ACTIVATION OF BRAIN MECHANISMS OF INVOLUNTARY ATTENTION TO DIFFERENT MAGNITUDES OF AUDITORY FREQUENCY DEVIATION

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Abstract

Event-related brain potentials (ERPs) were recorded to auditory frequency changes of different magnitudes in 13 subjects performing on a visual discrimination task. Subjects were presented with pairs of stimuli consisting of a sound followed after 300 ms by a visual target. Subjects were instructed to press a response button according to the type of visual stimulus (odd/even numbers) appearing on a computer screen and to ignore the sounds. These were a standard tone (p=0.82; 600Hz, 150ms, 90dB) and deviant tones that differed in frequency from the standard tone in 5% (630Hz), 10% (660Hz), 15% (690Hz), 20% (720Hz), 40% (840Hz) and 80% (1080Hz) (p=0.03 each). Standard minus deviant ERPs revealed the mismatch negativity (MMN) for the smallest deviations (from 5% to 20%) and an N1 enhancement for the largest deviations (from 15% to 80%). Following these responses, P3a was elicited by deviations from 15% to 80%, its amplitude increasing logarithmically as a function of deviation. A subsequent reorienting negativity (RON) was elicited for all deviations, with increasing amplitude as a function of deviation according to a linear function. The present data reveal that the brain mechanisms of involuntary attention are activated differently according to the salience of the frequency change.

The detection of subtle changes in the auditory stimulation is reflected in the brain electrophysiological response *mismatch negativity* (MMN; Näätänen et al., 1978). MMN is generated when a new incoming auditory input does not match with the neural trace of the previous repetitive stimulation held in auditory sensory memory (Näätänen, 1990; for a review, see Picton et al., 2000). MMN has bilateral generators in auditory cortex (for a review, see Escera et al., 2000), which have been proposed to reflect the analysis of the stimulus features and the sensory memory processes involved in MMN generation (Näätänen, 1992; Giard et al., 1990). MMN has additional generators in frontal cortex (for a review, see Escera et al., 2000), which have been proposed to reflect the orientation of attention towards the detected change (Näätänen, 1992; Giard et al., 1990).

Subsequently to MMN, the generation of the P3a response reflects the effective orienting of attention towards a change in the sensory environment (Knight, 1984). The P3a is generated

by a large-scale cerebral network at the occurrence of unexpected attention-catching novel events in a monotonous context of stimulation. Following the P3a, a large-amplitude negative response is generated over frontal areas when irrelevant auditory changes occur during the performance of a task. This response, called *reorienting negativity* (RON; Schröger and Wolff, 1998; Berti and Schröger, 2001), has been proposed to reflect the reorientation of attention towards the primary task after momentary distraction (Escera et al., in press).

Tiitinen et al. (1994) have reported shorter latency and larger amplitude of the MMN as a function of increasing the difference in frequency (from 0.5% to 13%) between the standard and the deviant sounds. These authors have also related these changes in MMN parameters to performance, as reaction time decreased as a function of increasing frequency deviation. Similar results have been obtained by Amenedo and Escera (2000), who reported that the amplitude of MMN to decreasing or increasing changes in stimulus duration predicts the accuracy of behavioral detection of these changes, suggesting that the MMN could be a reliable index of auditory discrimination.

These results suggest that, with increasing deviation, there is a larger activation of the cerebral mechanisms underlying MMN generation as reflected in its larger amplitude. One should therefore expect a similar parametric activation of the other cerebral mechanisms in the sequence of brain events leading to involuntary attention (i.e., P3a and RON) at the occurrence of increasing deviations. In the present study, behavioral and electrophysiological responses were studied to the occurrence of changes of increasing magnitude (from 5% to 80%) in the frequency of auditory stimulation.

Materials and methods

Thirteen healthy human subjects (mean age: 21.5 years, SD=4.38; 4 males; 2 left-handed), with normal hearing and normal or corrected-to-normal vision, participated in the study after informed written consent. Subjects were presented with 12 blocks of 375 stimulus pairs each delivered at a constant rate of one pair every 1.2 s. Each pair consisted of an irrelevant auditory stimulus followed after 300 ms (onset-to-onset) by a visual imperative stimulus. Auditory stimuli were a 600 Hz standard tone (probability=0.8) and 6 different deviant tones (probability=0.03 each), which differed in frequency from the standard tone at 5% (630Hz), 10% (660Hz), 15% (690Hz), 20% (720Hz), 40% (840Hz) and 80% (1080Hz). Each deviant stimulus appeared intermixed in all the stimulation blocks. All auditory stimuli were delivered binaurally through headphones with a duration of 150 ms (including 10 ms of rise and fall times) and an intensity of 90 dB SPL. The auditory stimuli were sequenced randomly, with the only exception that the trials in which the visual stimulus followed a deviant sound were always preceded by a trial in which the visual stimulus followed a standard tone. Visual stimuli were either an even (2, 4, 6, 8) or an odd (3, 5, 7, 9) digit, presented equiprobably on a computer screen for 200 ms with a vertical visual angle of 1.7° and a horizontal angle of 1.1°. Stimulus presentation and sequence control was carried out by means of Stim (NeuroScan, Inc.) software and hardware.

Subjects sat conformably in a reclining chair on a dimly lit, electrically and acoustically shielded room. They were instructed to press one response button with their right index finger to letters, and another response button with their right middle finger to numbers, and to ignore the auditory stimulation. Both speed and accuracy were emphasized. Response fingers and block order were counterbalanced across subjects. Before the experimental session, subjects

received one practice block in which the sounds were turned off. In the practice block all subjects reached a hit rate of at least 85%.

The EEG (bandpass 0-100 Hz) was continuously digitized at a rate of 500 Hz by a *SynAmps* amplifier (NeuroScan, Inc.), from 16 scalp electrodes located according to the 10-20 system (Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, O2), and from the left (LM) and right (RM) mastoids. Horizontal and vertical EOG was recorded with electrodes attached to the canthus and below the right eye, respectively. The common reference electrode was placed on the tip of the nose. ERPs were averaged off-line for each auditory stimulus type, for an epoch of 1200 ms including a pre-auditory stimulus period of 100 ms. Epochs in which the EEG or EOG exceeded $\pm 100\mu$ V, as well as the 5 first epochs of each block, were automatically excluded from averaging. The standard-tone trials immediately following deviant-tone or novel-sound trials were also excluded from the averages. Frequencies >30 Hz were digitally filtered out from individual ERPs.

A correct button press within 1100 ms after visual-stimulus onset was regarded as a hit, the mean reaction time (RT) being computed only for the hit trials. An incorrect button press during this period was classified as an error, and trials with no response as misses. Hits, errors, misses, and RTs were computed across odd and even numbers. Performance (hit rate and reaction time) in standard trials was compared by means of two-tailed t-tests with performance in each of the deviant trials.

Difference waves were obtained by subtracting the ERPs to the standard tones from that to the six different deviant tones. The mean amplitude of N1 and MMN were calculated in 50-ms time windows around their maximum peaks (90-140 ms and 150-200 ms, respectively) in the difference waves. P3a was identified in the difference waves as the largest positive peak following MMN/N1. Its mean amplitude was calculated in the 100-ms time window around its maximum peak (225-325 ms) in the difference waves. Following the P3a, a late negativity was identified as the RON response in the difference waves, its mean amplitude being computed in a 100-ms time window around its maximum peak (450-550 ms). T-test comparisons were run between the mean amplitude of each ERP component and the zero level. Regression analyses were also applied on the data, in order to estimate the best-fitting model of the amplitude of the different ERP components as a function of deviation.

Results and discussion

Standard minus deviant difference waves revealed a large negative response between 100 and 200 ms that was identified as the N1/MMN responses (Figure 1). The mean amplitude of the N1, measured in the 90-140 ms interval, was statistically different from the zero level to deviations larger than 10% (Figure 2). MMN mean amplitude, measured in the 150-200-ms time window, was significantly different from the zero level to deviations from 5% to 20% (Figure 2). The MMN was therefore elicited for the smaller deviations, whereas the larger deviations generated a more N1-like response, with larger amplitude and shorter latency as a function of the increase in the magnitude of stimulus deviation, in agreement with previous studies (Näätänen, 1992; Tiitinen et al., 1994; Amenedo and Escera, 2000).



Figure 1. Standard minus deviant difference waves at all scalp locations (left) and at midline electrodes (right) for the six types of deviant trials.



Figure 2. Mean amplitudes (in μ V) of the different ERP components as a function of the auditory deviation. Asterisks mark the significance level of the t-tests comparisons between mean amplitude of the ERP responses and the zero level at Fz (* p<0.1; **p<0.05; ***p<0.01).

Following the MMN, a positive response was identified in the difference waves as the P3a (Figure 1). The mean amplitude of P3a in a time window around its maximum peak (i.e., 225-325 ms) was significantly different from zero for the deviations larger than 10% (Figure 2). The amplitude of the P3a increased logarithmically as a function of deviation (F_4 =276.7; p<0.001).

Subsequently to the P3a response, a negative response was revealed in the difference waves (Figure 1), which was identified as the reorienting negativity or RON (Schröger and Wolff, 1998; Berti and Schröger, 2000; Escera et al., in press). The mean amplitude of the RON response was significantly different from the zero level for all types of deviant trials (Figure 2). The amplitude of RON increased linearly as a function of increasing deviation (F_4 =63.5; p<0.005).

The electrophysiological results revealed that the brain responses involved in auditory change detection and involuntary attention have different amplitudes according to the magnitude of the deviation in sound frequency. The present data therefore indicates that the brain mechanisms of involuntary attention are activated differently according to the salience of the frequency change, which suggests the existence of different brain mechanisms underlying involuntary attention as a function of the magnitude of deviation.

T-test comparisons revealed significant differences between performance in standard and each deviant trial type when visual stimuli were preceded by a 5% or a 10% deviant sound. In particular, reaction time decreased by 10.6 ms in 5% deviant trials (t₁₂=5.69; p<0.001) and increased by 6 ms in 10% deviant trials (t_{12} =-2.57; p<0.05) as compared to standard trials. Hit rate increased by 1.1% in 10% deviant trials as compared to standard trials (t_{12} =-2.24; p < 0.05). No significant behavioral effects were found in the other deviant trials. These results suggest the existence of a critical interval of deviation (i.e., from 5% to 10%) in which behavioral effects can be observed. However, the present results are in disagreement with previous studies reporting distraction effects as reflected in a hit rate decrease at the occurrence of 16% deviant sounds (Escera et al., 1998). Therefore, one should have expected to find increasing distraction effects as a function of increasing deviation, in parallelism with the electrophysiological responses. The lack of agreement between behavioral and electrophysiological measures suggests the involvement of further intervening cognitive processes that need to be clarified in future studies. For example, the context of stimulation should be taken into account, as all types of deviant sounds were presented intermixed in the same stimulation block, whereas in previous studies the distraction effects were found only when one type of deviant sound was embedded in a sequence of standard tones and novel sounds (Escera et al., 1998).

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