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Effects of involuntary auditory attention on visual task performance and brain activity

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INVOLUNTARY attention to auditory stimulus changes during a visual discrimination task was studied with event-related potentials (ERPs) recorded from the human scalp. A repetitive standard tone or an infrequent, slightly higher deviant tone preceded each visual target stimulus. Deviant tones elicited the mismatch negativity and P3a ERP components and caused increases in reaction time and error rate in the visual task indicating involuntary attention to an auditory stimulus change. These effects were observed even when the tones occurred simultaneously with a visual warning stimulus introduced to keep attention focused on the visual task. In the latter condition, involuntary switching of attention away from the visual task also attenuated the N1 ERP component to visual target stimuli preceded by the deviant tone.

Key words: Attention; Auditory; Event-related brain potential (ERP); Mismatch negativity; P3a; Reaction time; Visual

Introduction

A deviant sound in a sequence of repeating (standard) sounds elicits the mismatch negativity (MMN) component in the event-related brain potential (ERP) recorded from the scalp.[1] The MMN is elicited even when the subject is instructed to ignore the auditory stimuli and attend to other stimuli. In the ERP to deviant sounds, the MMN overlaps with the negative N1 (peak latency about 100 ms from stimulus onset) and subsequent positive P2 components which are also elicited by standard sounds. The MMN is apparently generated by a neuronal process activated by a mismatch between the afferent neuronal activity caused by a deviant stimulus and an automatically formed memory trace representing physical and temporal features of a repeated standard stimulus.

Source modelling has suggested MMN generators bilaterally in the auditory cortex[2–5] and an additional source in the frontal lobe.[3,5] MMN activity in the auditory cortex, which is also observed in intracranial recordings,[6,7] is presumably generated by the neuronal mismatch detection process described above, while the frontal activity might be generated by a frontal process initiating an involuntary switching of attention to a deviant sound.[1,3] The subsequent involuntary orienting of attention might, in turn, be reflected by the positive P3a component[8] following the MMN[9] and elicited with a large amplitude of several microvolts by attention-catching widely deviant sounds, such as a telephone ringing.[10–13] The P3a to such novel sounds appears to have sources in multiple brain areas, including the temporal and frontal cortices.[7,10–12,14–17]

According to recent studies,[18,19] even deviant tones differing by < 20% in frequency from standard tones and eliciting only small MMN and P3a responses (1–2 μV at the fronto-central scalp) may cause an involuntary switching of attention. In these studies, a deviant tone preceding an auditory or visual target stimulus prolonged reaction times to targets and increased response errors in relation to targets preceded by a standard tone. However, in both studies, the task-irrelevant standard and deviant tones preceding the target stimuli may have acted as warning stimuli informing about the time of target occurrence. Thus the subjects may have attended to each task-irrelevant tone and the detrimental effects of deviant tones on performance may not indicate involuntary attention to deviant tones, but distraction caused by a change in the attended warning stimuli. The present study examined effects of deviant tones on ERPs and visual task performance in a more controlled condition where a visual warning stimulus was presented simultaneously with each tone in order to keep attention away from the tones.

Materials and Methods

Ten right-handed students (age 19–25 years, four females) with normal hearing and normal or corrected-to-normal vision participated in the experiment.

Stimuli were generated with Stim software (NeuroScan, Inc.). In the auditory-visual (A-V) condition, five blocks of 200 stimulus pairs, consisting of a sinusoidal tone followed by a visual target stimulus, were presented at a constant rate of one pair every 1.5 s. Each tone was presented binaurally through headphones (intensity 75 dB SPL, duration 200 ms) and comprised either a 600 Hz standard tone or a 700 Hz deviant tone occurring randomly at a probability of 0.2, except that there was always at least one standard tone between two deviant tones. The visual stimulus was equiprobably either a white digit (between 2–9) or letter (A, E, J, P, R, S, U, or Y) subtending 36–37 mm vertically and 16–20 mm horizontally, and occurring 300 ms after the tone onset for 200 ms at the center of a black computer screen located 150 cm from the subject. Subjects sat in a dimly lit room and they were instructed to ignore the tones, to focus to the center of the screen, and to press one response button with the right index finger to letters and another button with the right middle finger to digits as fast and accurately as possible.

In the other condition, called the AV-V condition, 10 stimulus blocks were presented. In each stimulus block, there were 200 tones delivered as in the A-V condition. Simultaneously with each tone, a visual warning stimulus was presented for 200 ms at the center of the screen. The warning stimulus was equiprobably either a rectangular white frame subtending 30 mm horizontally and 55 mm vertically or a similar frame with a white asterisk (subtending 10 mm horizontally and 15 mm vertically) at the middle. The empty frame was a 'no-go' stimulus followed by no target stimulus, while the frame with an asterisk was a 'go' stimulus followed by a target digit or letter. The digits and letters, their probabilities, and the task instructions were similar to those in the A-V condition.

The order of conditions was counterbalanced between the subjects. Before each condition, the subject practiced the visual discrimination task during one stimulus block in which the tones were turned off. In these practice blocks, the proportion of correct responses was > 86% and the proportion of wrong responses < 8% in all subjects for both conditions.

Electroencephalogram (EEG; passband 0.1–100 Hz) was recorded with scalp electrodes referred to an electrode at the nose and digitized (sampling rate 500 Hz) with SynAmps amplifiers and Scan software (NeuroScan, Inc.). Voltage variation caused by eye movements and blinks was monitored with four electrodes located laterally and above the eyes and referred to the nose electrode. To obtain ERPs, EEG epochs of 1300 ms starting 100 ms before each tone onset were averaged separately for standard-tone and deviant-tone trials of each condition, and also separately for the go and no-go trials of the AV-V condition. Epochs with voltage variation exceeding ± 100 μV at any eye-movement or EEG electrode, epochs for the first four stimulus pairs of each block, and epochs for standard-tone trials immediately following a deviant-tone trial were excluded from the averaging. Frequencies > 30 Hz were digitally filtered out from the averaged ERPs.

In both conditions, a correct button press within 1100 ms after a target onset was regarded as a hit. An incorrect button press during this period was classified as an error and a trial with no response as a miss. Peak amplitudes of different ERP waves were measured from individual ERPs in relation to the mean amplitude during a 100 ms epoch preceding the tone onset. Peak amplitudes and latencies of MMN and P3a to deviant tones were measured from difference waves obtained for each subject by subtracting ERPs elicited in standard-tone trials from ERPs elicited in deviant-tone trials. In the statistical analysis of performance and ERP data, analyses of variance (ANOVAs) for repeated measures and *t*-tests were applied.

Results

ANOVAs with tone and condition as factors indicated that a deviant tone preceding a visual target stimulus significantly decreased the hit rate ($F(1,9) = 22.49$, $p < 0.002$), prolonged the hit RT ($F(1,9) = 10.08$, $p < 0.02$), and increased the error rate ($F(1,9) = 13.09$, $p < 0.01$) in relation to trials with a standard tone preceding a target (Table 1). Deviant tones had no significant effect on the miss rate. The only significant difference in performance measures between the two conditions was a lower error rate in the AV-V than in the A-V condition ($F(1,9) = 6.48$, $p < 0.04$). No significant tone × condition interaction was observed for any performance measure.

In the A-V condition, tones elicited a frontally maximal negative N1 wave followed by a P2 positivity, and a slower frontal negativity, presumably the contingent negative variation (CNV)[20] associated with anticipation of a target stimulus (Fig. 1). At the N1 and P2 latencies, the ERP to deviant tones was negatively displaced in relation to the standard tone ERP due to a MMN to deviant tones. The mean peak latency and amplitude of this frontally maximal MMN were 140 ms and –1.1 μV at the frontal midline

Table 1. Mean reaction times (RTs) for correct response to targets (hits), and mean hit, error, and miss percentages (calculated in relation to the number of targets) in the visual discrimination task for targets preceded by a standard tone and for those preceded by a deviant tone in the AV and AV-V conditions.

Condition	Preceding tone	Hit RT (ms)	Hit (%)	Error (%)	Miss (%)
AV	Standard	484	93.4	1.7	4.9
	Deviant	488	92.0	3.3	4.7
AV-V	Standard	491	96.8	1.6	1.7
	Deviant	498	95.7	2.0	2.3

electrode (Fz), the amplitude differing significantly from 0 μV ($t(9) = -4.12$, $p < 0.01$). The MMN was followed by a centrally maximal positive displacement of the deviant tone ERP in relation to the standard tone ERP caused by a P3a to deviant tones overlapping with the CNV negativity following the N1 and P2 and peaking at the central midline electrode (Cz) on the average at 338 ms with a mean amplitude of 1.9 μV, the amplitude differing significantly from 0 μV ($t(9) = 6.37$, $p < 0.001$). The auditory ERP was followed by the ERP to visual target stimuli. This visual ERP was characterized by a posteriorly maximal N1 wave preceded by a small P1 wave and followed by a frontally maximal N2 wave and a prominent, parietally maximal P3b wave (Fig. 1).

In the go trials of the AV-V condition, ERPs following the simultaneously presented tone and visual go stimulus consisted of a frontally maximal auditory N1 and a coinciding posteriorly maximal visual P1 to go stimuli followed by an N1 and a frontal negativity, presumably a mixture of CNV and N2 (Fig. 1). MMN and P3a to deviant tones caused successive frontally maximal negative and centrally maximal positive displacements of the ERP for deviant tone trials in relation to standard tone trials. The mean MMN peak latency and amplitude were 166 ms and −1.1 μV at Fz, the amplitude differing significantly from 0 μV ($t(9) = -5.68$, $p < 0.001$). The mean P3a peak latency and amplitude were 340 ms and 2.1 μV at Cz, the amplitude differing significantly from 0 μV ($t(9) = 6.90$, $p < 0.001$). The ERP to the subsequent visual targets was characterized by a broadly distributed negativity, apparently consisting of N1 and N2, followed by a larger P3b (Fig. 1). The peak amplitude of the occipital N1 to visual targets, determined as the first peak of the broad negativity (mean 01/02 latency 155 ms from target onset), was significantly smaller after deviant tones than after standard tones (mean 01/02 amplitudes −5.3 *vs* −6.1 μV, respectively; $F(1,9) = 11.26$, $p < 0.01$).

In the no-go trials of the AV-V condition, tones elicited a frontally maximal N1, while the coinciding

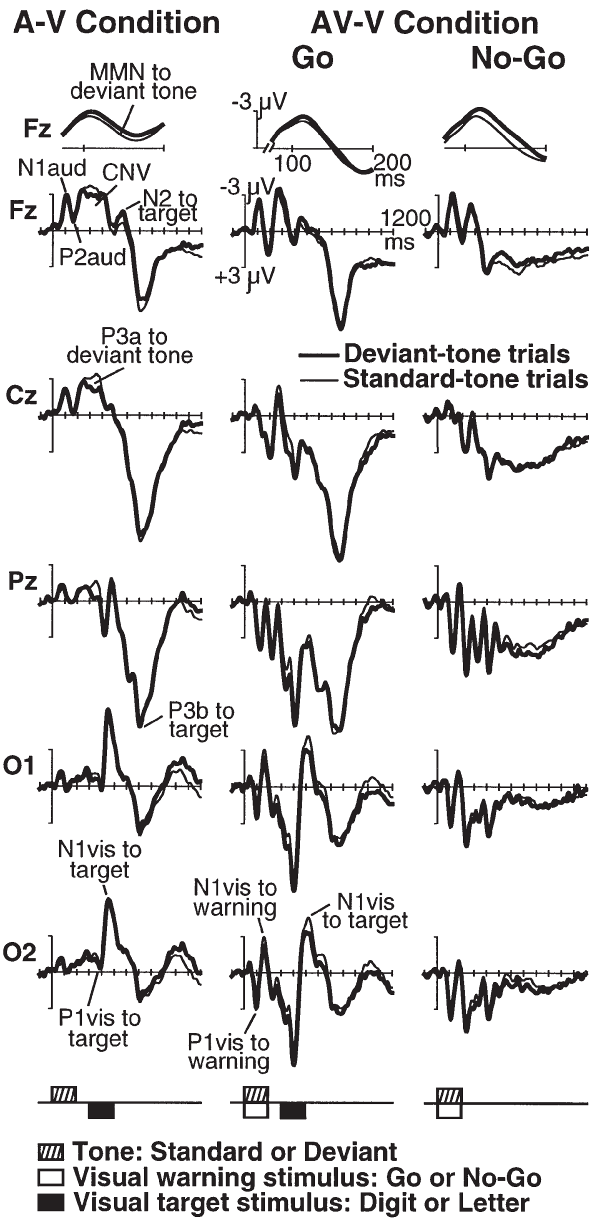

FIG. 1. Across the 10 subjects averaged ERPs at frontal (Fz), central (Cz) and parietal (Pz) midline scalp sites and at occipital sites over the left and right hemispheres (01 and 02, respectively) elicited in the deviant-tone (thick lines) and standard-tone (thin lines) trials in the A-V condition, where only a tone (a hatched rectangle at the bottom line), standard or deviant, preceded each visual target stimulus (indicated by a black rectangle), and in the AV-V condition, where a visual warning stimulus (indicated by a white rectangle|) was presented simultaneously with each tone and informed the subject whether a visual target stimulus was going to follow (a go trial) or not (a no-go trial). The auditory N1 and P2 responses to the tones, the subsequent CNV, the visual P1 and N1 responses to the warning stimulus, and the visual N1, N2, and P3b responses to target stimuli are labelled. The inserts at the top show with a magnified time scale (from 75 to 200 ms after the tone onset) the frontally maximal negative displacements of the ERPs in deviant tone trials in relation to standard tone trials caused by the MMN to deviant tones. The subsequent P3a to deviant tones, in turn, caused a centrally maximal positive displacement of the ERPs in deviant tone trials in relation to standard tone trials.

visual no-go stimuli elicited at posterior scalp sites P1 and N1 waves and a frontal N2 followed by a slow positivity (Fig. 1). The P1 (mean 01/02 peak latency 108 ms) was almost significantly larger ($F(1,9) = 3.91$, $p < 0.08$) and the N1 (mean 01/02 latency 160 ms) was significantly smaller ($F(1,9) = 6.26$, $p < 0.04$) at the occipital electrodes (01/02) for the no-go than for the go stimuli (mean P1 amplitudes for the no-go and go stimuli 4.6 *vs* 3.3 μV, respectively, and mean N1 amplitudes –2.7 *vs* –4.8 μV, respectively). In the no-go trials, MMN and P3a to deviant tones also caused successive frontal negative and central positive displacements of ERP for deviant tone trials in relation to standard tone trials (Fig. 1). The mean peak latency and amplitude of this MMN were 170 ms and –1.5 μV at Fz, the amplitude differing significantly from 0 μV ($t(9) = -4.36$, $p < 0.002$), while the latency and amplitude of P3a were 302 ms and 2.0 μV at Cz, this amplitude also differing significantly from 0 μV ($t(9) = 4.74$, $p < 0.002$).

Discussion

The present results replicate the previous finding[18,19] that even a slightly deviant tone replacing a repeating standard tone may catch the subject's attention and deteriorate performance in an attention-demanding task. Moreover, the present data demonstrate that such involuntary switching of attention to a small auditory stimulus change may occur even when the subject's attention is kept away from the tones by presentation of a simultaneous visual stimulus relevant for the task performance.

Presumably the generators of the MMN observed in the ERP to deviant tones triggered the switching of attention to these tones, while the subsequent P3a component reflected brain mechanisms participating in the actual involuntary orienting of attention, as also suggested previously.[1,3,8,9,18,19] However, previous studies did not demonstrate the association of MMN and P3a to deviant tones with involuntary attention switching to these tones in a well controlled condition, as the present AV-V condition where a task-relevant stimulus coincided with a deviant tone eliciting the MMN and P3a.

In the go trials of the present AV-V condition, the deviant tones occurring simultaneously with the visual warning stimulus not only prolonged the reaction time to subsequent target stimuli and increased the number of wrong responses, but they also caused an attenuation of the N1 wave in the ERP to the targets. It has been shown previously[21] that the P1 and N1 waves to cued visual target stimuli are enhanced due to effects of attention of visual processing in the extrastriate cortex.[22] These attentional P1 and N1 enhancements presumably also occurred in the present 'go' trials, but the N1 effect was attenuated by a deviant tone catching attention just before the target stimulus onset. Thus, the involuntary switching of attention to deviant tones interfered with early processing of the successive visual stimulus. A similar effect was observed in a recent study where the N1 to an auditory target stimulus was attenuated by a preceding, attention-catching deviant tone.[18]

The present results also demonstrate a larger P1 and a smaller N1 to no-go than to go warning stimuli. These early effects are in contrast with previous studies showing differences only at N2 and P3 latencies between ERPs to go and no-go stimuli.[23,24] Since the present study was not designed to examine such ERP effects, physical differences between the go and no-go stimuli were not controlled. Visual stimuli with high spatial frequencies are known to elicit larger P1 waves than low-frequency stimuli.[25] The present go stimulus (a frame surrounding an asterisk) consisted of a larger amount of high spatial frequencies than the no-go stimulus (an empty frame). Therefore it is unlikely that the go stimuli would have elicited a smaller P1 than the no-go stimuli because of physical stimulus differences. Thus, the differences observed in the P1 and N1 waves between the two stimuli may reflect a genuine effect of task relevance on early cortical processing of warning stimuli, perhaps an early 'selection negativity'[1,25] to the go stimuli starting as early as at the P1 latency.

Conclusion

The present data demonstrate that a small auditory stimulus change may cause an involuntary switching of attention away from an attention-demanding task performed by the subject. The attenuation of the N1 wave to the cued visual target stimulus after an occurrence of a deviant tone in the present go trials suggests that a slightly deviant sound may affect the early cortical processing of a subsequent visual stimulus. The involuntary attention switching to deviant tones was presumably triggered by the auditory cortex and frontal mechanisms[1,3] generating the MMN to these sounds and reflected by the subsequent P3a component generated in multiple brain areas, including the temporal and frontal cortices.[7,10–12,14–17]

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