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Short Communication

Occasional changes in sound location enhance middle latency evoked responses

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ABSTRACT

Rapid processing of sound location is critical for orienting attention. The present study investigated whether contextually sensitive early neural responses elicited by occasional changes in sound location could be measured. Using an oddball paradigm with stimuli consisting of brief noise bursts whose location was occasionally varied using head-related transfer functions, we found significant enhanced negativities in the event-related potentials elicited by deviant stimuli as early as 25 ms after stimulus onset, in addition to the differences around 125 ms which have previously been reported. Recent research suggests that occasional changes in auditory location information are processed in areas beyond primary auditory cortex. Our data suggest that any such processing is in fact preceded by activation in primary auditory cortex.

The ability to detect a change in the location of a sound source is important for steering the visual and attentional systems (McDonald and Ward, 2000; McDonald et al., 2000; Kubovy and Van, 2001). It serves as a primary cue for warning us of potential dangers that are outside of our visual and attentional foci (Heffner and Heffner, 1988, 1992), and can also guide us out of harms way (Boer and Withington, 2004). Given this, one might expect relatively fast 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. Indeed there is emerging evidence for distinct parallel pathways for 'what' and 'where' information from relatively peripheral levels in the auditory system (Alain et al., 2001; Weeks et al., 1999; Arnott et al., 2004; Eggermont, 2001) and for information regarding the location of a sound being available below the level of auditory cortex (Eggermont, 2001; McAlpine et al., 2001). Recent imaging studies, however, also show activation in regions posterior to primary auditory cortex when participants are asked to perform auditory spatial tasks (Alain et al., 2001; Arnott et al., 2004; Rauschecker and Tian, 2000; Tian et al., 2001). Other studies further implicate auditory cortex in sound localisation (Weeks et al., 1999; Efron et al., 1983; Al'tman et al., 2004), with some reporting profound deficits in localisation abilities when lesions affect the right hemisphere (Al'tman et al., 2004; Clarke et al., 2002; Cornelisse and Kelly, 1987). Thus, it seems that processing the location of an auditory stimulus activates a large neural network of areas, with many different stages and levels of processing.

Previous work using event-related potentials (ERPs) shows that neural responses to changes in location of an auditory

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stimulus can be recorded as early as around 120 ms (McEvoy et al., 1990, 1991; Picton et al., 1991; Sonnadara et al., in press), and appear to involve both the mismatch negativity (MMN) (Picton et al., 2000a,b) and the N1 responses (Naatanen and Picton, 1987). Nevertheless, given the large number of areas which are involved in processing location cues for auditory stimuli, and how important this information could be for survival, it seems unlikely that the first cortical registration of a change in location of an acoustic stimulus would occur this late after stimulus onset. Although a few studies have investigated the effects of stimulus location on the middle latency auditory-evoked potentials (MLAEPs) (Itoh et al., 2000; McEvoy et al., 1994), to date, very little work has been done looking at whether MLAEPs can be used as an index of change detection for location of an auditory stimulus in humans. In this study, we examined whether occasional changes in the location of a rapidly repeating stimulus are reflected in MLAEP responses, specifically the Na component, a negative deflection around 22 ms thought to reflect activity from primary auditory cortex (Eggermont and Ponton, 2002; Scherg and Von Cramon, 1986).

Eight paid volunteers (mean age = 26.1; 2 males, 6 females), all of whom were right handed, and without hearing problems, participated in this experiment. 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. All stimuli were single Gaussian white noise bursts of 20 ms duration, presented with a rectangularly distributed random SOA ranging between 100 and 200 ms (in 10 ms steps). Locations of the stimuli were specified by applying head-related transfer function coefficients to the stimuli prior to sending them to the headphone buffer (Sonnadara et al., in press; Wightman and Kistler, 1989a, b; Wenzel et al., 1993). All participants ran through an initial calibration procedure to ensure that appropriate coefficients were selected (Sonnadara et al., in press). The experiment was run using Matlab software on a PC computer, and was conducted in a sound-attenuating chamber (Industrial Acoustics Company). The continuous electroencephalogram (EEG) was recorded with Neuroscan software using a Synamps neural amplifier and 64-channel tin electrode caps (Electro-Cap International). EEG recordings were made at a sample rate of 2000 Hz using a Cz reference, and were digitally filtered between 0.1 Hz and 500 Hz at time of acquisition.

The experiment consisted of two blocks, each with 10,000 stimuli. In one block, standard stimuli consisted of a single noise burst presented from straight ahead (0°) whereas the deviant stimuli consisted of a single noise burst presented from 30° to the left (−30°). In the other block, the positions of the standard and deviant stimuli were reversed such that standard stimuli were all presented from −30° and deviant trials were all presented from 0°. The probability of receiving a standard stimulus was 90% across blocks, and trials were constrained such that at least 2 standard stimuli followed each deviant stimulus. Blocks were presented in random order across participants. To control for attentional effects, participants were instructed not to focus on the stimuli, but rather on a silent (captioned) DVD of their choosing, about which they were told that they would be questioned after the experiment.

The continuous EEG was first band pass filtered between 0.5 and 100 Hz, then re-referenced to a common-average reference (Picton et al., 2000a,b), and segmented into 400 ms epochs including a 100 ms prestimulus window. All epochs on which the measured activity at any electrode exceeded ± 100 μV were rejected as containing movement/blink artifact. Remaining epochs were then sorted, baseline corrected on the prestimulus window, and averaged so that for each participant, both presentation locations (−30/0°) under each context (standard/deviant) had their own average. Across participants and blocks, the number of included deviant trials varied between 434 and 838 (means = 642 for deviant stimuli presented from −30°, and 655 for deviant stimuli presented from 0°). For each condition, fronto-central waveforms were dominated by an early negative component (Na) peaking around 25 ms, a positive component (P50), peaking around 50 ms, a negative component peaking around 125 ms probably reflecting N1 and MMN, and then a positive component peaking around 185 ms probably reflecting P2 and P3 (see Figs. 1, 3, and 4). The polarity of all of these components reversed at mastoid and occipital sites, consistent with generators in auditory areas.

Statistical analyses were carried out on 2 clusters of electrodes [C5/C3/C1] and [C6/C4/C2] since these best captured the components of interest. To investigate the early Na and P50 components, the mean amplitudes of the evoked response within 10 ms windows centred around 25 ms and 50 ms after stimulus onset were measured. To investigate changes in the later components, the mean amplitudes of the evoked response within a 30 ms window centred around 125 ms and 185 ms after stimulus onset were measured. For all windows, the effects of stimulus context (standard/deviant) were examined with separate analyses of variance.

For the Na component (25 ms), there was a significant main effect of context, with deviant stimuli eliciting a more negative response than standard stimuli ($F[1,7] = 17.43$, $P < 0.005$) (see Figs. 1 and 2). Visual inspection revealed that when deviant stimuli were presented on the left, the

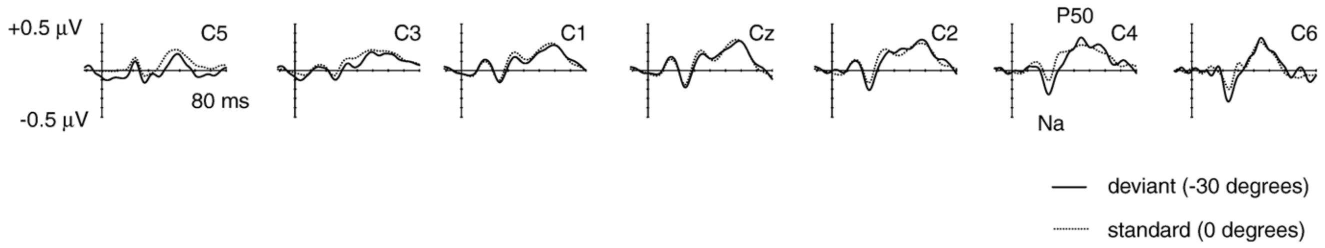

Fig. 1 – Coronal electrodes showing the group mean event-related potentials elicited by standard (0°) and deviant (− 30°) stimuli.

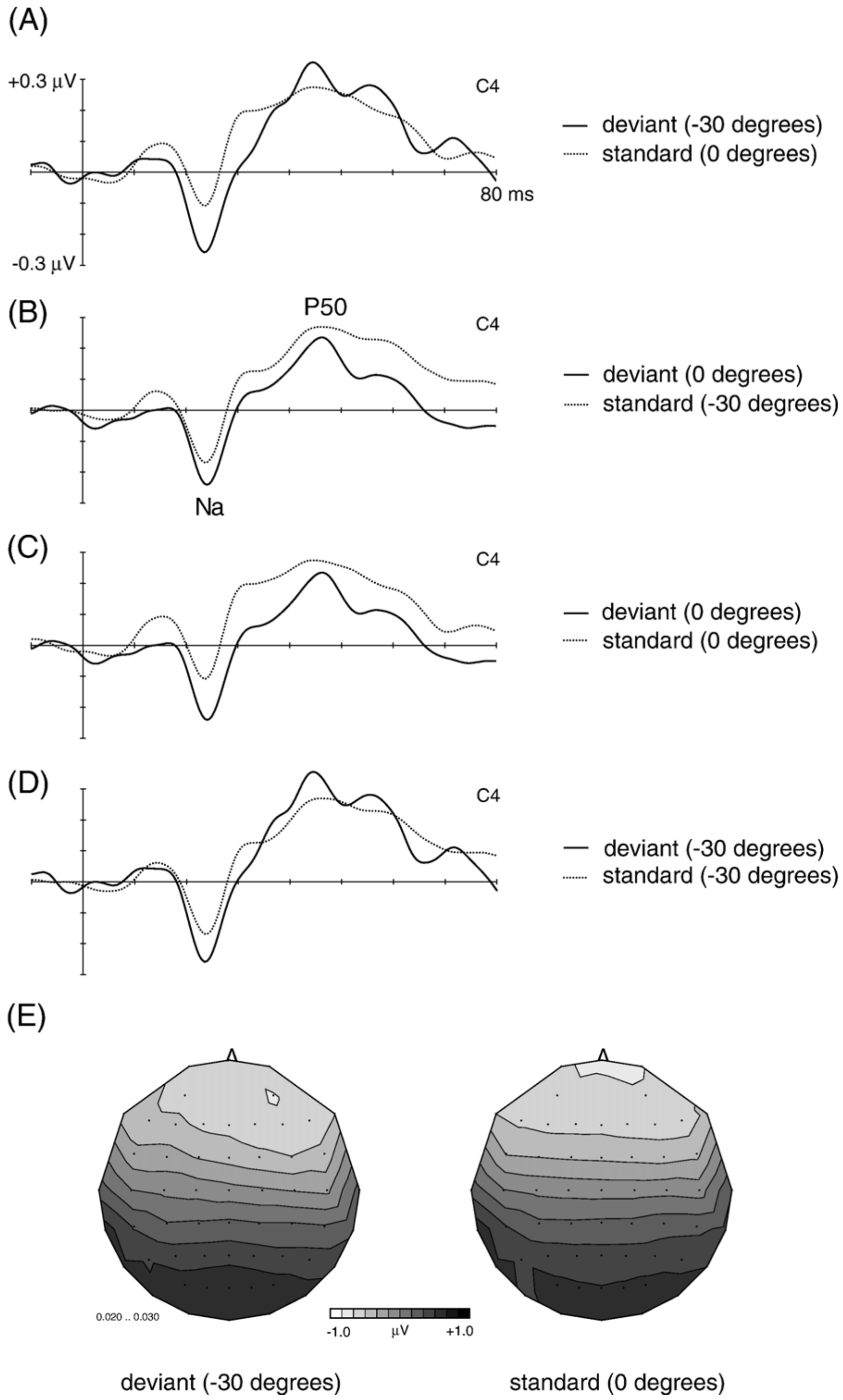

Fig. 2 – Group mean event-related potentials recorded at C4. The ERPs elicited by standards and deviants from the same block of trials are illustrated in panels A and B. Those coming from different blocks but emanating from the same location are illustrated in panels C and D, which show that enhanced Na amplitude depends on the context of the stimuli presented, rather than their physical location. Panel E shows scalp topographies elicited by standard (0°) and deviant (–30°) stimuli. Statistical analysis on the normalised mean amplitudes revealed no significant differences between the distributions.

difference between responses to the standard and deviant stimuli was larger on the right (see Figs. 1 and 3A). When standard stimuli were presented on the left and deviant stimuli from the centre, there were no hemispheric differences apparent in the difference waves. We statistically compared the normalised mean amplitudes within the 10 ms window used for the previous analyses. For both deviant locations, we found no significant differences between the standard and deviant distributions, indicating that the enhanced negativity around 25 ms is either being caused

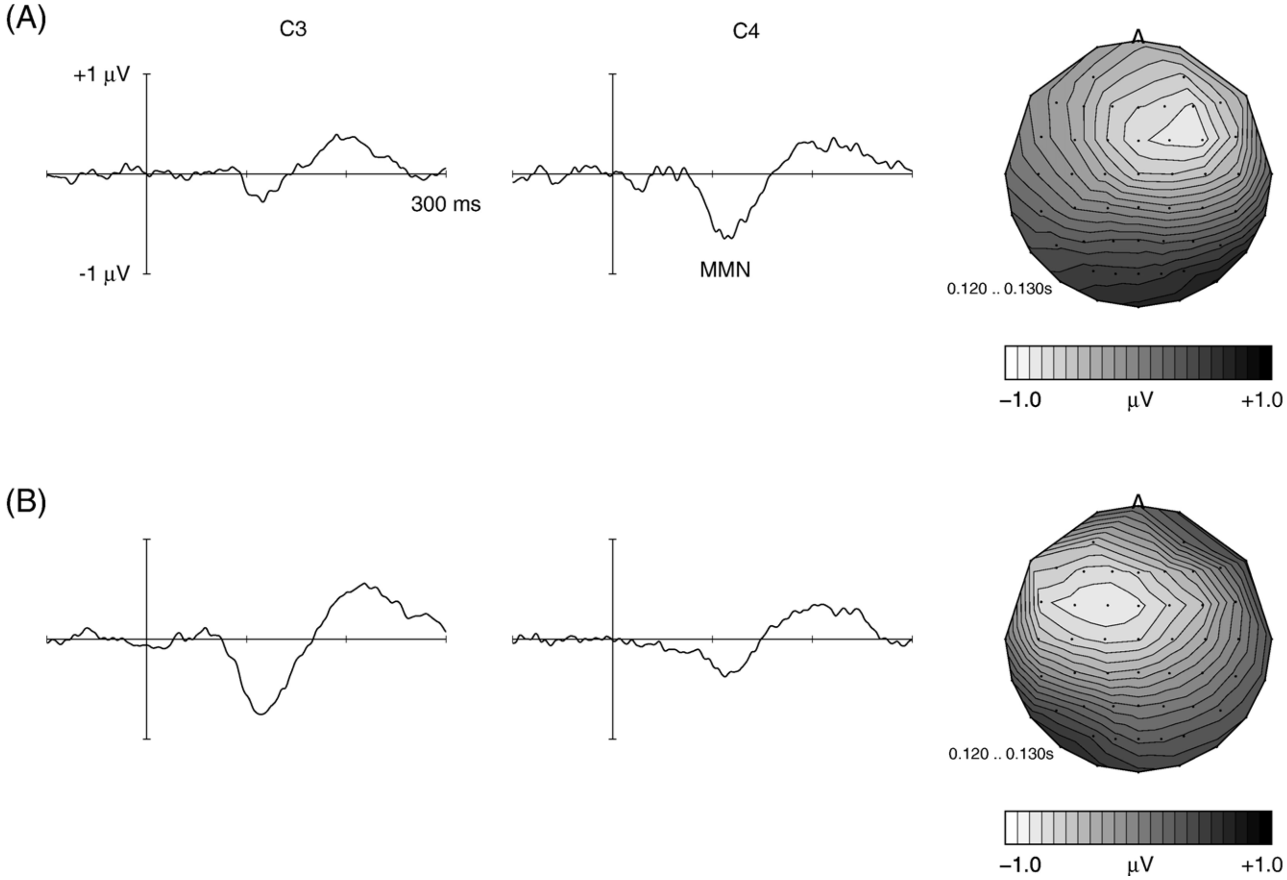

Fig. 3 – Group difference waves showing the full 400 ms epoch and topographic maps for the period 120–130 ms. (A) When deviant stimuli are presented from 30° on the left, and standards from 0°, differences in the ERPs are larger on the right. (B) When deviant stimuli are presented from 0°, and standard stimuli from 30° on the left, differences in the ERPs are larger on the left.

by modulation of the Na response, or by an additional nearby source which cannot be distinguished from the original generator.

There were no significant differences in the P50 component across conditions. There was a main effect of context for the later negativity (125 ms), with deviant stimuli again generating

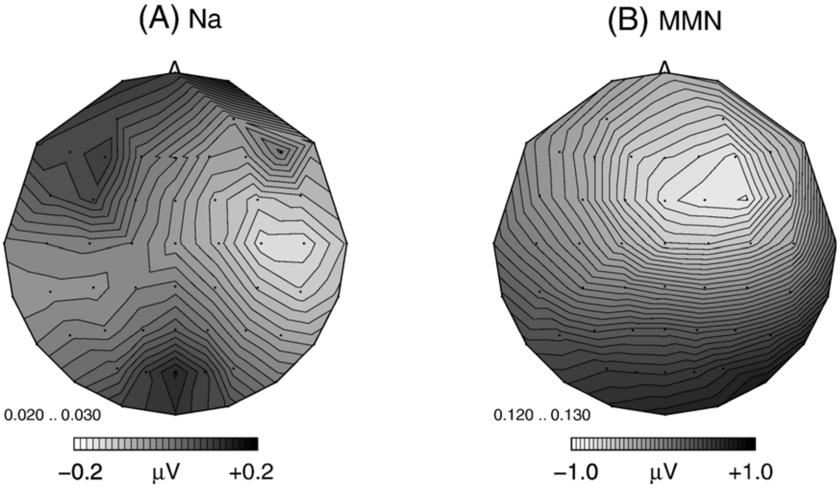

Fig. 4 – Scalp topographies showing the distribution for (A) Na and (B) MMN components of the difference waves elicited when deviant stimuli, presented from −30°, occasionally interrupt a repeating standard stimulus presented from 0°. Statistical analysis revealed these distributions to be significantly different from each other.

a more negative response than standard stimuli ($F[1,7] = 28.45$, $P < 0.001$). As with the Na, voltage topographies revealed that for deviant stimuli presented on the left, the difference between responses to the standard and deviant stimuli was larger on the right (see Fig. 3A). However, unlike the Na response, when standard stimuli were presented on the left and deviant stimuli from centre, the difference between responses to the standard and deviant stimuli was larger on the left (see Fig. 3B). The later positivity also showed a main effect of context, with deviant stimuli generating a more positive response than standard stimuli ($F[1,7] = 38.67$, $P < 0.001$). Visual inspection of the voltage topographies revealed a similar lateralisation pattern to the later negative response (see Fig. 3).

To investigate whether the Na response had a different scalp distribution from the MMN response, we examined scalp topographies for normalised mean amplitudes within the 10 ms windows reported for the Na and MMN components using a repeated measures analysis of variance with electrode, angle of presentation (30 or 0°), and component (Na or MMN). This analysis revealed a significant 2-way electode × component interaction ($F[60,240] = 30.532$, $P < 0.01$), and also a significant 3-way angle × electrode × component interaction ($F[60,240] = 24.121$, $P < 0.01$). To examine this further, separate ANOVAs were run on the different components, with electrode and angle as the factors. This analysis revealed a significant interaction for the MMN component ($F[60,240] = 11.564$, $P < 0.01$), but not the Na component ($P > 0.05$). These analyses suggest that the Na and MMN responses had at least somewhat different neural generators (see Fig. 4).

The later negative and positive deflections we observed are consistent with previous work which shows that occasional changes in the location of a stimulus elicit a biphasic negative/positive response at fronto-central sites, with difference waves showing a fronto-central negativity peaking around 125 ms and a positivity peaking around 200 ms (Sonnadara et al., in press; Sams et al., 1985; Paavilainen et al., 1989; Snyder and Hillyard, 1976). Using Brain Electrical Source Analysis (Scherg, 1990), we were able to localise the sources eliciting this later negative response to posterior areas of the temporal lobe, complementing the findings of other recent neuroimaging studies (Kaiser et al., 2000; Arnott et al., 2005; Kaiser and Lutzenberger, 2001) which lend support to models which suggest separate processing streams for 'what' and 'where' information in the auditory system (Alain et al., 2001; Arnott et al., 2004; Rauschecker and Tian, 2000; Tian et al., 2001; Hart et al., 2004).

Interestingly, we also observed an early enhanced negativity to deviant stimuli which preceded this later response by almost 100 ms. This enhanced negativity was present irrespective of physical location of the standard and deviant stimuli (see Figs. 2C and D). We propose that this enhanced Na amplitude indexes a preattentive change detection process which may precede more attention-dependent analyses of deviant stimuli. Information from this early cortical processing is perhaps sufficient to orient visual and attentional resources to unexpected changes in location in our acoustic environment. Further work is required to investigate whether this processing extends to different magnitudes of stimulus change and to other stimulus dimensions such as pitch, timbre, and intensity.

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