Research report

An electrophysiological and behavioral investigation of involuntary attention towards auditory frequency, duration and intensity changes

Carles Escera*, Maria-Jose Corral, Elena Yago

Neurodynamics Laboratory, Department of Psychiatry and Clinical Psychobiology, University of Barcelona, P. Vall d’Hebron 171, 08035 Barcelona, Catalonia, Spain

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Abstract

We measured behavior and event-related brain potentials (ERPs) in 12 subjects performing on an audio-visual distraction paradigm to investigate the cerebral mechanisms of involuntary attention towards stimulus changes in the acoustic environment. Subjects classified odd/even numbers presented on a computer screen 300 ms after the occurrence of a task-irrelevant auditory stimulus, by pressing the corresponding response button. Auditory stimuli were standard tones (600 Hz, 200 ms, 85 dB; \( P = 0.8 \)) or deviant tones (\( P = 0.2 \)), these differing from the standard either in frequency (700 Hz), duration (50 ms) or intensity (79 dB), in separate blocks. In comparison to performance to visual stimuli following the standard tones, reaction time increased by 24 ms (\( F(1,11) = 10.91, P < 0.01 \)) and hit rate decreased by 4.6% (\( F(1,11) = 35.47, P < 0.001 \)) to visual stimuli following the deviant tones, indicating behavioral distraction. ERPs revealed the mismatch negativity (MMN) elicited to deviant tones, which was larger for the duration deviant than for the frequency and intensity deviants (\( F(2,22) = 19.43, P < 0.001, \varepsilon = 0.83 \)), and which had different scalp distribution for all three deviant conditions (\( F(16,176) = 2.40, P < 0.05, \varepsilon = 0.12 \)). As the shorter duration and softer intensity deviant tones were unlikely to engage fresh neurons responding to their specific physical features, the present results indicate that a genuine change detection mechanism is involved in triggering attention switching towards sound changes, and suggest a largely distributed neural network of the auditory cortex underlying such involuntary attention switching.

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1. Introduction

Surviving in a challenging environment requires both selective and involuntary attention capabilities. Selective attention is necessary to select relevant stimuli from the wealth of information impinging our senses, in order to allow goal-directed behavior. Involuntary attention, in turn, refers to the ability to switch attention automatically towards potentially relevant events occurring outside the current focus of attention. At least two cerebral mechanisms have been proposed to account for such involuntary orienting of attention. One mechanism is activated by sudden onsets or offsets of stimuli, such as a flashing light or an alarm siren, or as when a drilling machine that has been working all day long suddenly stops. Another mechanism is activated by a particular stimulus that violates a neural trace of the preceding homogeneous stimulation, therefore involving a ‘change’ detection process. A naive usage of such a change detector mechanism has been used for years by news broadcasters, who, before they begin, usually ‘call’ listener’s attention by playing a short series of repeating tone pips finishing with another one of longer duration or higher frequency. In the auditory modality, sound onsets breaking a long silent period and sound offsets terminating a long noisy period activate a transient-detector mechanism, associated to the auditory N1 event-related brain potential (ERP) [15,29,34], whereas the
change detector mechanism is reflected in the mismatch negativity (MMN) component of the ERPs [11,29].

The MMN [31] is elicited to deviant stimuli differing from the preceding standard stimuli in any of their physical features, such as frequency, duration, intensity or location. It appears as a negative peak of the difference wave obtained by subtracting the ERPs elicited to the standard tones from those elicited to the deviant tones, at a latency between 100 and 200 ms. MMN has a frontocentral scalp distribution, with polarity reversal at electrode locations below the Sylvian fissure, suggesting generator sources located bilaterally to the supratemporal auditory cortex [16,41]. This auditory cortex location has been confirmed by a range of cognitive neuroscience methods, including intracranial recordings in animals [8,22,24] and humans [17,26,27], source modeling of magnetoencephalographic (MEG) signals in humans [4,9,18], analysis of scalp current density (SCD) of deviant-related negativities [10,16,38,48], functional magnetic resonance imaging (fMRI) [7,35], positron emission tomography (PET) [46], and event-related optical signals (EROS) [39] (for reviews see Refs. [2,11]). A further contribution to MMN from the frontal cortex has been suggested by studies of patients with cerebral lesions [1,5], and confirmed by scalp current density analysis [10,16,38,48].

It has been suggested that the MMN reflects the outcome of a comparison process resulting in disparity between a neural code of the incoming stimulus and a neural trace of the physical features of the repetitive preceding stimulation stored in sensory memory [29,30]. This process is apparently sustained by the neural populations generating the MMN in the supratemporal auditory cortex [23,25]. As a result of this mismatch detection, an attention switching signal is triggered to activate a chain of cerebral events leading to the effective orienting of attention towards the detected change [29,30]. The frontal MMN source has been suggested to underlie such a neural signal triggering the attention switching response [16,30], although the positive correlation between activation of the supratemporal MMN source and orienting of attention towards the eliciting sounds, as indicated by behavioral distraction [48], leaves this issue still open.

The strongest evidence supporting the role of the MMN generating mechanism in triggering attention switches is provided by studies showing deterioration of task performance at the occurrence of unexpected task-irrelevant deviant sounds eliciting the MMN. In a series of these studies, subjects had to classify visual stimuli presented after ~300 ms of the occurrence of an irrelevant sound. Deviant tones in this task-irrelevant auditory sequence elicited the MMN and caused reaction time increases and hit rate decreases to the successive visual stimuli [3,12,13,47,48] (see review in Ref. [11]), indicating behavioral distraction as a result of a transient orienting of attention towards the originally unattended deviant sound. Similarly, in an auditory–auditory distraction paradigm, task-irrelevant changes in sound frequency caused also reaction time increases and hit rate decreases to target or task-relevant aspects of the auditory stimulation [6,42–45].

However, all these ‘distraction’ studies reviewed above used a frequency deviant, i.e., a distractor stimulus differing in its spectral content from the standard sound, and therefore it cannot be fully ruled out that the cerebral mechanism leading to attention switching and distraction was associated to the N1 generated by fresh neurons responding selectively to the specific frequency of the deviant sound (see Refs. [21,48]). Only in the study of Schröger and Wolff [45], was a control condition used, in which the deviant frequency was presented among nine different frequencies in the same stimulus sequence. By comparing the performance and the ERPs obtained in this control condition with those obtained when the deviant frequency was presented in the context of a high-probability standard frequency (i.e., in an oddball condition), the authors were able to demonstrate that a memory-related change-detection mechanism, as indicated by the MMN, was involved in triggering involuntary attention switches towards stimulus changes within the auditory modality. In the present experiment, we also sought to investigate whether genuine change detection was involved in cross-modal attention switching, i.e., in directing attention involuntarily from the current visual performance to unexpected auditory changes. We used a variant of our auditory–visual distraction paradigm in which the ‘distracting’ sounds were either shorter in duration or softer in intensity, in separate blocks, than the corresponding standard stimuli. An additional condition with frequency deviants was also used. Shorter or softer deviant tones are unlikely to activate new fresh neural elements [32,33], and therefore observation of behavioral distraction to these sounds will strongly support the involvement of a genuine change detection mechanism in controlling involuntarily the cross-modal direction of attention.

2. Materials and methods

2.1. Participants and procedure

Twelve healthy, right-handed human subjects (mean age 21.2±1.1 years; two males), with normal hearing and normal or corrected-to-normal vision participated in the study after informed written consent. While seating comfortably in a reclining chair in a dimly lit, electrically and acoustically shielded room, subjects were presented with six blocks of 500 stimulus pairs (trials) delivered at a constant rate of one pair every 1.2 s. Each trial consisted of an irrelevant auditory stimulus followed after 300 ms (onset-to-onset) by a visual imperative stimulus. The auditory sequence consisted of repetitive standard tones (600 Hz, 200 ms and 85 dB; \( P = 0.8 \)) occasionally replaced, in separate counterbalanced blocks, by a slightly
higher (700 Hz), shorter (50 ms) or softer (79 dB) deviant tone \(P = 0.2\). All auditory stimuli were delivered binaurally through headphones in random order, with the only exception that the trials in which the visual stimulus followed a deviant tone were always preceded by a trial in which the visual stimulus followed a standard tone. Visual stimuli were the digits from 1 to 8 presented one at a time in random order on a computer screen for 200 ms. They subtended a vertical angle of 1.7° and a horizontal angle of 1.1° at 150 cm from the subject’s eyes.

Subjects were instructed to focus on a small fixation cross appearing in the middle of the screen and to press one response button with their right-hand index finger for even numbers and another response button with their right-hand middle finger for odd numbers. Instructions were also given to ignore the auditory stimulation. Both speed and accuracy were emphasized for the visual task. Before the experimental session, subjects received one practice block in which the auditory stimulation was omitted, all of them reaching a hit rate level of at least 85%. To avoid tiredness, subjects had a short rest period after each of the blocks.

2.2. EEG recording

The EEG (bandpass 0.1–100 Hz) was continuously recorded and digitized at a rate of 500 Hz by a SynAmps amplifier (Neuroscan) from an array of 30 scalp electrodes, 18 of them positioned according to the 10–20 system (Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, and Oz), and 12 of them from the following additional locations: M1 (left mastoid), IM1 (70% of the distance from the preauricular point to the inion), TP3 (halfway between T3 and P3), CP1 (halfway between C3 and Pz), FT3 (halfway between F3 and T3), FC1 (halfway between Fz and C3), and the homonymous positions over the right hemisphere. Horizontal and vertical EOG were recorded with two additional electrodes placed at the canthus and below the left eye, respectively. The common reference electrode for all EEG and EOG measurements was placed on the tip of the nose.

2.3. Data analysis

A correct button press within 800 ms after visual stimulus onset was regarded as a hit, the mean reaction time 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 reaction time were computed across odd and even numbers. Distraction effects caused by deviant tones were analyzed by means of analysis of variance (ANOVA) for repeated measures with type of auditory stimulus (two levels: standard and deviant tones) and condition (three levels: frequency, duration, and intensity deviants) as factors, performed on the mean reaction time, hit rate and error rate to visual stimuli preceded by a standard tone and those preceded by a deviant tone.

ERPs were averaged off-line, separately for standard and deviant tones, for an epoch of 1300 ms including a pre-auditory stimulus baseline of 100 ms. Epochs in which the EEG or EOG exceeded ±100 μV, as well as the first five epochs of each block, were automatically excluded from averaging. Standard-tone trials immediately following deviant-tone trials were also excluded from the averages. Frequencies higher than 30 Hz were filtered out from the individual ERPs. All ERP amplitudes were measured against the mean amplitude of the 100 ms baseline preceding the auditory-stimulus onset.

MMN was measured in the difference waves obtained by subtracting the ERPs elicited to the standard tones from those elicited to the deviant tones as the mean amplitude in a 100-ms latency window around its maximum peak at Fz. The MMN peaks were identified, for each deviant condition separately, in the grand-average difference wave, yielding the following latency windows: frequency deviant, 100–200 ms; duration deviant, 150–250 ms; intensity deviant, 180–280 ms. As the MMN inverts polarity when the nose is used as the reference electrode [2,11], significant activation of MMN generators was analyzed by a t-test comparison between its mean amplitude at Fz and the left mastoid (M1). Comparison of MMN across deviant conditions was carried out by means of a one-way ANOVA with deviant condition as factor, performed on MMN mean amplitudes at Fz.

Scalp distribution analyses of MMN were performed on ERP amplitudes at 15 electrodes (F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6) after normalization, to prevent genuine differences in scalp distribution from being washed out by amplitude differences. This normalization was done by dividing the amplitude at each electrode by the square root of the sum of the squared amplitudes at the selected electrodes [28]. The scalp distribution ANOVA included three factors: frontal (frontal/central/parietal), laterality (five levels from left to right) and deviant condition (frequency/duration/intensity).

In the ANOVAs and when appropriate, the Greenhouse–Geisser correction of the degrees of freedom was applied, the uncorrected degrees of freedom, the corrected \(P\) values, and the \(\epsilon\) factors being reported.

3. Results

3.1. Performance

As shown in Fig. 1, subjects had an overall high performance level of about 90% in the visual classification task across the stimulus and deviant conditions. However, the statistical analyses revealed that hit rate decreased significantly by an average 4.6% when the visual stimuli
to visual stimuli preceded by the standard tones ($F(1,11) = 10.91, P < 0.01$). No statistical differences in reaction time were found between deviant conditions.

### 3.2. MMN elicited to frequency, duration and intensity deviant tones

The ERPs elicited by the auditory–visual stimulus pairs during visual performance were characterized by a complex waveform, including auditory, visual and target ERP components (Fig. 2). Of interest for the present research was the MMN, which appeared as an increased negativity in the deviant-trial ERPs in comparison to the standard-trial ERPs at Fz, in a latency range varying from 100 to 250–280 ms, depending on deviant condition (Fig. 2). The MMN is usually analyzed in the difference wave obtained by subtracting the standard-tone ERPs from the deviant-tone ERPs. The difference waves thus obtained separately for each of the deviant conditions are shown in Fig. 3, where negative voltages at the frontal electrode line and positive voltages (i.e., polarity reversal) at mastoid electrodes can be seen. Significant MMNs were elicited in all three deviant conditions, as indicated by $t$-test comparisons between the mean amplitude of the MMN at Fz and at the left mastoid (M1) ($t(11) = -3.79, P < 0.004$ for the frequency deviant; $t(11) = -8.87, P < 0.001$ for the duration deviant; and $t(11) = -2.65, P < 0.03$ for the intensity deviant).

As can be seen in Fig. 3, the MMN elicited in the three deviant conditions differed considerably in amplitude, the duration-deviant MMN being the largest. A one-way ANOVA for repeated measures revealed that MMN amplitude differed significantly indeed among conditions ($F(2,22) = 19.43, P < 0.001, \varepsilon = 0.83$; at Fz). Post-hoc $t$-test comparisons revealed that the duration-MMN was larger than the frequency- ($t(11) = -6.62, P < 0.001$) and intensity-MMN ($t(11) = -4.94, P < 0.001$) MMNs, whereas these two latter MMNs were of similar amplitude ($t(11) = -0.69, P = 0.51, \text{n.s.}$).

### 3.3. Scalp distribution of MMN

When the nose is used as the reference electrode, the MMN typically has a frontal negative maximum, and a polarity reversal, i.e., positive voltages, over the electrodes positioned below the Sylvian fissure. This typical scalp distribution was observed in all three deviant conditions in the present experiment. However, as can be seen in Fig. 4, there were pronounced differences in the particular scalp distribution yielded by each type of deviant tone. The duration-MMN was frontally distributed, with little polarity reversal at posterior sites, whereas the frequency-MMN had a clear positive distribution over posterior areas, with small amplitudes over the frontal electrodes. The intensity-MMN, in turn, showed two clear maxima located over the
Fig. 2. Event-related brain potentials (ERPs) at Fz, Cz, Pz, and Oz elicited in the three deviant conditions. The left column shows the standard (thin line) and deviant (thick line) ERPs elicited in the frequency deviant condition, and the middle and right columns correspond to the duration and intensity deviant conditions, respectively. Note that the auditory–visual pairs elicited a complex ERP response, characterized by auditory N1–P2 at Cz (aN1, aP2), visual P1–N1 at Oz (vP1, vN1), and by target (visual) N2–P3b at Pz (tN2, tP3b). Notice also that deviant tones elicited the MMN, which appeared as an increased negativity in the deviant tone ERP as compared to the standard tone ERP at Fz, in the latency range comprised between 100 and 250 ms, depending on deviant conditions.

left and the right temporal regions, respectively. A three-way ANOVA for repeated measures, with the factors deviant-type, frontality and laterality performed on MMN mean amplitudes, yielded significant deviant-type×laterality ($F(8,88)=3.75$, $P<0.02$, $\epsilon=0.45$) and deviant-type×frontality×laterality ($F(16,176)=2.40$, $P<0.05$, $\epsilon=0.31$) interactions, confirming the existence of such scalp distribution differences.

4. Discussion

The results obtained in the present experiment demonstrate that, in addition to frequency changes [3,6,12,13,42–45,47,48], changes in duration and intensity of unexpected, task-irrelevant sounds activate the cerebral network of involuntary attention to cause behavioral distraction. Indeed, the occurrence of slightly shorter or softer deviant
The aim of the present experiment was to investigate whether a genuine change detector mechanism, as reflected in the MMN, was involved in triggering involuntary attention switches towards unexpected auditory deviant sounds during visual performance. Previous studies had shown that frequency deviant tones, eliciting the MMN, caused behavioral distraction, as indicated by reaction time delays and hit rate decreases in the performance of a concurrent task, both in the auditory [6,42–45] and visual modalities [3,12,13,47,48]. As in all of these studies the MMN could be recorded, it was concluded that change detection, as reflected in this ERP component, was involved in triggering the attention switching signal to drive attention involuntarily towards those frequency changes. However, this interpretation should be considered with caution, at least for the studies conducted during visual performance. Indeed, as a result of the tonotopic organization of the auditory cortex [36,40], it cannot be ruled out that a frequency change, even of very small magnitude, activate specific neurons responding to its particular frequency, and therefore that the MMN seen in the recordings correspond in fact, at least in part, to the N1 generated by those specific neurons, remaining in a less refractory state than those responding to the standard frequency due to the lower rate of deviant stimulus presentation [21]. Furthermore, in a study of the temporal dynamics of the SCD of the MMN elicited to frequency changes, Yago et al. [48] found that the frontal MMN generating source was activated over the right hemisphere on average 20 ms before than the supratemporal MMN source. The authors suggested that this anticipation may be due to N1 activity associated with the analysis of the physical features of the deviant tone, and therefore concluded that detection of frequency changes leading to behavioral distraction may involve the transient-detector mechanism associated to N1 [29,34]. The data obtained in the present experiment, however, suggest that a genuine change detection mechanism is involved in involuntary attention switching. Indeed, in addition to frequency deviant tones, we also obtained MMNs elicited to both duration and intensity deviant tones as well as concomitant behavioral distraction. As shown by Näätänen and co-workers, shorter duration [33] and softer intensity [32] deviant tones are unlikely to activate new fresh element responding to decreases in stimulus energy, and therefore the MMN recorded in the present experiment may reflect a genuine change detection mechanism of the auditory cortex. Recent studies, however, have shown an ampliotopic organization of the cat auditory cortex [20] (see also Pantev et al. [37]) and the existence of specific duration neurons also in the

discrimination task. However, one should be cautious when comparing the magnitude of change in different sound parameters and the corresponding distracting effects, as it is well established that there are specific rules governing the relationships between the physical and perceptual features of each sound parameter.

tones shortly preceding visual targets increased reaction time and error rate to these targets, as compared to performance to visual targets preceded by standard tones. These distracting effects were of similar magnitude (about 24 ms increase in reaction time and 5.6% increase in error rate) regardless the type of auditory feature changed in the deviant tone with regard to the standard tone. This similar amount of distraction is intriguing because the magnitude of change used in each of the deviant conditions varied from about 7% in intensity to about 17% in frequency, and to 75% in duration, and contrasts with the distracting effects of small and large deviances observed in the study of auditory distraction of auditory performance by Schröger [42]. This author found that a large frequency change (29%), compared to a small frequency change (7%), caused larger behavioral distraction on an auditory
cat auditory cortex [19], and therefore a direct demonstration of the involvement of truly change detection in cross-modal involuntary attention switching would require a control condition similar to that used by Schröger and Wolff [45] with frequency deviants.

The MMNs recorded to the frequency, duration and intensity deviant tones differed considerably in scalp topography. These differences in scalp distribution are in agreement with those reported by Giard et al. [14], who described that the MMN elicited to these same types of deviant tones could be modeled by dipoles differing in location within the supratemporal auditory cortex, and confirm the suggestion that detecting changes of specific auditory features is carried out by different neural populations of the human auditory cortex. As the activation of the MMN generating neural populations was associated with behavioral distraction, and considering the positive correlation between the supratemporal MMN activation and behavioral distraction described elsewhere [48], the present results suggest that a largely distributed neural network of the auditory cortex subserves involuntary attention switching towards auditory change.

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