

REPRESENTATIONS of abstract attributes of auditory stimuli in the human brain were demonstrated using the mismatch negativity (MMN), an event-related potential component elicited by a change in a repetitive sound. Stimuli were pairs of sinusoidal tones. There were two types of tone pairs in each block, standard ($p = 85\%$) and deviant pairs ($p = 15\%$), delivered in a random order. Standard and deviant tone pairs differed only in the direction of within-pair frequency change. In addition, the frequency levels of both the standard and deviant pairs varied randomly within a wide range in a block; thus the standard pairs shared the direction of the within-pair frequency change but not the absolute frequency level. Correspondingly, the deviant pairs only shared the opposite direction of the within-pair change. Nevertheless, the deviant tone pairs elicited MMN, implying that even the direction of the within-pair frequency change of the standard stimuli, and not just their absolute frequencies, developed a neural representation.

Key words: Neural representations; Audition; Event-related potential; Mismatch negativity

Representation of abstract attributes of auditory stimuli in the human brain

Jukka Saarinen,^{CA} Petri Paavilainen, Erich Schöger,¹ Mari Tervaniemi and Risto Näätänen

University of Helsinki, Department of Psychology, Ritarikatu 5, SF-00170 Helsinki, Finland; ¹Ludwig-Maximilians-Universität München, Institut für Psychologie, Allgemeine Psychologie, Leopoldstrasse 13, 8000 München 40, Germany

^{CA} Corresponding Author

Introduction

Both audition and vision derive various kinds of representations of the physical environment from information contained in sensory signals. That is, the sensory systems develop representations for such stimulus attributes which are not explicit in signals but require computations to become unambiguously represented.¹ In the present communication, we demonstrate the existence of an early neural representation for an abstract attribute of auditory stimuli, that is, for a 'concept', in the human brain.

We used the recently discovered 'mismatch negativity' (MMN) component² of the event-related potential (ERP) to probe the neural representations of auditory stimuli. In the MMN paradigm, an auditory stimulus, the 'standard', is repeatedly presented with short intervals. When some physical dimension of the 'standard' stimulus, such as intensity, frequency, duration, or spatial location,³ is occasionally and randomly changed, the 'deviant' stimulus triggers MMN, which is generated in the auditory cortex.^{4,5} Because MMN is not elicited by infrequent stimuli *per se* (i.e. without standard stimuli), it implicates a comparison process between the auditory input from a deviant stimulus and a neural representation of the standard stimulus:⁶ if a deviant stimulus is delivered during the duration of the neural trace of the standard stimulus, a mismatch process generating MMN occurs. It also seems that MMN reflects early ('preattentive', 'automatic') stages of auditory information processing because MMN is elicited even in the absence of attention.^{2,3} Hence, MMN provides a tool for investigating the early neural

representations of auditory stimuli. The present aim was to determine whether these traces could, besides physical stimulus features, also represent abstract stimulus attributes: if a change in such an attribute elicits MMN, then even this attribute is, presumably, represented by these traces.

The abstract stimulus attribute studied here was *the direction of frequency change*. The standard and deviant stimuli consisted of pairs of short sinusoidal tones. The frequency of the second tone in a pair was either (1) identical to the first tone ('no change'), (2) higher ('an ascending pair'), or (3) lower ('a descending pair') than the first tone. The standard and deviant pairs differed from each other in the direction of the frequency change. For example, when standards were ascending pairs, deviants were either descending or no-change pairs in different blocks. In addition, the frequency levels of both the standard and deviant pairs varied randomly within a stimulus block. The frequency of the first tone in a pair was either 523, 587, 659, 740, 831, or 932 Hz (musical scale). If there was a frequency change within a pair, it was limited to one frequency step in magnitude. So the question was whether the neural trace was able to encode the direction of the within-pair frequency change *per se*, that is, despite the large random fluctuation of the *absolute* frequency levels of the pairs. The standard and deviant tone pairs of the four experimental conditions are schematically depicted in Figure 1. In *Condition 1*, the standards were ascending pairs and the deviants descending pairs. In *Condition 2*, the standards were ascending pairs and deviants no-change pairs. *Condition 3* was the reversal of Condition 2: the standards were no-

change pairs and deviants ascending pairs. In *Condition 4*, the standards consisted of both ascending and descending tone pairs in a random order while deviants were no-change pairs.

Materials and Methods

The standard and deviant tone pairs (the intensity being 80 dB SPL) were presented in a random order through earphones to the subject's left ear in an acoustically and electrically shielded room. The silent time interval between two sinusoidal tones of 60 ms (including 10 ms rise and fall times) was 40 ms and the inter-pair offset-onset interval was 640 ms. Stimuli were delivered in blocks of 400 tone pairs with the probability of 0.15 for a deviant pair. Each block was repeated three times in each condition. Subjects were instructed to ignore the auditory stimuli and read a self-selected book.

The EEG was recorded at frontal (F_z) and central (C_z) midline locations with Ag-AgCl electrodes. The nose was the reference for both electrodes. The EEG was amplified with frequency limits of 0.1–100 Hz

(continuous sampling) and stored on a computer disk for off-line averaging. The EEG epochs during which the EEG changes exceeded 150 μ V were automatically omitted from averaging. The averaging period was 550 ms, starting 50 ms before the onset of the first tone in a pair. Frequencies higher than 30 Hz were digitally filtered out (FFT filter) from the ERPs.

Results and Discussion

Figure 1 shows that MMN occurred to the deviant tone pair in all four conditions. The MMN responses typically started 50–100 ms after the onset of the second tone in a pair and reached the maximum amplitude at 100–200 ms.

To test the statistical significance of MMN, we calculated the difference waveforms where ERPs to standards were subtracted from those to the corresponding deviants. MMN was measured from the difference waves as a mean amplitude during a latency-window of 200–300 ms from the onset of the stimulus pair (Table 1). One-tailed *t*-tests confirmed that the negativity differed significantly from zero in that

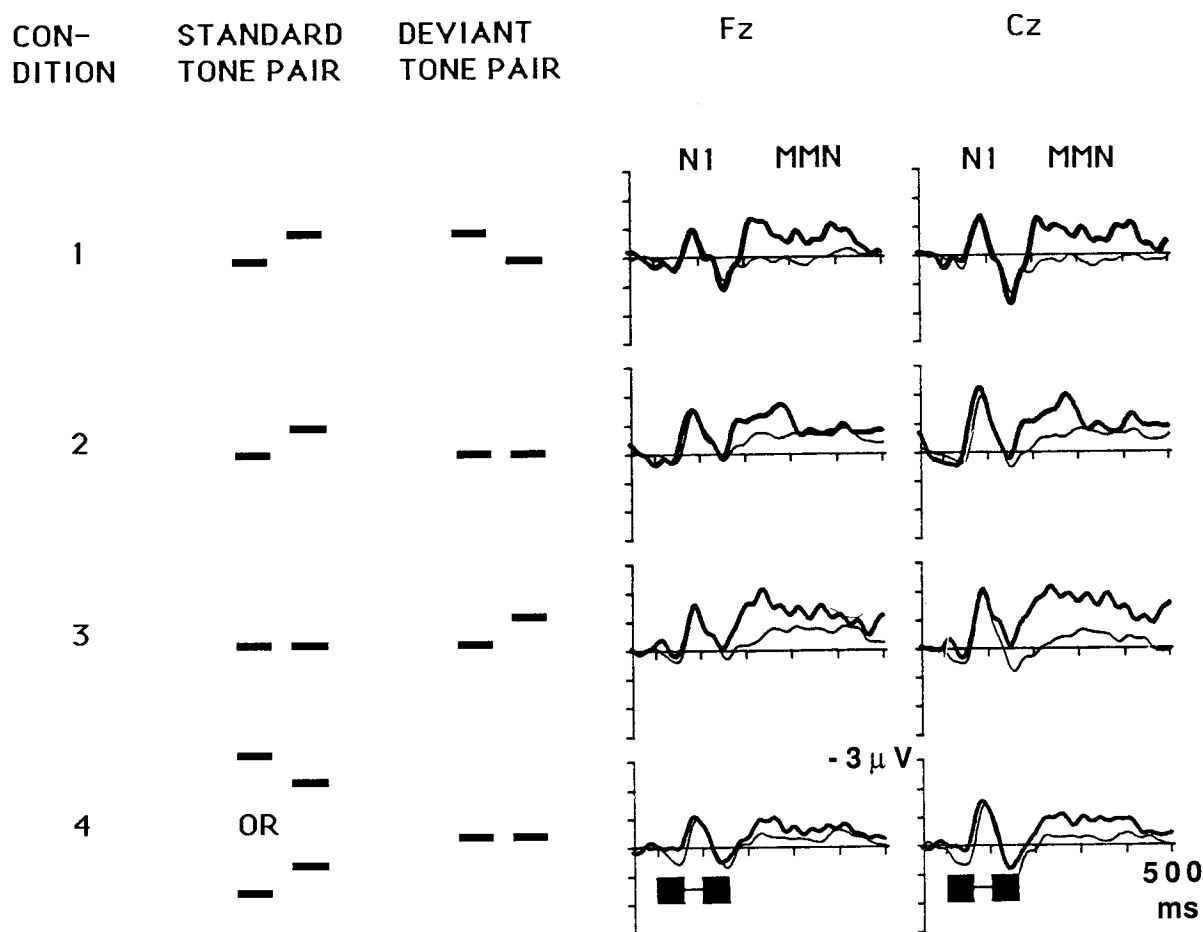


FIG. 1. Grand-average (10 subjects) frontal (F_z) and central (C_z) ERPs to the standard and deviant tone pairs in the four experimental conditions schematically illustrated on the left. Standard and deviant tone pairs differed in the direction of the within-pair frequency change, but not in the (mean) absolute frequency which was randomly varied. Temporal course of a stimulus pair is shown below. Thin lines represent responses to the standard tone pairs and thick lines represent responses to the deviant pairs. The N_1 wave was very similar to the standard and deviant tone pairs, whereas only the deviant tone pairs elicited MMN.

Table 1. Mean MMN amplitudes (μV), measured from the difference waves where ERPs to standard pairs were subtracted from those to deviant pairs, during a latency-window of 200–300 ms from the onset of the stimulus pair.

Experimental condition	F_z		C_z	
	Mean amplitude	t(9) amplitude	Mean	t(9)
1	-1.03	-2.93**	-1.09	-2.18*
2	-0.79	-1.27	-0.98	-1.98*
3	-1.15	-2.60*	-1.63	-2.61*
4	-0.44	-1.02	-0.63	-2.08*

* $p < 0.05$, ** $p < 0.01$, one-tailed t -test

latency-window in all four experimental conditions (Table 1), but did not differ between the different conditions (F_z : $F(3,27) = 0.37 < 1$; C_z : $F(3,27) = 0.60 < 1$).

The results thus indicated that the pairs with a within-pair frequency change differing in direction from that of the standards elicited MMN even though the absolute level of the frequency pairs varied randomly. This implies that the direction of frequency change *per se* was represented in the neural memory trace reflected by MMN.

Conclusions

The early neural representation seems to be able to encode not only physical features of repetitive stimuli,³ but also abstract attributes corresponding to simple concepts ('rise', 'fall'), that is, to derive a common invariant feature from a set of individual varying physical events.

References

1. Marr D. *Vision*. San Francisco: Freeman, 1982.
2. Näätänen R, Gaillard AWK and Mäntysalo S. *Acta Psychologica* **42**, 313–329 (1978).
3. Näätänen R. *Behav Brain Sci* **13**, 201–288 (1990).
4. Sams M, Hämäläinen M, Antervo A *et al*. *Electroenceph clin Neurophysiol* **61**, 254–266 (1985).
5. Giard M-H, Perrin F, Pernier J *et al*. *Psychophysiol* **27**, 627–640 (1990).
6. Näätänen R, Paavilainen P, Alho K *et al*. *Neurosci Lett* **98**, 217–221 (1989).

ACKNOWLEDGEMENTS: This study was supported by The Academy of Finland.

Received 21 September 1992;
accepted 11 October 1992