

Visual task complexity modulates the brain's response to unattended auditory novelty

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New, unusual, and changing events are important environmental cues, and the ability to detect these types of stimuli in the environment constitutes a biologically significant survival skill. We used event-related potentials to examine whether sensory and cognitive neural responses to unattended novel events are modulated by the complexity of a primary visuomotor task. Event-related potentials were elicited by unattended task-irrelevant pitch-deviant tones and novel environmental sounds while study participants

performed a continuous visuomotor tracking task at two levels of difficulty, achieved by manipulating the control dynamics of a joystick. The results revealed that increased task complexity modulated evoked sensory and cognitive event-related potential components, indicating that detection of change and novelty in the unattended auditory channel is resource-limited. *NeuroReport* 16:1031–1036 © 2005 Lippincott Williams & Wilkins.

Key words: Involuntary auditory attention; Mismatch negativity; N2b; Novelty detection; P3a; Resource allocation; Visuomotor task

INTRODUCTION

The ability to discriminate and identify novel events is important for both survival and adaptation to environmental changes [1]. Electroencephalography (EEG) studies of attention and involuntary distraction in response to change or novelty in the environment have identified both early sensory and later cognitive event-related brain potential (ERP) components associated with the processing of stimulus mismatch, novelty, and salience. Among these components, the frontocentrally maximal mismatch negativity (MMN) is evoked by a change or deviation in auditory stimulation that falls outside the focus of the participant's attention [2]. The main neuronal generators of MMN have been proposed to be localized bilaterally in the left and right supratemporal auditory cortex [2–5], with additional contributions from frontal generators [3,6–8]. In comparison, unattended task-irrelevant but more salient and novel stimuli elicit a centrally maximal negativity, the N2b, and a frontocentrally maximal positive component, the P3a, both associated with the orienting of attention to novel and salient information in the environment [9,10]. Both the N2b and the P3a components are hypothesized to have sources in the prefrontal cortex, but also in more posterior regions, including the temporoparietal junction and the posterior hippocampal regions, as suggested by their attenuation following focal lesions in any of these areas [11,12].

Whether these neural responses to unattended sensory changes in the environment are automatic, or depend on the overall attentional and arousal level of the organism, is an issue of contention. The MMN has long been considered to be automatic and immune to attentional modulation, maintaining relatively unaltered amplitudes regardless of the amount of attention allocated to primary tasks [3,10,13].

Some recent studies have challenged this assertion [14] and have reported a reduced MMN during more demanding visual tasks, thus challenging the hypothesis of the automaticity of the MMN. Similarly, although numerous studies [15–17] examined the neural substrates of unattended and task-irrelevant salience and novelty processing indexed by the N2b and P3a ERP components, the attentional modulation of these components remains unclear.

The present study used ERP measures to examine the neural activity evoked by deviant tones and complex salient environmental sounds while participants engaged in continuously demanding visuomotor tracking tasks at two levels of difficulty. The tasks' attentional demands were raised by increasing the difficulty level of tracking. We measured the effects of tracking difficulty on the amplitude and latency of sensory evoked P1, N1, and P2 components elicited by the frequent standard tones, and of sensory and cognitive MMN, N2b, and P3a components elicited by the infrequent pitch-deviant (MMN) and complex environmental novel (N2b and P3a) sounds [9,10].

MATERIALS AND METHODS

Study participants: Sixteen participants (nine females, seven males, mean age: 19 years) participated in the study and received course credit. The data of three participants were discarded because of excessive artifacts. The experiment was approved by the Duke University Institutional Review Board and all participants provided informed consent. None reported serious neurological or psychiatric problems. All participants were right-handed, as confirmed by the Edinburgh Handedness Questionnaire [18].

Stimuli and experimental design: We implemented a continuous visuomotor tracking task in which participants used an isometric joystick to center a small cursor on a visual display. The cursor's position was perturbed by a two-dimensional forcing function that consisted of band-limited noise with brief, large deviations or steps superimposed. Following prior studies by Wickens *et al.* [19], we created two difficulty levels by altering the dynamics of the joystick. Velocity dynamics were used for the lower level of difficulty (first order), and acceleration dynamics were used for the higher level of difficulty (second order). Tracking error was quantified as the Euclidian distance between the cursor's position and the small fixation cross at the center of the display. Tracking error was continuously sampled at 10 Hz and stored for offline analysis. This permitted an analysis of short-term changes in tracking performance associated with the tones.

Auditory tone pips were presented concurrently with the visuomotor tracking task. The auditory stimuli consisted of pure tones and novel environmental sounds delivered through earphones at a constant rate of one tone per 1500 ms. The pure tones were 600 Hz (standard, $p=82%$) and 700 Hz (deviant, $p=9%$). The deviant tones and novel sounds ($p=9%$) were introduced into sequences with an interval randomized between 3 and 9 s. A total of 200 different complex environmental sounds (rain, telephone ringing, dog barking, etc.) were presented only once during the sequence as novel sounds. All stimuli were 200 ms in duration, including 10 ms rise/fall times. The intensity of the tone stimuli was 75 dB sound pressure level (SPL) and the intensity of the novel sounds ranged from 60 to 80 dB SPL, with a mean value of 70 dB SPL.

During the ERP session, participants were comfortably seated in a chair in a dimly lit, electrically shielded, and sound-attenuated chamber. They completed the visuomotor tracking task and were instructed to ignore the auditory stimuli. The tracking task was presented on a gray background on a computer screen placed 75–80 cm from the participant. Participants performed eight runs of the lower-difficulty and eight runs of the higher-difficulty tracking task while stimuli were presented. The run order was randomized. Each of the 16 runs lasted ~3 min, during which time 135 auditory tones were delivered. Before recording, a practice run of ~75 s was conducted to familiarize the participants with the task.

Electroencephalogram recording: The EEG was recorded from an array of 31 tin electrodes (Electro-Cap International Inc., Eaton, Ohio, USA). The array included the locations of the 10–20 system, and two additional electrodes placed at the outer canthus and below the right eye to record the electrooculogram (EOG). Electrode impedances were kept below 5 k Ω . All electrodes were referred to the nose tip. The EEG was amplified with a gain of 20 000 through a band pass of 0.1–100 Hz, digitized at 250 Hz per channel, and stored for offline analysis.

Data analysis: Epochs of 600 ms length (including 100 ms prestimulus baseline) were extracted from the continuous EEG recordings and then averaged into separate bins for each participant, electrode, tracking difficulty condition, and stimulus type (standard, deviant, or novel). Epochs contaminated with EOG artifacts were detected by an

automated algorithm and excluded from the bin averaging procedure. To avoid excessive novelty effects on the first trials of the stimuli, the first six stimuli were also rejected from averaging. The resulting averaged ERPs were low-pass filtered (15 Hz) [20]. The mean voltage of the 100 ms prestimulus period served as a baseline for amplitude measurement.

The P1, N1, and P2 peak mean amplitudes and latencies, within 30–60, 88–120, and 140–250 ms, respectively, were measured from the ERPs elicited by the standard-tone responses. Difference waveforms were created at each electrode site representing the difference between the ERPs evoked by the standard and deviant stimuli. Such difference waveforms have been used in prior studies to isolate the broad negative ERP component referred to as the MMN. The N2b and P3a were extracted by subtracting the responses to the standards from those to the novel sounds. The ERP peak latencies were measured from the largest negative-going peak within the 100–240 ms window for the MMN and N2b and from the largest positive-going peak within the 210–390 ms window for the P3a. The mean amplitudes of the ERP components were measured from 40 ms windows centered on the peaks of the grand-averaged waveforms for each tracking difficulty level in each individual.

The electrodes included in the analysis were Fz and Cz, chosen from the frontocentral scalp locations where the particular ERP components of interest are traditionally quantified [10]. The statistical significance was determined with one-tailed *t*-tests: Cz, for the P1, N1, P2, N2b, and P3a, and also Fz for the MMN and Pz for the N2b and P3a. Additionally, because the MMN reversed polarity at the mastoids (left, LM; right, RM) when using the nose as a reference, N1, N2b, and MMN amplitudes were also evaluated at the mastoids by comparing them with zero, with one-tailed *t*-tests. The behavioral data were statistically analyzed by analysis of variance (ANOVA) with repeated measures. Where appropriate, Greenhouse–Geisser corrections were applied, with the original degrees of freedom and corrected probability levels reported here.

RESULTS

Behavioral data: ANOVAs were conducted on the tracking error rate data to examine task-difficulty effects and any interactions between task difficulty and tone presentation. The average tracking error rate of the cursor position was computed from a 3-s time window preceding and following each deviant tone or novel sound. A significant main effect of tracking difficulty on tracking error was observed, with tracking under second-order control dynamics resulting in a larger error of the cursor position than first order [$F(1,12)=99.250$, $p<0.0001$ for deviant tones; $F(1,12)=89.409$, $p<0.0001$ for novel sounds]. However, neither a significant difference in the tracking error measured before or after the onset of auditory stimulus (a deviant tone and a novel tone) nor an interaction effect for both auditory stimuli was observed, indicating that the pitch change in the unattended channel did not interfere with participants' performance on the tracking tasks.

Event-related potential data: Figure 1 shows the ERPs elicited by unattended auditory (deviant and novel) stimuli

by collapsing across task difficulty at Fz, Cz, and Pz. As seen in Fig. 1b, the largest amplitude for the MMN and N2b was at Fz and Cz, respectively. However, the largest amplitude of P3a in the grand average of all participants was at Pz. Thus, Fz, Cz, and Pz were included in subsequent statistical analyses.

The amplitude and latency of measured ERP components are presented in Table 1. The N1 component was largest at the frontocentral scalp sites with a peak latency around 100 ms in the ERPs elicited by the standard tones, and did not differ between tracking difficulty levels (Table 1). Also, no amplitude difference between tracking difficulty levels was detected for the N1, P1, and P2 components at Cz electrode sites. However, a significant task-difficulty difference was observed at LM for the N1 [$t(12)=-2.09$, $p<0.04$].

Figure 2 depicts the mean amplitude of the MMN (Figs. 2a and b) and its scalp topographic distribution under the low and high-difficulty tracking conditions (Fig. 2c). The MMN mean amplitude at Fz was significantly smaller during the high-difficulty tracking task [$t(12)=-1.94$, $p<0.03$] than during the low-difficulty tracking task (Fig. 2b and Table 1). The topographic map at 152–192 ms shown in Fig. 2c confirms the frontocentral distribution of the MMN. As these maps have the same scale, the color difference between the maps obtained during both tracking difficulty

conditions depicts the diminished amplitude of the MMN during high-difficulty tracking.

The N2b component did not show any significant task-difficulty effect at Cz or at the mastoids. (Fig. 3 and Table 1). However, we found a significant task-difficulty effect at a negative peak that occurred after the polarity-reversed N2b at the LM and RM sites [$t(12)=-3.30$ $p<0.004$; $t(12)=-2.154$ $p<0.04$, respectively] within the 170–220 ms window. The reduction in the positive peak in the P3a range is also depicted in the topographic maps (Fig. 3c). This peak has been considered a part of the early P3a component in some studies [15–17] (Fig. 3b). Visuomotor tracking difficulty did not alter the amplitude of the P3a component measured at either Cz or Pz ($p>0.1$).

DISCUSSION

The goal of the present study was to examine the attentional modulation of neural activity elicited by task-irrelevant pitch-deviant tones and complex novel environmental sounds using ERPs. To our knowledge, this is the first report of a modulation of the neural processing of unattended task-irrelevant pitch-deviant tones and novel sounds by the attentional demands of a primary visual task. The results replicated our previous findings [14] and

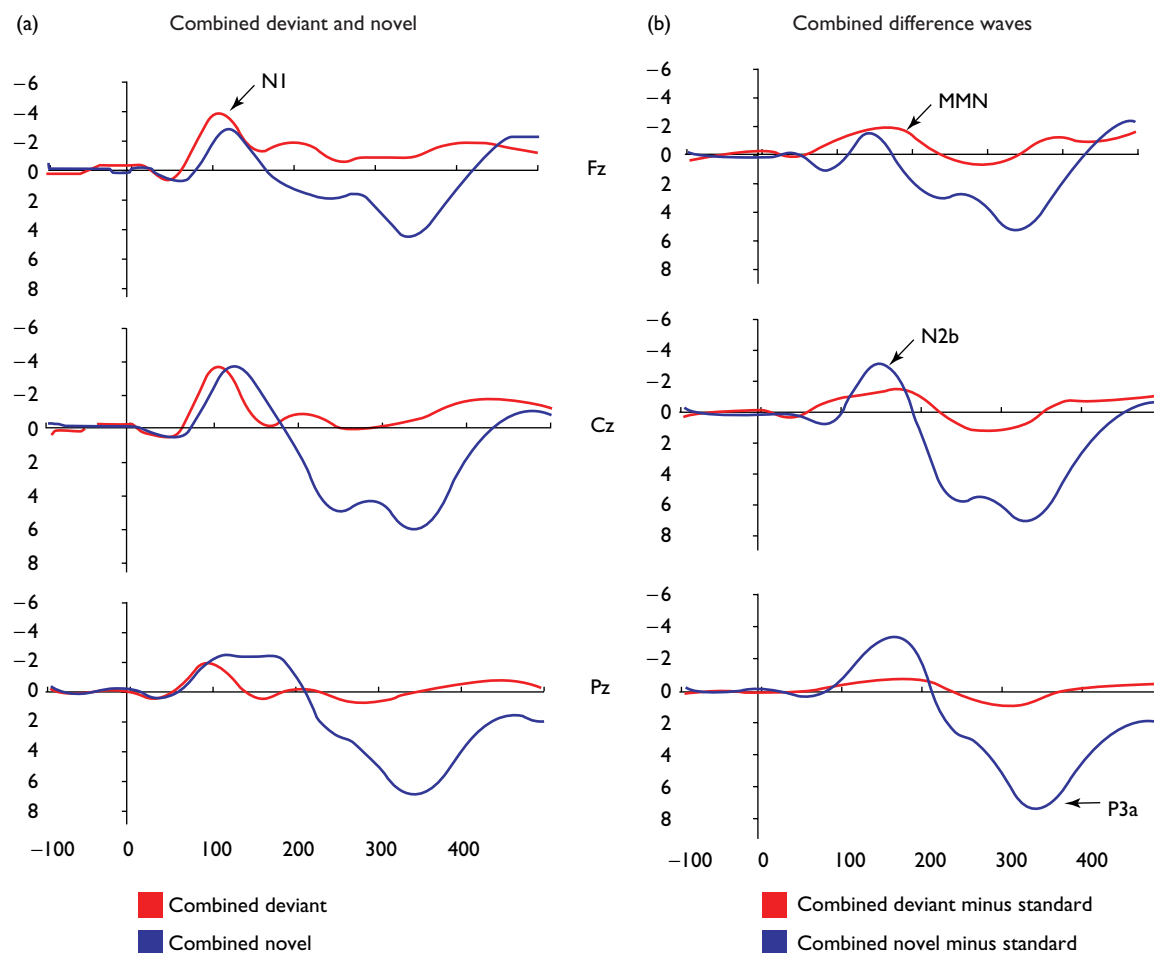


Fig. 1. (a) Grand-averaged event-related potentials to the auditory stimuli (deviant: red lines; novel: blue lines) recorded at the Fz, Cz, and Pz by combining across task difficulties in the left column. (b) The corresponding difference waveforms (deviant minus standard: red lines; novel minus standard: blue lines) are presented in the right column.

Table 1. Grand mean amplitudes and latencies of the event-related potentials (ERPs).

ERP responses	Amplitude (μV)		Latency (ms)	
	Tracking difficulty		Tracking difficulty	
	Low	High	Low	High
P1 to standards (Cz)	0.2452 (0.3)	0.4380 (0.2)	45 (2.5)	45 (3.4)
N1 to standards (Cz)	-2.5562 (0.3)	-2.3008 (0.3)	99 (2.2)	100 (1.9)
P2 to standards (Cz)	1.2056 (0.4)	1.4329 (0.3)	163 (2.6)	170 (7.1)
MMN to deviants (Fz)	-2.7518 (0.4)*	-2.1357 (0.3)	176 (8.2)	170 (7.7)
N2b to novel sounds (Cz)	-3.3316 (1)	-3.8119 (0.8)	152 (6.0)	147 (6.6)
P3a to novel sounds (Cz)	9.6031 (1.4)	8.2450 (1.3)	307 (14.1)	316 (13.3)

The standard error of the mean is given in parentheses.

* $p < 0.03$.

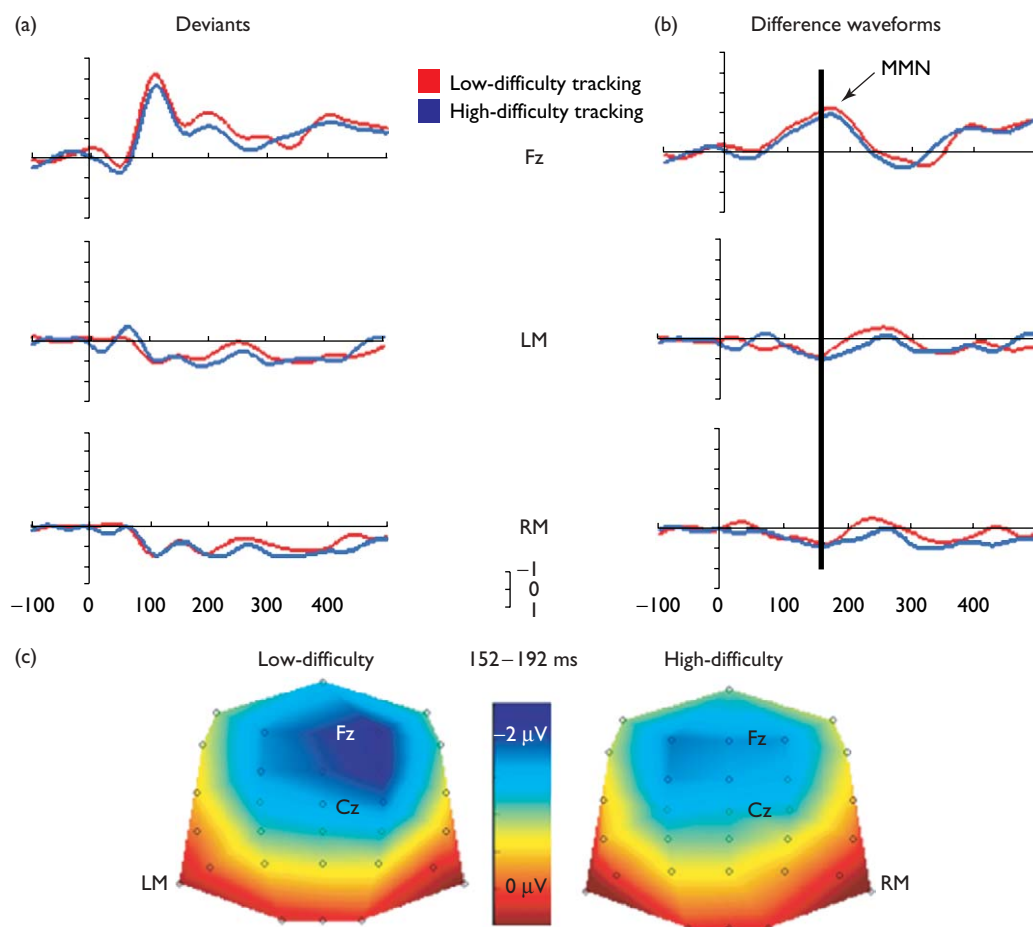


Fig. 2. (a) Grand-averaged event-related potentials to deviant stimuli recorded at the Fz, left (LM) and right (RM) mastoids while performing low-difficulty (red lines) and high-difficulty (blue lines) tracking tasks in the left column. (b) The mismatch negativity (MMN) (deviant minus standard) components are presented in the right column (low-difficulty tracking: red line; high-difficulty tracking: blue line). (c) Isovoltage maps depicting the MMN scalp distribution between 152 and 192 ms during the two tracking tasks.

revealed that increasing the amount of attention allocated to the primary tasks reduced not only neural responses evoked by pitch-deviant tones at frontal scalp sites, but also ERP components elicited by novel sounds at the mastoids.

Participants produced reliable MMN responses to deviant tones, and N2b and P3a responses to novel sounds during

both visuomotor tracking tasks. As seen in Table 1 and Figs 1 and 2, the MMN to deviant tones peaked and returned to baseline later than the N2b component (Fig. 3). Deviant tones elicited a distinct MMN that was followed by a small P3a, possibly indexing an early orienting of attention. However, novel sounds elicited a large, broadly distributed,

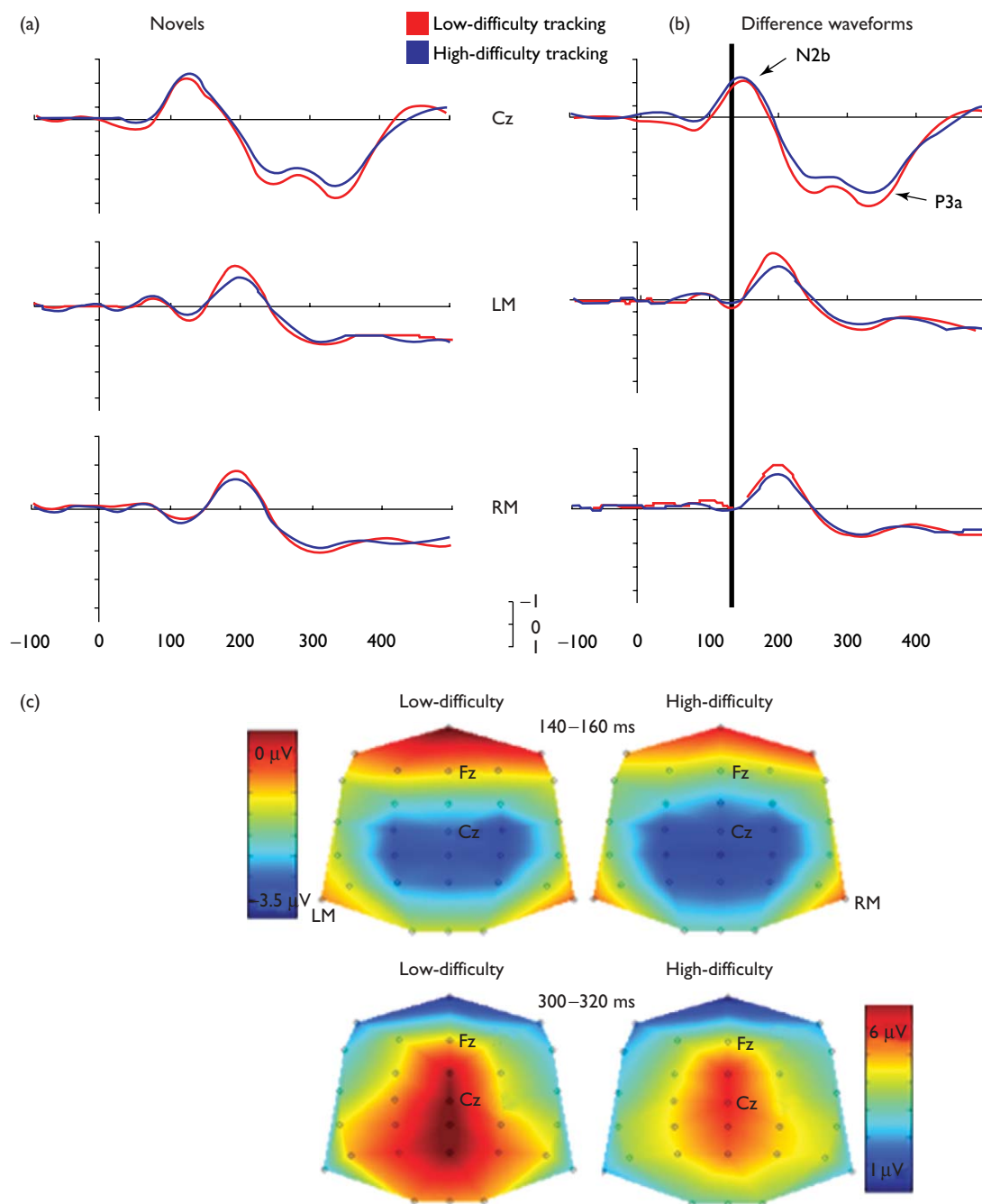


Fig. 3. (a) Grand-averaged event-related potentials to the novel sounds recorded at the Cz, left (LM) and right (RM) mastoids while performing low-difficulty (red lines) and high-difficulty (blue lines) tracking tasks in the left column. (b) The difference waveforms (novel minus standard tone) are presented in the right column (low-difficulty tracking: red line; high-difficulty tracking: blue line). (c) Isovoltage maps depicting the N2b and P3a scalp distribution between 140–160 ms and 300–320 ms during the two tracking difficulty tasks, respectively.

and long-lasting P3a component with double peaks at the Fz and Cz scalp sites (Figs 1 and 3). Moreover, in the range of P3a, a negative peak was found just after the N2b at the mastoids (Fig. 3b). The significance of this negative peak occurring just after the N2b that reverses in polarity at the mastoids needs to be further explored. Thus, the topographic distribution of the MMN, N2b, and P3a ERP components, elicited in the present study by deviant tones and novel sounds [2,15,16,21], is consistent with previous published reports.

Increasing the difficulty of the primary tracking task reduced the mean amplitude of the MMN component elicited by the pitch-deviant tones at Fz, reflecting a modulation of this component by the overall attentional state of the system. In contrast, the effect of tracking difficulty on the ERP component elicited by the unattended novel sounds were picked up at the mastoid electrodes (LM and RM), at later latencies approaching the P3 range, immediately following the N2b. We suggest that because each novel sound occurred only once in the study, an

orienting response to novel sounds might have occurred and may have been affected by task difficulty at the mastoids rather than at the frontocentral electrode sites. Further investigation needs to clarify the orienting of attention at these sensory channels. Thus, the present study extends prior findings on electrophysiological responses to unattended auditory stimuli by demonstrating that MMN components elicited by unattended deviant tones are sensitive to the demands of concurrent tasks. In contrast, attentional modulations of ERP components elicited by more salient and novel sounds appear at later latencies. Observations of attentional limitations, even under conditions in which the primary and unattended tasks are presented in different modalities, suggest a more central attentional bottleneck.

CONCLUSION

Our findings revealed that, as the demands of a primary task were increased, a corresponding decrease was observed in the neural activity elicited by deviant, task-irrelevant sensory changes. In contrast, early sensory neural responses elicited by more salient, novel, unattended stimuli did not show attenuations as a function of primary task difficulty. Rather, attention effects appeared at later latencies, as reflected in differences in the N2–P3a range. This greater effect of primary task difficulty on early sensory processing of simple pitch-deviant tones suggests that sensory stimulus salience can overcome overall cognitive demands to preserve the capacity to orient to novel environmental tones. The reduction in attentive control over highly salient novel sounds may reflect an interplay between local auditory sensory processes and top-down attentional capture phenomena activated by stimulus salience. These findings may have implications for clinical studies utilizing involuntary attention measures to assess neural capacity in patient populations, and suggests that the properties and demands of the primary tasks under those circumstances must be carefully characterized. Indeed, recent studies of various clinical populations, including children at genetic risk for dyslexia [22] and adults with intellectual disabilities, as reflected in low IQ measures [23] have been reported to show abnormal MMN components relative to their respective control groups. Given our current findings, such deficits may well be attributable to reduced higher-order attentional capacity in these populations, rather than simply localized auditory cortex dysfunction. Further research will be essential to gain a more precise understanding of the effects of primary task difficulty and attentional resource availability on the amplitudes of the MMN, N2b, and P3a responses to auditory stimuli.

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