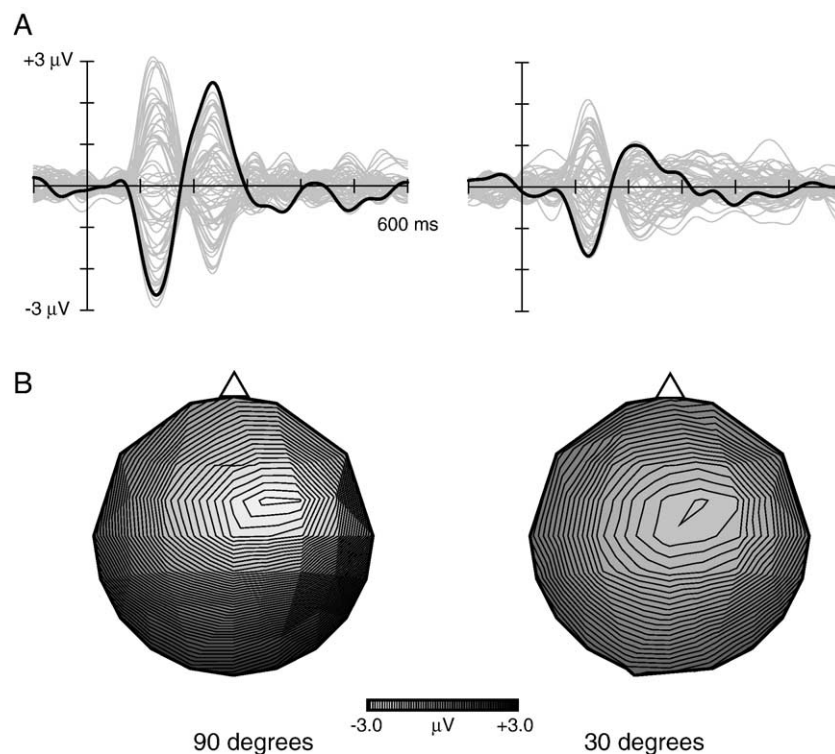


Fig. 3 – (A) A butterfly plot showing difference waves from Experiment 1. For the condition in which 90% of trials are standard trials (presented from directly in front of participants), deviant stimuli presented from 90° to the left illicit larger peaks than deviant stimuli presented from 30° to the left. (B) Isovoltage contour maps showing small differences in the voltage distribution at the scalp between 120 and 130 ms for difference waves elicited by deviants from 90° to the left and 30° to the left.

Table 1 – Group mean MMN amplitudes and latencies

Probability of deviant (%)	Mean absolute amplitude of MMN response (μV)	Mean latency of MMN response (ms)
2.5%	2.093	128
5.0%	0.981	124
7.5%	0.842	121

Angle of presentation of deviant ($^{\circ}$)	Mean absolute amplitude of MMN response (μV)	Mean latency of MMN response (ms)
90	2.093	127
30	0.981	122

Mean amplitudes and latencies of the MMN response from Experiment 1. Less probable deviants elicited larger and later responses. Larger spatial separation between standard and deviant stimuli also elicited larger and later responses.

interaction, $F(2,14) = 20.819, P < 0.01$). Finally, the side of presentation \times side of electrode cluster \times angle of presentation interaction was also significant, indicating that the scalp distribution difference across angles was larger for left than for right stimulus presentation, $F(1, 7) = 10.95, P < 0.05$.

The ANOVA examining latency revealed that peaks were earlier the more probable the deviant [main effect of probability, $F(2,14) = 5.632, P < 0.05$], and earlier for 30 $^{\circ}$ deviants than for 90 $^{\circ}$

deviants [main effect of angle of presentation, $F(1,7) = 10.018, P < 0.05$]. There was also an interaction between side of presentation and side of electrode, with earlier peaks in the hemisphere opposite to the stimulus presentation, $F(1,7) = 11.846, P < 0.05$.

3.2.2. Positive peak

Single sample *t* tests comparing observed voltages with the expected mean under the null hypothesis ($0 \mu\text{V}$) revealed windows of significance around latencies of 201–257 ms for frontal sites (positive voltages), and mastoidal and occipital sites (negative voltages).

As before, peak amplitude and latency data were separately averaged into four clusters. Two ANOVAs were conducted, one on absolute peak amplitude and one on peak latency data, using the same factors as above.

As for the negative component, peak amplitude increased with decreasing deviant probability [$F(2, 14) = 16.142, P < 0.01$], and with increasing spatial separation between standard and deviant stimuli [$F(1, 7) = 15.42, P < 0.01$] (see Figs. 2 and 3A). Peak amplitude was again larger for posterior compared to anterior electrode clusters [$F(1,7) = 15.82, P < 0.01$].

Again, there were also a number of interactions. Importantly, there was an interaction between angle of presentation and side of electrode cluster, $F(1,7) = 12.731, P < 0.01$ again suggesting that the difference waves had a slightly different scalp distribution for the 90 $^{\circ}$ and 30 $^{\circ}$ angles (Fig. 4).

There was also an expected interaction between side of presentation and side of electrode cluster, with larger peaks in the hemisphere opposite to the side of presentation [$F(1, 7) = 13.10,$

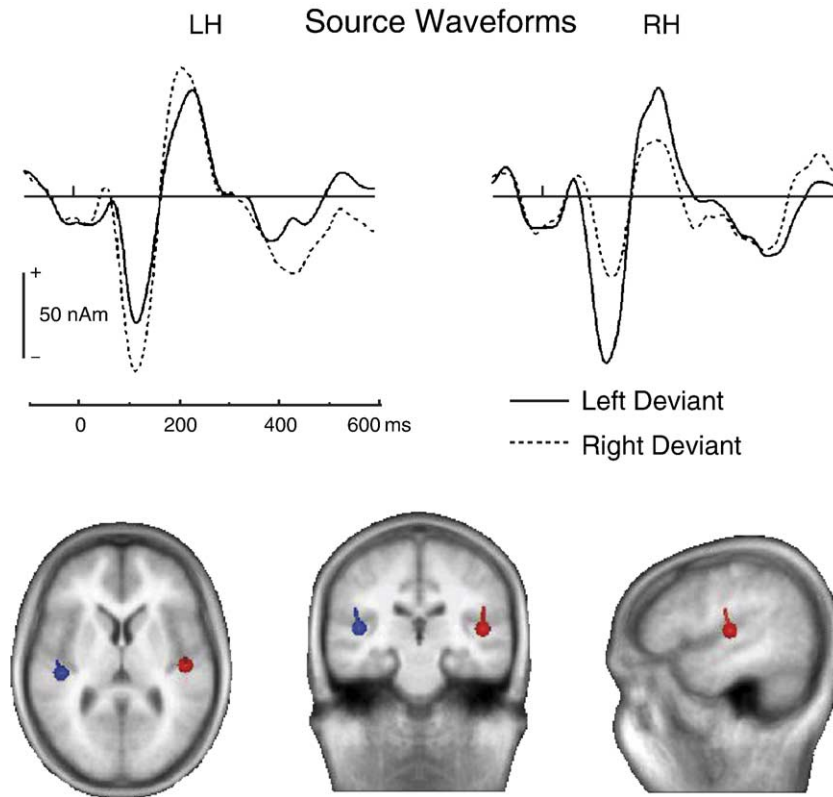


Fig. 4 – Source analysis of the EEG data from Experiment 1 was carried out in BESA software (version 5.1) using a 4-shell ellipsoidal head model. The left panel (LH) shows the activity for the left source for deviant stimuli presented from the left and the right (collapsed across angle and probability conditions). The right panel (RH) shows the activity for the right source for deviant stimuli. Activity is greater for sources contralateral to the side of presentation. The lower panel shows that locations of the left (blue) and right (red) sources are posterior to the primary and secondary auditory cortices along the superior temporal plane.

$P < .01$]. Rarer deviants generated larger amplitude differences across probabilities than did less rare deviants [probability \times angle interaction, $F(2,14) = 8.12$, $P < 0.01$] and larger differences between front and back electrodes [probability \times anterior/posterior electrode interaction, $F(2,14) = 19.12$, $P < 0.01$]. Finally, the side of presentation \times side of electrode cluster \times angle of presentation interaction was again significant, indicating that the scalp distribution difference across angles was again larger for left than for right stimulus presentation, $F(1, 7) = 9.94$, $P < 0.02$.

The ANOVA examining latency revealed that peaks were earlier the more probable the deviant [main effect of probability, $F(2,14) = 7.42$, $P < 0.01$], and earlier for 30° deviants than for 90° deviants [main effect of angle of presentation, $F(1,7) = 9.12$, $P < 0.05$]. There was also an interaction between side of presentation and side of electrode, with earlier peaks in the hemisphere opposite to the stimulus presentation, $F(1,7) = 8.21$, $P < 0.05$.

3.2.3. Brain electrical source analysis

Source analysis was applied using BESA software (Scherg, 1990). The location of the generator(s) giving rise to the early negative peak in the difference wave of the ERPs elicited by standard and deviant stimuli was examined using dipole source modeling. The data were collapsed across probability and deviant location to improve the signal to noise ratio. The analysis was carried out using a 4-shell ellipsoidal head model with relative conductivities of 0.33, 1.0, 0.0042 and 0.33 for the brain, cerebrospinal fluid, skull and scalp. The thickness for head, scalp, bone, and cerebrospinal fluid were 85, 6, 7, and 1 mm, respectively. The first principal component of the difference wave for the 100–170 ms interval accounted for more than 98% of the variance, suggesting that a single source of variability contributed to the ERPs over this time interval. First, we modeled the neural activity using a pair of regional sources. As a starting solution, the regional sources were forced to be symmetrical in the left and right temporal lobe. Then, the regional sources were transformed into single dipole sources. In the last step, we let the dipoles move freely without constraint. The dipoles localized to posterior areas of the temporal lobe, consistent with other neuroimaging studies (Arnott et al., 2005; Kaiser and Lutzenberger, 2001; Kaiser et al., 2000). The residual variance for the solution was 5.05% for the right deviant and 4.12% for the left deviant, suggesting that the model provides a good fit to the scalp recorded data. Note that the dipole location was very similar for left and right deviants, with only the dipole strength varying in each hemisphere as a function of the deviant location. These results are consistent with current models of auditory processing which emphasize the roles of posterior temporal cortex and dorsal regions of the brain in sound localization (Alain et al., 2001; Arnott et al., 2004; Weeks et al., 1999).

3.2.4. Summary

The morphology and behavior of the difference waves as revealed by the peak amplitude and latency data are consistent with the first peak being an MMN-like component, thought to reflect the automatic detection of a change in an auditory stimulus (Paavilainen et al., 1989; Picton et al., 2000a): the amplitude of the peaks increases with decreasing probability, and larger angles of displacement for the deviant stimuli. The morphology and behavior of the subsequent positive component are consistent with it being a P3a-type component, thought to reflect an inadvertent capture of attention by occasional stimuli (Sams et al., 1985; Snyder and Hillyard, 1976). However, the mean latencies are earlier than is typical for both MMN and P3a, and one might have predicted that smaller and less probable changes would elicit later, rather than earlier MMN as is seen in our data. The deviant is larger for our 90° condition than for the 30° condition. If both MMN processes began at the same time, the former might peak later than the latter. Alternative explanations are also possible. Picton et al. (2000a) stress the need for disentangling the

difficulty of discrimination from the timing of the discrimination process when interpreting MMN latency as both are contributing factors. A second possibility, then, is that our latency data reflect the ease at which our participants are able to discriminate between different stimuli, although it seems unlikely that smaller, rather than larger discriminations would be easier. A third possibility is related to Boehnke and Phillips' (1999) suggestion that the 0° and 30° locations would be processed in the same spatial channel whereas the 0° and 90° locations would be processed in different spatial channels. Faster within-channel discrimination might be predicted as such processing could be done at more peripheral levels of the auditory system, even though the discrimination task itself might be harder. Such a hypothesis much more plausibly explains why we found earlier MMN for the 30° condition. A fourth possible explanation for our data is that the first and second peaks could be described as an N1–P2 complex, generated by differences in the acoustic properties, rather than MMN and P3a components (see Martin and Boothroyd, 1999; Naatanen, 1992; Naatanen and Picton, 1987 for a review of the N1 and P2 components). In other words, it remains possible that a simple change in location, irrespective of context, could account for the responses we recorded. To examine this possibility, in Experiment 2, we remove the context required for the generation of MMN by presenting every location with equal probability, and examine whether there are other components contributing to the waveforms.

3.3. Experiment 2

3.3.1. Participants

Eight paid subjects (mean age = 23.5; 2 males, 6 females) participated in this study. All were right handed, and none reported any hearing problems. Four of the subjects had previously completed Experiment 1.

3.3.2. Apparatus, stimuli and recordings

Stimuli and apparatus were the same as in Experiment 1. All tones were 1000 Hz pure tones of 50 ms duration including 5 ms cosine ramps. Continuous EEG was recorded with Neuroscan software using a Synamps neural amplifier and 64-channel tin electrode caps (Electro-Cap International), with electrodes placed according to the 10–20 system (Jasper, 1958). EEG recordings were made at a sample rate of 2000 Hz, using a CZ reference.

3.3.3. Procedure

The same calibration procedure from Experiment 1 was used in order to find the most suitable HRTF co-efficients for each subject. Participants were then fitted with the electrode cap.

Trials consisted of single tones presented from one of 5 equally probable locations: straight ahead (0), 30° or 90° to the left (–30, –90), and 30° or 90° to the right (+30, +90). 3000 trials (600 trials from each location), were presented in random order, constrained so that no location was repeated on successive trials. The stimulus onset asynchrony was 104 ms.

As in the first experiment, participants watched a silent (captioned) DVD film of their choosing. Participants were instructed to focus their attention on the film they were watching, rather than on the sounds being presented, and were told that they would later be asked questions about the film.

3.3.4. Data analysis

Data were processed as in Experiment 1. The continuous EEG files were segmented into 700 ms epochs including a 100-ms pre-stimulus window. These epochs were then re-referenced to a common-average reference, and baseline corrected over the pre-stimulus window. All epochs on which the measured activity at any electrode exceeded $\pm 100 \mu\text{V}$ were rejected as containing movement / blink artifact. Remaining epochs were then sorted and averaged based on both the location of the sound presented

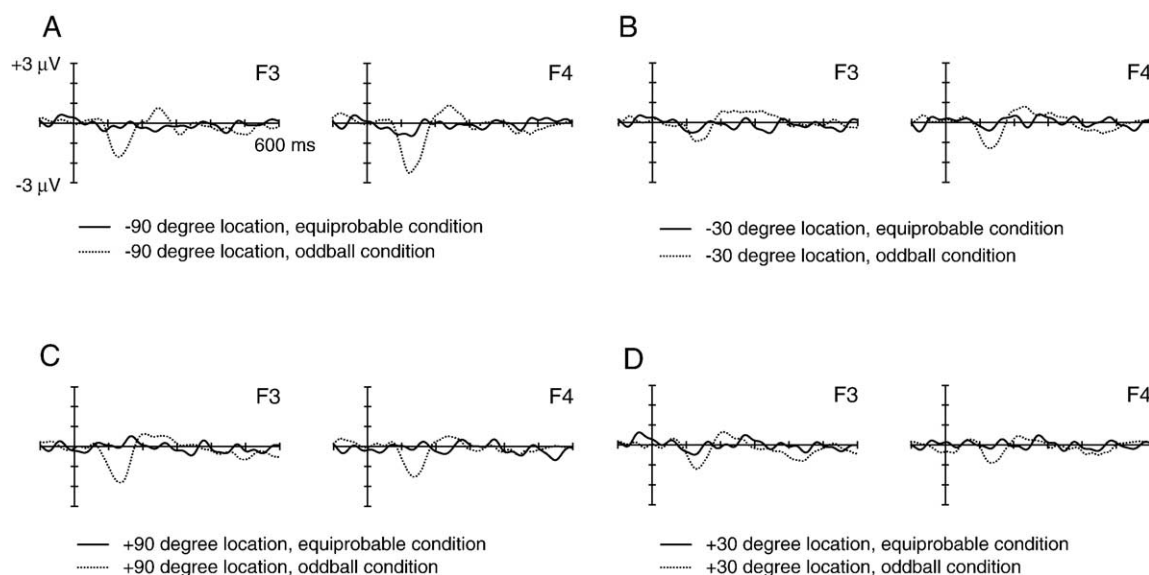


Fig. 5 – When the context required to generate MMN is removed, evoked responses from Experiment 2 (the control condition) are much smaller than responses from Experiment 1 (MMN condition) and show no significant components.

on that trial and the location of the preceding trial, since we were only interested in the response evoked when a sound moved from the center location (the ‘standard’ location in Experiment 1) to one of the four ‘deviant’ locations tested in Experiment 1 (-90° , -30° , 30° and 90°). Across participants and locations, the number of included trials for each ‘deviant’ location varied between 129 and 237 (mean = 152 trials). Finally, all averages were linear detrended, filtered between 0.5 and 20 Hz, and baseline corrected again.

Two-tailed *t* tests were employed to determine the portions of the resulting waveforms that were significantly different from 0 across participants.

3.4. Results and discussion

There were no significant differences between the data from the four subjects who had previously completed Experiment 1 and the new participants, so data from both groups were collapsed for the final analysis. In this study, there were no standard and deviant trials. Rather, all trial types were equally probable. We examined four averaged waveforms made up of trials presented from $+90^\circ$ that followed 0° trials, -90° that followed 0° trials, $+30^\circ$ that followed 0° trials, and -30° that followed 0° trials. Visual inspection of the waveforms revealed no clear components for any of the four averages. The two-tailed *t* tests revealed that there were no significant deflections in the waveforms (all *P*'s > 0.36), indicating that when the context required for generating MMN (a frequently repeating standard stimulus with occasional deviant stimuli) is removed, there are no other significant components present in our data (see Fig. 5). To further confirm this, we looked at the data for the 4 subjects who participated in both experiments, and compared the response to the deviant locations in Experiment 1 with the response to the same locations in Experiment 2. For these subjects, *t* tests revealed significant differences in the amplitude of the response between 100 and 135 ms and between 200 and 235 ms across a number of electrodes (all *P*'s < 0.05), further confirming that when the context for MMN is removed, the evoked response is considerably smaller. Although the difference in time between successive presentations at the same location in Experiment 1 (1.5–4 s) and Experiment 2 (around 0.5 s) make it impossible to completely rule out some contribution

of the N1–P2 complex to the evoked response in Experiment 1, we are confident that the majority of the response is the result of a change-detection process.

Acknowledgments

This work was supported by a grant from the National Science and Engineering Council to LJT and a Canadian Institutes of Health Research student fellowship to RS. We thank Patricia Van Roon and Yu He for laboratory assistance, Chenghua Wang for technical support, and Lisa Hotson for help preparing the manuscript.

REFERENCES

- Al'tman, Y.A., Vaitulevich, S.F., Shestopalova, L.B., 2004. Changes in evoked potentials during the action of sound signals with different localizing characteristics. *Neurosci. Behav. Physiol.* 34, 139–146.
- Alain, C., Arnott, S.R., 2000. Selectively attending to auditory objects. *Front. Biosci.* 5, D202–D212.
- Alain, C., Woods, D.L., 1997. Attention modulates auditory pattern memory as indexed by event-related brain potentials. *Psychophysiology* 34, 534–546.
- Alain, C., Woods, D.L., Ogawa, K.H., 1994. Brain indices of automatic pattern processing. *NeuroReport* 6, 140–144.
- Alain, C., Achim, A., Woods, D.L., 1999. Separate memory-related processing for auditory frequency and patterns. *Psychophysiology* 36, 737–744.
- Alain, C., Arnott, S.R., Hevenor, S., Graham, S., Grady, C.L., 2001. “What” and “where” in the human auditory system. *Proc. Natl. Acad. Sci. U. S. A.* 98, 12301–12306.
- Arnott, S.R., Binns, M.A., Grady, C.L., Alain, C., 2004. Assessing the auditory dual-pathway model in humans. *NeuroImage* 22, 401–408.
- Arnott, S.R., Grady, C.L., Hevenor, S.J., Graham, S., Alain, C., 2005.

- The functional organization of auditory working memory as revealed by fMRI. *J. Cogn. Neurosci.* 17, 819–831.
- Boehnke, S.E., Phillips, D.P., 1999. Azimuthal tuning of human perceptual channels for sound location. *J. Acoust. Soc. Am.* 106, 1948–1955.
- Bregman, A.S., 1990. *Auditory Scene Analysis*. MIT Press, Cambridge, MA.
- Butler, R.A., 1972. The influence of spatial separation of sound sources on the auditory evoked response. *Neuropsychologia* 10, 219–225.
- Colin, C., Radeau, M., Soquet, A., Dachy, B., Deltenre, P., 2002. Electrophysiology of spatial scene analysis: the mismatch negativity (MMN) is sensitive to the ventriloquism illusion. *Clin. Neurophysiol.* 113, 507–518.
- Deouell, L.Y., Bentin, S., 1998. Variable cerebral responses to equally distinct deviance in four auditory dimensions: a mismatch negativity study. *Psychophysiology* 35, 745–754.
- Doeller, C.F., Opitz, B., Mecklinger, A., Krick, C., Reith, W., Schroger, E., 2003. Prefrontal cortex involvement in preattentive auditory deviance detection: neuroimaging and electrophysiological evidence. *NeuroImage* 20, 1270–1282.
- Eggermont, J.J., 2001. Between sound and perception: reviewing the search for a neural code. *Hear. Res.* 157, 1–42.
- Giard, M.H., Lavikainen, J., Reinikainen, K., Perrin, F., Bertrand, O., Pernier, J., Naatanen, R., 1995. Separate representation of stimulus frequency, intensity, and duration in auditory sensory memory: an event-related potential and dipole-model analysis. *J. Cogn. Neurosci.* 7, 133–143.
- Hawley, M.L., Litovsky, R.Y., Culling, J.F., 2004. The benefit of binaural hearing in a cocktail party: effect of location and type of interferer. *J. Acoust. Soc. Am.* 115, 833–843.
- Haykin, S., Chen, Z., 2005. The cocktail party problem. *Neural Comput.* 17, 1875–1902.
- Jasper, H.H., 1958. The ten–twenty electrode system of the international federation. *Electroencephalogr. Clin. Neurophysiol.* 10, 371–375.
- Kaiser, J., Lutzenberger, W., 2001. Location changes enhance hemispheric asymmetry of magnetic fields evoked by lateralized sounds in humans. *Neurosci. Lett.* 314, 17–20.
- Kaiser, J., Lutzenberger, W., Birbaumer, N., 2000. Simultaneous bilateral mismatch response to right—but not leftward sound lateralization. *NeuroReport* 11, 2889–2892.
- Martin, B.A., Boothroyd, A., 1999. Cortical, auditory, event-related potentials in response to periodic and aperiodic stimuli with the same spectral envelope. *Ear Hear.* 20, 33–44.
- McAlpine, D., Jiang, D., Palmer, A.R., 2001. A neural code for low-frequency sound localization in mammals. *Nat. Neurosci.* 4, 396–401.
- McDonald, K.L., Alain, C., 2005. Contribution of harmonicity and location cues to auditory object formation in free field: evidence from event-related brain potentials. *J. Acoust. Soc. Am.* 118, 1593–1604.
- McDonald, J.J., Teder-Salejarvi, W.A., Hillyard, S.A., 2000. Involuntary orienting to sound improves visual perception. *Nature* 407, 906–908.
- McEvoy, L.K., Picton, T.W., Champagne, S.C., Kellett, A.J., Kelly, J.B., 1990. Human evoked potentials to shifts in the lateralization of a noise. *Audiology* 29, 163–180.
- McEvoy, L.K., Picton, T.W., Champagne, S.C., 1991. Effects of stimulus parameters on human evoked potentials to shifts in the lateralization of a noise. *Audiology* 30, 286–302.
- Naatanen, R., 1991. Mismatch negativity outside strong attentional focus: a commentary on Woldorff et al. *Psychophysiology* 28, 478–484.
- Naatanen, R., 1992. *Attention and Brain Function*. Lawrence Erlbaum, Hillsdale, NJ.
- Naatanen, R., Picton, T., 1987. The N1 wave of the human electric and magnetic response to sound: a review and an analysis of the component structure. *Psychophysiology* 24, 375–425.
- Naatanen, R., Sams, M., Alho, K., Paavilainen, P., Reinikainen, K., Sokolov, E.N., 1988. Frequency and location specificity of the human vertex N1 wave. *Electroencephalogr. Clin. Neurophysiol.* 69, 523–531.
- Nager, W., Kohlmetz, C., Joppich, G., Mobes, J., Munte, T.F., 2003. Tracking of multiple sound sources defined by interaural time differences: brain potential evidence in humans. *Neurosci. Lett.* 344, 181–184.
- Paavilainen, P., Karlsson, M.L., Reinikainen, K., Naatanen, R., 1989. Mismatch negativity to change in spatial location of an auditory stimulus. *Electroencephalogr. Clin. Neurophysiol.* 73, 129–141.
- Picton, T.W., McEvoy, L.K., Champagne, S.C., 1991. Human evoked potentials and the lateralization of a sound. *Acta Oto-Laryngol., Suppl.* 491, 139–143.
- Picton, T.W., Alain, C., Otten, L., Ritter, W., Achim, A., 2000a. Mismatch negativity: different water in the same river. *Audiol. Neuro-Otol.* 5, 111–139.
- Picton, T.W., Bentin, S., Berg, P., Donchin, E., Hillyard, S.A., Johnson Jr., R., Miller, G.A., Ritter, W., Ruchkin, D.S., Rugg, M.D., Taylor, M.J., 2000b. Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria. *Psychophysiology* 37, 127–152.
- Pritchard, W.S., Shappell, S.A., Brandt, M.E., 1991. Psychophysiology of N200/N400: a review and classification scheme. *Adv. Psychophysiol.*, vol. 4. Jessica Kingsley, pp. 43–106.
- Ritter, W., Paavilainen, P., Lavikainen, J., Reinikainen, K., Alho, K., Sams, M., Naatanen, R., 1992. Event-related potentials to repetition and change of auditory stimuli. *Electroencephalogr. Clin. Neurophysiol.* 83, 306–321.
- Roeber, U., Widmann, A., Schroger, E., 2003. Auditory distraction by duration and location deviants: a behavioral and event-related potential study. *Brain Res. Cogn. Brain Res.* 17, 347–357.
- Ruusuvirta, T., 1999. From spatial acoustic changes to attentive behavioral responses within 200 ms in humans. *Neurosci. Lett.* 275, 49–52.
- Sams, M., Paavilainen, P., Alho, K., Naatanen, R., 1985. Auditory frequency discrimination and event-related potentials. *Electroencephalogr. Clin. Neurophysiol.* 62, 437–448.
- Scherg, M., 1990. Fundamentals of dipole source potential analysis. In: Grandori, F., Hoke, M., Romani, G.L. (Eds.), *Auditory Evoked Magnetic Fields and Electric Potentials*. Karger, Basel, pp. 40–69.
- Schroger, E., 1996. Interaural time and level differences: integrated or separated processing? *Hear. Res.* 96, 191–198.
- Schroger, E., Wolff, C., 1996. Mismatch response of the human brain to changes in sound location. *NeuroReport* 7, 3005–3008.
- Schroger, E., Wolff, C., 1997. Fast preattentive processing of location: a functional basis for selective listening in humans. *Neurosci. Lett.* 232, 5–8.
- Schroger, E., Tervaniemi, M., Winkler, I., Wolff, C., Naatanen, R., 1997. Processing of interaural cues used for auditory lateralization as revealed by the mismatch negativity. In: Schick, A., Klatte, M. (Eds.), *Contributions to Psychological Acoustics. Results of the Seventh Oldenburg Symposium on Psychological Acoustics*. Bibliotheks- und Informationssystem der Universität Oldenburg, Oldenburg, pp. 50–56.
- Shestakova, A., Ceponiene, R., Huottilainen, M., Yaguchi, K., 2002. Involuntary attention in children as a function of sound source location: evidence from event-related potentials. *Clin. Neurophysiol.* 113, 162–168.
- Snyder, E., Hillyard, S.A., 1976. Long-latency evoked potentials to irrelevant, deviant stimuli. *Behav. Biol.* 16, 319–331.
- Stekelenburg, J.J., Vroomen, J., de Gelder, B., 2004. Illusory sound shifts induced by the ventriloquist illusion evoke the mismatch negativity. *Neurosci. Lett.* 357, 163–166.
- Tervaniemi, M., Just, V., Koelsch, S., Widmann, A., Schroger, E., 2004. Pitch discrimination accuracy in musicians vs.

- nonmusicians: an event-related potential and behavioral study. *Exp. Brain Res.* 161, 1–10.
- Trainor, L.J., 2005. Event-related potential measures in auditory developmental research. In: Schmidt, L., Segalowitz, S. (Eds.), *Developmental Psychophysiology*. Cambridge Univ. Press.
- Trainor, L.J., McFadden, M., Hodgson, L., Darragh, L., Matsos, L., Barlow, J., Sonnadara, R.R., 2003. Changes in auditory cortex and the development of mismatch negativity between 2 and 6 months of age. *Int. J. Psychophysiol.* 51, 5–15.
- Trainor, L.J., Sonnadara, R.R., Wiklund, K., Bondy, J., Gupta, S., Becker, S., Bruce, I.C., Haykin, S., 2004. Development of a flexible, realistic hearing in noise test environment (R-HINT-E). *Signal Process.* 84, 299–309.
- Weeks, R.A., ziz-Sultan, A., Bushara, K.O., Tian, B., Wessinger, C.M., Dang, N., Rauschecker, J.P., Hallett, M., 1999. A PET study of human auditory spatial processing. *Neurosci. Lett.* 262, 155–158.
- Wenzel, E.M., Wightman, F.L., Kistler, D.J., 1991. Localization with non-individualized virtual acoustic display cues. Proceedings of the CHI'91 ACM Conference on Computer-Human Interaction. ACM Press, New York, pp. 351–359.
- Wenzel, E.M., Arruda, M., Kistler, D.J., Wightman, F.L., 1993. Localization using nonindividualized head-related transfer functions. *J. Acoust. Soc. Am.* 94, 111–123.
- Wightman, F.L., Kistler, D.J., 1989a. Headphone simulation of free-field listening: I. Stimulus synthesis. *J. Acoust. Soc. Am.* 85, 858–867.
- Wightman, F.L., Kistler, D.J., 1989b. Headphone simulation of free-field listening: II. Psychophysical validation. *J. Acoust. Soc. Am.* 85, 868–878.
- Woldorff, M.G., Hackley, S.A., Hillyard, S.A., 1991. The effects of channel-selective attention on the mismatch negativity wave elicited by deviant tones. *Psychophysiology* 28, 30–42.
- Woods, D.L., Alho, K., Algazi, A., 1992. Intermodal selective attention: I. Effects on event-related potentials to lateralized auditory and visual stimuli. *Electroencephalogr. Clin. Neurophysiol.* 82, 341–355.