# Spatial asymmetries of auditory event-synthesis in humans

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**Abstract**

We used the mismatch negativity event-related potential to examine how spatial location and feature variation affect the capacity of the auditory system to automatically respond to pairs of rapid (180 ms apart) acoustic changes within a single tone. When a tone first deviated from a standard tone in source location and then in its duration, we found independent responses to both deviations for right but not left field stimuli. In contrast, when the first deviation was in pitch and the second in duration, only the first deviation elicited a response, regardless of presentation side. These results suggest that information from either side of space is asymmetrically processed even in a free-field, and that the extent of the temporal window of integration is not a fixed property of the auditory system.
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In a complex auditory scene, a rapid flow of multi-dimensional information emanates from multiple locations. This flow must be organized into coherent percepts to allow predictive processes, detection of changes, and goal directed action. Yet, previous research pointed to constraints in the way the human auditory system processes rapidly occurring events [1]. The auditory system apparently applies a temporal window of integration (TWI) to the sensory stream so that individual changes within the TWI cannot be treated separately [1,15,18]. Here we show, using the mismatch negativity (MMN) event-related potential as a probe, that the TWI depends on the location of the stimulus in space as well as on the features to be processed.

The MMN is an automatic brain response to acoustic change. Experimentally, it is elicited by presenting a series of repetitive tones (standards) infrequently interrupted by a tone that differs in one or more features (deviant). Subjects usually attend to a visual task, ignoring the tones. The MMN potential is negative at the frontal scalp and positive at lower temporal sites, peaking 100–250 ms following the deviation. It is assumed to reflect the manipulation of auditory sensory memory in response to a deviant event, either in detecting the deviation and triggering an attention switch [9], or in updating a predictive model of the environment [16].

Winkler et al. probed the temporal constraints of this process using paradigms in which two deviations occur in close temporal proximity [2,13–15]. For example, when a deviant tone is both lower in pitch and shorter than the standard tone, the pitch change is detectable at the onset of the tone, but the duration change cannot be detected until the deviant tone has ended [2]. Since the MMN is time-locked to the moment of deviation, two temporally separated MMNs may be elicited. However, two MMNs were in fact elicited only if deviations in a single tone were separated by more than about 170 ms, suggesting a TWI within which the sensory information is processed as a single event (see also Refs. [17,18]). Presumably, the TWI precludes consecutive MMN responses for changes from a given regularity within the window's limits [13], as if there is no ecological merit in tagging an event as a deviant twice. Yet, to what extent is this window a fixed property of the auditory system? There is compelling evidence for independence of the memory traces for individual features [3,4,7,10]. The side of space where stimuli are presented also affects the processing of deviation [5,6]. To explore the effect of feature and side of presentation on the TWI, we separated two deviations in the same stimulus by 180 ms, on the border of the TWI, thus increasing the sensitivity to the experimental manipulation.

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Experiment 1 examined the effect of presentation side with deviations in spatial location of the stimulus source (7% of trials), duration of the stimulus (7%) or both ('double-deviants'; 7%). Standard stimuli (79% of trials) were 180 ms long tones (fundamental of 540 Hz and three attenuated harmonics) presented at 75 dB(a) SPL from loud-speakers located, in separate blocks, 60° to the left or right of the subjects' mid-plane. Location deviants and double deviants originated from a loudspeaker on the same side as the standard, but 30° closer to the midline. Duration deviants and double deviants were 300 ms long. Twelve undergraduate students (mean age: 22.9, six males, 11 right- and one left-handed) were asked to ignore the sounds, while watching a silent movie. Two subjects' data were rejected for excessive artifacts. Five blocks of 500 stimuli were presented on each side in an alternating sequence, counterbalanced across subjects. The electroencephalogram was sampled at 250 Hz (analog filter:0.01–40 Hz) from 61 scalp electrodes referenced to the tip of the nose. Trials contaminated by muscle or ocular artifacts (measured by two EOG channels) or amplifier saturation were rejected. The MMN was identified by subtracting the waveform elicited by the standard from that of each deviant. Differ-ence waves were digitally filtered with a band pass of 1–12 Hz [11] and measured relative to the mean of a pre-stimulus baseline of 100 ms. Statistical analysis was based on a spatial average of the following pre-selected group of fron-tal electrodes: AF3/4, F3/4, FC3/4, Fz, FCz, F5/6.

Duration deviants and location deviants elicited similar MMNs (Fig. 1) most prominent frontally and accompanied by polarity inversion at the mastoids (not shown). There were no significant amplitude differences across sides of presentation. The peak latency at Fz of the location MMN on the right and left was 188 and 192 ms, respectively. Duration deviance on either side elicited a MMN with a peak latency of 332 ms (onset: 240 ms, offset: 376 ms). We used these latencies as time tags for examining the waveform elicited by the double deviant. The double devi-ant elicited a clear MMN at a latency compatible with a response to the location change for both right and left side presentation, whereas a second MMN with latency compa-tible with the duration change, can be clearly seen only for right side presentation (Fig. 1a). However, at the time when a duration MMN is expected, the waveform for single loca-tion change is characterized by a positivity (P3a [12]) that may mask the second MMN in the double deviant case. We reasoned that if the double deviant elicited two independent MMN/P3a responses then its waveform should be similar to the sum of the location and duration single deviant wave-forms. Fig. 1b presents the calculated sum of the single deviants superimposed on the response to the double devi-ant. Whereas the two waveforms are quite similar in the case of right side stimuli, they differ in the case of left side stimuli, especially at the latency range of the single duration deviant (shaded area). A within-subject ANOVA of Side (left, right) × Condition (double, sum) of mean amplitude
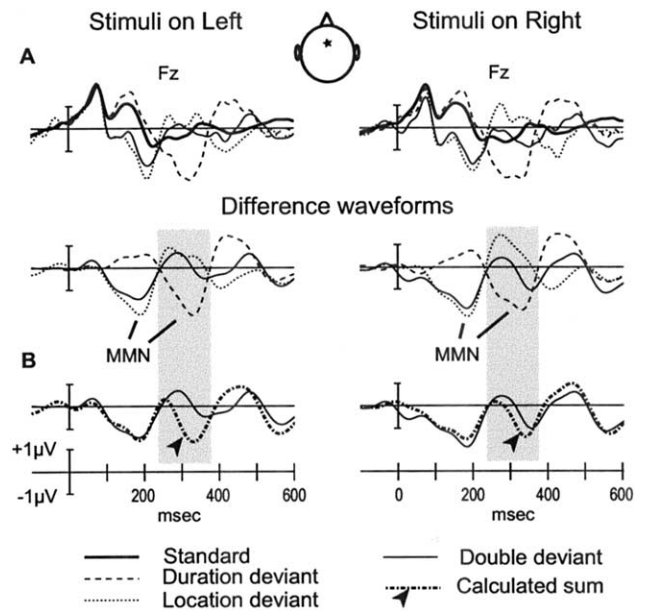


Fig. 1. Results of Experiment 1. Waveforms show the evolution of scalp electrical potential from 100 ms before to 600 ms after the onset of tones, measured at a midline frontal site (Fz, star in head inset), in response to presentation on the left and on the right. Time zero is at the onset time of the stimuli. (A) Top row: Response to standards and three deviants: location, duration and location and duration together (double-deviant). Middle row: Difference waves (deviant minus standard) for the three types of deviants highlight the MMN. The MMN to the duration change is later than for location change, because is it triggered by the point of *offset* of the standard (180 ms). (B) Double-deviant difference wave (same as in A) and the sum (black arrowhead) of the two single deviants (location + duration). The shaded area denotes the latency of the duration MMN, where a second response is expected in the double deviant condition. Note that the sum of the single deviant waveforms only predicts the double deviant waveform in the case of right side presentation.

at this latency range revealed an effect of condition ($F(1, 9) = 15.1$, $P < .001$) no effect of side ($F(1, 9) < 1$) and a trend toward an interaction ($F(1, 9) = 4.48$, $P = 0.063$). In fact, examining the individual results, the size of the interaction may have been reduced by the presence of a single (right handed) subject who showed a prominent reversed side effect. Excluding this subject, the interaction between the side and the condition was robust ($F(1, 8) = 12$, $P < 0.01$). Planned comparisons (including all ten subjects) for each side showed that the double-devi-ant and the sum waveforms did not significantly differ during the latency of the duration MMN in the case of right side stimuli ($t(9) = 2.107$, n.s.). Thus, the prediction of linear summation cannot be rejected. In contrast, there was a significant difference in the case of left side stimuli ($t(9) = 3.619$, $P < 0.01$). In summary, a duration change occurring 180 ms after a location change in the same stimu-lus elicited an MMN only when the stimuli were on the right.

Previously, two MMNs within time windows shorter than 200 ms were elicited only when the deviations violated two
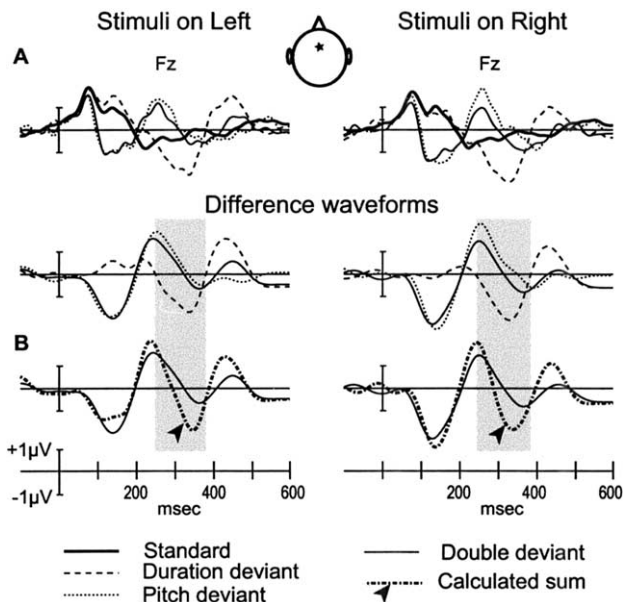
Fig. 2. Results of Experiment 2. As in Fig. 1, except that pitch deviance replaces location deviant. Note that for both left and right side presentation the sum of the single deviant waveforms does not predict the double deviant waveform.

distinct regularities: the within-stimulus feature combination of the standard (its pitch, intensity, duration etc.), and the between-stimuli temporal order [13,14]. If the two deviations were within one regularity (e.g. pitch and duration), only one MMN was elicited [13,14]. Here, we found two MMNs for consecutive deviations violating the within-stimulus regularity, albeit limited to right-side stimuli. We considered two explanations for this side effect: (1), rapidly occurring changes on the right are better processed because of the left hemisphere's presumed specialization for high frequency event processing (the 'frequency hypothesis') [8]; (2), spatial changes on the right are less well perceived because the left hemisphere is less apt at processing spatial information [8], and therefore a second MMN can be elicited despite the detection of the first (spatial) deviation (the 'feature hypothesis').

In Experiment 2 we replicated the methodology of Experiment 1, except that pitch replaced location as the initial deviant feature (deviant pitch fundamental of 600 Hz vs. the 540 Hz standard). If the 'frequency hypothesis' is valid, the dissociation between right and left stimuli should persist. However, if the dissociation is related to the spatial nature of the deviance in Experiment 1 (the 'feature hypothesis'), it should disappear in Experiment 2.

Twelve subjects (mean age: 21, seven males, 11 right handed, one ambidextrous) participated in Experiment 2, four of whom also participated in Experiment 1. Single deviants again elicited robust MMN/P3a complexes (Fig. 2). For both right and left side deviations, the double deviant waveform was different than the sum of the single deviant waveforms in the latency range of the duration MMN (Fig. 2b). Within-subject ANOVA of Side (left, right) ×

Condition (double, sum) showed a Condition effect ($F(1, 11) = 6.8$, $P < 0.05$) no Side effect ($F(1, 11) = 1.1$, n.s.) and no interaction ($F(1, 11) < 1$). In fact, the response to the double deviant followed closely the response to the single pitch deviant (Fig. 2a). Hence, in Experiment 2 a second MMN could not be observed in the double deviant condition, regardless of side of presentation.

The principal finding in this study was that a second MMN could be elicited 180 ms after a location deviation in the right hemifield, but not in any other condition. This is in line with our 'feature hypothesis,' implicating hemispheric asymmetry in processing spatial information, consistent with the finding that in patients with right hemisphere damage, MMN to location deviation on the left is specifically affected [5]. Single deviations in location are apparently not sensitive to this asymmetry (current results and references [4,5]) perhaps because the deviations tested are supra-threshold. In conclusion, the TWI is not a universal property of auditory processing, but depends on the features processed and the spatial location of stimuli. Although we intuitively view the space around us as symmetrical in respect to sensory processing capacities, this may not be the case, even when sounds in free-field reach both ears and both hemispheres. That is, not only is there considerable lateralization in the way our hemispheres are specialized, but this specialization affects the way we process information depending on its spatial source location.

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