Two separate mechanisms underlie auditory change detection and involuntary control of attention

Teemu Rinne\textsuperscript{a,b,*}, Anna Särkkä\textsuperscript{c}, Alexander Degerman\textsuperscript{a}, Erich Schröger\textsuperscript{d}, Kimmo Alho\textsuperscript{a}

\textsuperscript{a}Department of Psychology, University of Helsinki, Finland
\textsuperscript{b}Human Cognitive Neurophysiology Laboratory, UC Davis and VANCHCS, Martinez, CA 95616, USA
\textsuperscript{c}Cognitive Brain Research Unit, Department of Psychology, University of Helsinki, Finland
\textsuperscript{d}Institute for Psychology, University of Leipzig, Germany

ARTICLE INFO

Article history:
Accepted 11 January 2006

Keywords:
Auditory change detection
Distraction
Event-related potential
N1
MMN
P3a

ABSTRACT

We used behavioral and event-related potential (ERP) measures to study the neural mechanisms of involuntary attention switching to changes in unattended sounds. Our subjects discriminated two equiprobable sounds differing in frequency (fundamental frequency 186 or 196 Hz) while task-irrelevant intensity decrements or increments (−3, −6, −9, +3, +6, or +9 dB, standard intensity 60 dB HL) infrequently occurred in the same sounds. In line with the results of previous studies, discrimination performance deteriorated with increasing magnitude of the task-irrelevant intensity change. However, these distraction effects were dissimilar for intensity increments and decrements: while there were no differences in reaction time (RT) between intensity decrements and increments, hit rates (HR) were lower for large intensity increments than for large decrements. ERPs to task-irrelevant intensity increments and decrements were also distinctly different: the response to intensity increments consisted of an N1 enhancement, mismatch negativity (MMN), and P3a, while the response to intensity decrements consisted only of MMN. These results are consistent with the assumption that two separate mechanisms (indexed by N1 and MMN) underlie auditory change detection. However, the finding that distinct distraction effects were obtained for both intensity decrements and increments but that the P3a is elicited only by the intensity increments seems to suggest that P3a may not be regarded as a general index of attentional shift but rather it is only generated in conditions in which an enhanced N1 is elicited, too.

© 2006 Published by Elsevier B.V.

1. Introduction

Sudden changes in unattended sounds may distract performance of an ongoing task as attention is involuntarily captured away from the task to the previously disregarded sounds. Such stimulus-driven control of attentional resources is referred to as involuntary attention. Based on the results of previous studies recording event-related potentials (ERP) to infrequent changes in repetitive acoustic stimulation, it has been suggested that involuntary attention is triggered by two distinct auditory cortex change detection mechanisms that respond to different information about the preceding acoustic input (Escera et al., 1998; Näätänen, 1992; Picton et al., 2000). The first mechanism, reflected in the N1 component of the ERP, detects acoustic changes based on activation of new neural units when a sound is presented in silence (i.e., after a long enough break) or when a distinct sound frequency change or intensity increment occurs against a monotonous acoustic background (Butler, 1968; Korzyukov et al., 1999; Näätänen and Picton, 1987). The other mechanism, reflected

* Corresponding author. Department of Psychology, P.O. Box 9, FI-00014 University of Helsinki, Finland.
E-mail address: teemu.rinne@helsinki.fi (T. Rinne).

0006-8993/$ – see front matter © 2006 Published by Elsevier B.V.
doi:10.1016/j.brainres.2006.01.043
in the mismatch negativity (MMN), detects changes that violate regular features of sound sequences, apparently based on integrated representations of auditory events (Näätänen and Winkler, 1999).

Although the N1 and MMN occur in close temporal succession within 100–200 ms from change onset and may even partly overlap in time, these components have been dissociated from each other in several ways such as (for a recent extensive discussion on N1 and MMN differences, see Näätänen et al., 2005): (1) N1 can be elicited by a single presentation of a sound, whereas MMN requires the context formed by the previous sound sequence (Korzyukov et al., 1999; Näätänen et al., 1989). (2) MMN is elicited by both sound intensity increases and decreases and its magnitude follows the magnitude of intensity changes irrespective of the direction of change (Näätänen, 1992, pp. 139–143), whereas N1 amplitude diminishes when the intensity is decreased (Rapin et al., 1966). (3) Analyses of ERP sources based on electric and magnetic recordings have suggested that N1 and MMN are generated by separate neural populations in the auditory areas of supratemporal cortex (Alho et al., 1998; Korzyukov et al., 1999; Levänen et al., 1996; Sams et al., 1991; Scherg et al., 1989; Tiitinen et al., 1993).

On the behavioral level, the effect of involuntary attention switching may be examined using the so-called auditory distraction paradigm (Berti et al., 2004; Escera et al., 2000; Schröger and Wolff, 1998). In this paradigm, subjects are required to discriminate two equiprobable sounds that differ in duration. Duration discrimination performance deteriorates when relatively small frequency changes occur in the same sounds. As the ERP response to such changes is dominated by MMN, it is assumed that the task-irrelevant frequency changes are detected by the MMN mechanism triggering involuntary attention switching away from the task to task-irrelevant features of the sounds so that the subject is distracted in the duration discrimination task. Furthermore, it is assumed that switching of attention is indexed by the P3a component of the ERP which is elicited when the task-irrelevant frequency changes impair the subject’s performance (Escera et al., 1998) but not when the distraction effect of the same task-irrelevant changes is eliminated by making sound changes predictable with a visual cue (Sussman et al., 2003). Similar behavioral and ERP results have been obtained by using different versions of the auditory distraction paradigm (e.g., sound location discrimination task with infrequent sound duration changes) (Roebert et al., 2003).

Some previous studies have reported dissimilar effects of small and large frequency changes on reaction time (RT) and hit rate (HR) in a visual discrimination task. This suggests that attention switching triggered by N1 or MMN mechanisms, which are activated differently by small and large frequency changes, result in different behavioral effects (Alho et al., 1998; Escera et al., 1998). However, as even relatively small frequency changes are likely to activate both N1 (Näätänen et al., 1988) and MMN (Sams et al., 1985) mechanisms, it is difficult to examine the behavioral effects of these two mechanisms separately using frequency changes. Therefore, in the present study, we modified the auditory distraction paradigm to examine behavioral distraction effects in conditions where N1 and MMN can be dissociated from each other. Our subjects were required to discriminate two equiprobable sounds differing in frequency while task-irrelevant intensity

Fig. 1 – Left column: Mean (±SEM) RT and HR for each sound type (bars, scale on left) and mean performance deterioration (within-subject difference in performance between infrequent intensity change and frequent sound; lines, scale on right). Right column: Mean (±SEM) MMN, N1, and P3a (absolute) amplitudes. Amplitudes of the N1 enhancement and MMN were measured from a frontal midline electrode (marked with a filled circle in Fig. 3), while P3a amplitude was measured from a central midline electrode (marked in Fig. 4).
increments or decrements infrequently occurred in the same sounds. The task-irrelevant intensity change was parametrically varied in three steps for both increments and decrements. We assumed that the infrequent intensity increments would elicit enhanced N1 and MMN responses while the intensity decrements would elicit only the MMN (Näätänen, 1992; Näätänen et al., 1989). Furthermore, we hypothesized that, if the N1 and MMN mechanisms are functionally separate and result in different behavioral distraction effects, then the behavioral responses to intensity increments (N1 + MMN) and decrements (MMN) should differ.

2. Results

2.1. Behavioral task

As expected, frequency discrimination performance deteriorated when sound intensity differed from the standard (Fig. 1, left). RT and HR were affected differently by the intensity increments and decrements: increase of RT was similar for intensity increments and decrements (top left), while decrease of HR depended on the direction of the intensity change (bottom left).

Reaction time increased with the magnitude of the intensity change (2-factor repeated-measures ANOVA, Change Direction (Increment/Decrement) * Change Magnitude (±3, ±6, and ±9 dB; Small, Medium, and Large Change, respectively), main effect of Change Magnitude: F(2,26) = 4.98, P < 0.05, linear trend across Change Magnitude: F(1,13) = 5.65, P < 0.05). In this and subsequent ANOVAs, the original degrees of freedom are reported and probabilities are Greenhouse-Geisser-corrected when appropriate.

Hit rate was different for intensity increments and decrements (ANOVA, Change Direction * Change Magnitude, main effect of Change Direction: F(1,13) = 20.74, P < 0.001) and for the different levels of intensity change (main effect of Change Magnitude: F(2,26) = 12.79, P < 0.01), HR decreased with the magnitude of the intensity change (linear trend across Change Magnitude: F(1,13) = 13.00, P < 0.01). Furthermore, hit rates for intensity increments and decrements changed differently with the magnitude of change (interaction of Change Magnitude and Direction: F(2,26) = 16.15, P < 0.001). This was due to greater HR effects for Large and Medium intensity increments than for Large and Medium decrements (two-tailed t test, Medium and Large Increments vs. Medium and Large Decrements: t = 5.36, P < 0.001).

2.2. ERPs

Grand-averaged ERPs to frequent sounds and infrequent intensity changes are shown in Fig. 2. The frequent sound elicited a typical N1 response at 95 ms from sound onset. Note that the peak latency of the N1 to the frequent sound and infrequent intensity increments is about the same. The responses to infrequent sound intensity changes were negatively displaced between 100 and 200 ms from sound onset as compared to the response to frequent sounds. This change-related displacement can be best seen in the difference waveforms (response to infrequent intensity change – response to frequent sound, Fig. 2, right). The difference waveform showing the change-related response to Large intensity increment (Fig. 2, right, thick blue) consists clearly of two peaks: one peaking at about 100 ms and the other peaking later at about 180 ms from sound onset. The difference waveform to Large intensity decrement (red), in turn, shows a distinct response peaking close to 200 ms but no peak at 100 ms from sound onset. These findings are consistent with the hypothesis that the large change-related response to infrequent intensity increments consists of enhanced N1 and MMN while the response to intensity decrements is dominated by the MMN response.

The effects of task-irrelevant intensity changes on N1 and MMN were estimated as mean amplitudes in the difference

![Fig. 2](image-url)

Fig. 2 – Left and middle: grand-averaged ERPs for task-irrelevant intensity decrements (red) and increments (blue) as compared to the response to frequent sounds (dashed black). Right: difference waveforms (response to infrequent intensity change – response to frequent sound) for intensity increments and decrements. Vertical gray line (dashed) indicates typical N1 latency (100 ms from sound onset). Data from a frontal midline electrode are presented (marked with a filled circle in Fig. 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
waveforms over 85–110 ms and 160–185 ms time windows, respectively. These mean amplitudes were used for all analysis and figures. Scalp potential distributions at these two time windows are illustrated in Fig. 3. To facilitate the visual comparison of the location of the negative scalp maxima (darkest gray), the amplitude values were scaled to 0–1 range. The scalp distributions of the N1 enhancement and MMN responses were statistically compared with each other using normalized amplitude values from eight midline electrodes (approximately from Fpz to Pz). Normalization was done separately for each subject by dividing the amplitude value at each electrode by the sum of squared amplitudes at all 8 electrodes. The distribution of the N1 enhancement was different than the distributions of the MMN to intensity increments (2-factor repeated measures ANOVA, Latency (N1 enhancement/MMN) * Electrode (8 midline electrodes), interaction of Latency and Electrode (F(7,91) = 5.37, P < 0.05) and decrements (interaction of Latency and Electrode: F(7,91) = 5.77, P < 0.01). These differences suggest that at least partially different patterns of brain activation underlie N1 enhancement and MMN. Note that, at the N1 latency, the scalp potential distribution of the response to the largest intensity decrement (Fig. 3, bottom left) is remarkably different from a typical N1 pattern which is seen for the largest intensity increment (top left). In subsequent analyses, the N1 and MMN responses were estimated from a fronto-central midline electrode (corresponding roughly to Fz; marked with a filled circle in Fig. 3, top left).

The difference waveforms to Medium and Large intensity increments (Fig. 2, right) differed from zero at N1 latency (two-tailed t test, Medium change: t = 2.55, P < 0.05; Large change: t = 5.8, P < 0.001). At the MMN latency, only the waveform to Large intensity increment differed significantly from zero (t = 2.94, P < 0.02). The lack of significant response to Small and Medium intensity increments at the MMN latency may be caused by the partially overlapping positivity (P3a, see below) emerging after 200 ms from sound onset. The difference waveforms to intensity decrements did not differ from zero at the N1 latency, while, at the MMN latency, all differences were significant (Small change: t = 2.39, P < 0.05; Medium change: t = 2.97, P < 0.01; Large change: t = 6.62, P < 0.001).

Mean N1 and MMN amplitudes are shown in Fig. 1 (right). The N1 amplitude (right bottom, continuous line) increased with the magnitude of intensity increment (1-factor repeated-measures ANOVA, main effect of Change Magnitude: F (2,26) = 16.49, P < 0.001; linear trend across Change Magnitude: 0.001).

Fig. 3 – Scalp potential distributions for grand-averaged difference waveforms (response to infrequent intensity change – response to frequent sound) for the largest intensity increment (+9 dB, top) and decrement (−9 dB, bottom) at the N1 (left) and MMN (right) latencies. The maps show a two-dimensional projection of the scalp potential distribution seen from above the head. Amplitude values are scaled (to 0–1 range) so that maximum negativity (within the time range) is presented with darkest gray in each map. Scaling of amplitudes was applied to facilitate the visual comparison of the relative location of the scalp potential negative maxima. The electrode locations are marked with circles. A filled circle marks the electrode used to measure the mean amplitudes at these latencies. Note that the potential distribution for intensity decrements at N1 latency (bottom left) is not typical for N1 enhancement or MMN.
The MMN amplitude increased with the magnitude of the intensity change (2-factor repeated-measures ANOVA, main effect of Change Magnitude: \(F(2,26) = 21.44, P < 0.001\); linear trend across Change Magnitude: \(F(1,13) = 30.86, P < 0.001\)). Although the MMNs seemed to be slightly larger in amplitude for intensity decrements than for increments (presumably due to overlapping P3a with intensity increments), these differences were not significant.

In addition to N1 enhancement and MMN, a P3a response can be seen in the difference waveforms (Fig. 2). Interestingly, this response is elicited only by the intensity increments (mean amplitude at 300–325 ms estimated from a central midline electrode marked with a filled circle in Fig. 4; two-tailed t test, P3a mean amplitude vs. 0, Medium change: \(t = 4.17, P < 0.01\); Large change: \(t = 3.85, P < 0.01\)). The P3a amplitude increased with the magnitude of intensity increment (Fig. 1, right bottom, dashed line; 1-factor repeated-measures ANOVA, main effect of Change Magnitude: \(F(2,26) = 15.36, P < 0.01\); linear trend across Change Magnitude: \(F(1,13) = 17.84, P < 0.001\).

Scalp potential distributions (scaled to 0–1 range, see above) at N2 (185–210 ms), P3a (300–325 ms) and P3b (365–390 ms) latencies for responses to largest intensity increments and decrements are shown in Fig. 4. At the N2 latency (left), the distributions of responses to intensity increments and decrements seem to differ. This difference could be caused by a different contribution of N2b to Large intensity increments and decrements (note that the subjects were performing a
forced-choice discrimination task, that is, all sounds are targets). Alternatively, the difference at the N2 latency might be due to an enhanced P2 to intensity increments. At the P3a latency (middle), the distribution maps suggest that a P3a, albeit a very small one, was elicited also by the intensity decrements. The ERP to frequent sounds shows a P3b at about 380 ms from sound onset (Fig. 2), and it seems to slightly increase in positivity in response to intensity decrements. In the case of intensity increments, the possible P3b is difficult to separate from P3a. However, the distribution maps (Fig. 4, right) are consistent with the assumed more posterior positive maximum of the P3b as compared with that of the P3a (Alho et al., 1998; Squires et al., 1975).

2.3. Behavioral control condition

The results of the behavioral control condition are shown in Fig. 5. RT was not affected by sound intensity in absence of change. HR was lower for the high than low intensity sounds (differences in relative intensity to the 60 dB HL sound were analyzed; ANOVA, Sound Type (Low/High intensity) * Intensity Difference (Small, Medium, Large), main effect of Sound Type: F(1,11) = 6.71, P < 0.05.

3. Discussion

In line with previous studies using different stimulus parameters (e.g., Ahveninen et al., 2002; Berti et al., 2004; Roebroek et al., 2005; Sussman et al., 2003; Wetzel et al., 2004), task-irrelevant intensity changes were associated with distinct behavioral distraction effects in a forced-choice frequency discrimination task. However, we found that the distraction effects were dissimilar for intensity increments and decrements: while there were no differences in RT between intensity decrements and increments, HRs were lower for large intensity increments than for decrements. This difference between HR and RT is consistent with the hypothesis that two separate attention switching mechanisms are differently activated by infrequent intensity increments and decrements.

The monotonic increase of distraction effects with increasing magnitude of intensity change supports the conclusion of a previous study using the original version of the auditory discrimination task (duration discrimination with task-irrelevant frequency change) (Berti et al., 2004): the behavioral distraction effect due to involuntary switching of attention to task-irrelevant sound changes is not a categorical (all or none) phenomenon, but, rather, it is modulated by the strength of the distracting event. However, this does not necessarily mean that the attention switch itself is a gradual process. It is also possible that the modulation of the behavioral distraction effect by the magnitude of the task-irrelevant sound change is caused by fluctuation of focus of attention between the task and the distracting event so that the time attention is directed away from the current task varies depending on the requirements of the current task, the salience of the distracting event and situational factors.

In ERPs, the responses to infrequent intensity increments and decrements were also distinctly different. The response to task-irrelevant increments consisted of two peaks (Fig. 2): one at (typical) N1 latency (about 100 ms from sound onset) and a later one corresponding to MMN (at about 180 ms). In contrast, the response to intensity decrements consisted only of the latter peak (MMN). These results are consistent with the assumptions of the prevailing model of auditory change detection (Escera et al., 2000; Näätänen, 1992; Näätänen et al., 2005; Näätänen and Winkler, 1999): (1) N1 enhancement to infrequent intensity increments is generated by the recruitment of new neural units, while no new units are activated by infrequent intensity decrements. (2) The MMN mechanism detects both intensity increments and decrements based on a representation of the past auditory events.

Alternatively, it could be argued that the intensity decrements did not trigger attention switching at all since the intensity decrements did not elicit P3a (see below). However, this view is not easily compatible with the behavioral data showing increase of distraction effects (RT) with the magnitude of intensity decrement.

It could also be argued that the differential effects of intensity decrements and increments on frequency discrimination performance are not due to attention switching triggered by auditory change detection but that the frequency discrimination performance depends on the sound intensity and, thus, deteriorates when the intensity of the sounds is decreased or increased. However, although frequency discrimination thresholds decrease when sound intensity is increased from 0 to about 40 dB, they remain relatively stable at higher intensities (Nelson et al., 1983). Thus, we expected no significant differences in frequency discrimination thresholds for the low and high intensity levels used in the present study. However, van der Molen and Keuss (1979) have shown that RT in a two-button forced-choice frequency discrimination task depends on sound intensity in a U-shaped manner. In one condition of their study, the subjects discriminated between low (1 kHz) and high (3 kHz) frequency sounds. The intensity of the sounds varied randomly from 70 to 105 dB in steps of 5 dB. The RTs were longest for 70 and 105 dB and shortest for 90 dB, while error rates were highest for the highest intensities. These results match the present results (Fig. 1) and seem to suggest that the present behavioral results were caused simply by the effects of sound intensity on frequency discrimination. However, van der Molen and Keuss did not control for the possibility that, in a sequence of sounds with randomly varying intensities (range 70–105 dB), there will be mini-sequences with relatively low (or high) sound intensity against which high (or low) intensity sounds appear as changes. These intensity changes activate the N1 and MMN mechanisms. Thus, in addition to a genuine intensity/frequency dependency, their results might be explained by effects of pretarget auditory change detection of task-irrelevant intensity changes on the frequency discrimination task.

In the present control condition, we measured the effects of sound intensity per se on frequency discrimination so that the possible contribution of auditory change detection mechanisms on task performance was minimized. The sounds of the main condition were presented in constant-
The difference between P3a elicitation (P3a was elicited by the intensity increments which were more conspicuous than the decrements due to the difference in the magnitude of the overlapping N1 enhancement and MMN) and decrements was equally strong for both increments and decrements. According to this suggestion, P3a was elicited only by the intensity increments which were more conspicuous than the decrements due to the difference in the magnitude of the overall attention switch signal. However, in the present study, both the intensity increments and decrements were associated with a distinct deterioration of discrimination performance (increase of reaction time). Thus, the present data do not support the idea that the lack of P3a to intensity decrements is due to the weakness of the attention switch signal as compared to that for intensity increments.

The difference between P3a elicitation (P3a was elicited only by intensity increments) and behavioral indices of attention switching (distraction effect for both intensity increments and decrements) is at odds with the commonly accepted notion that P3a is a general index of attention switching (Escera et al., 1998; Friedman et al., 2001; Knight and Scabini, 1998; Schröger, 1996; Woods, 1992). Furthermore, the present results are not consistent with the assumption that the elicitation of P3a is connected to, or even triggered by, the MMN mechanism (Berti et al., 2004; Escera et al., 2000; Näätänen, 1992; Ulanovsky et al., 2004). Rather, the present results suggest that P3a occurs only in conditions when N1 enhancement is elicited (e.g., after a frequency change or intensity increment). The connection of N1 and P3a is, at least indirectly, supported by previous studies showing that novel sounds presented among repeating standard sounds are associated with both large N1 and large P3a deflections (Escera et al., 1998, 2000). This new interpretation of P3a is not easily refuted by the results of previous studies. Although numerous studies have used experimental conditions (e.g., sound duration or intensity decrements, stimulus omission, sound repetition, or abstract changes as the irregular feature eliciting MMN) in which the MMN but no N1 enhancement should be elicited, those studies have either not specifically examined the connection between MMN and P3a, failed to report on P3a, or failed to produce an unambiguous interpretation of reported MMN/P3a responses.

A recent study by Sussman et al. (2003) used the auditory distraction paradigm with duration discrimination amid task-irrelevant frequency changes (repeating sound: 440 Hz, infrequent sound: 494 Hz). The sounds were presented in pairs with red or green circles (visual stimuli were always present 350 ms before the sounds) so that the different colors either indicated the pitch of the following sound (predictable condition) or were not associated with the pitch (unpredictable condition). The authors reported that the MMN was elicited by both predictable and unpredictable frequency changes while the P3a was elicited only in the unpredictable condition, suggesting that switching of attention only occurred when the task-irrelevant frequency changes could not be predicted. Correspondingly, the behavioral measures showed distraction (longer reaction times) for unpredictable, but not for predictable, frequency changes. These results support the notion that P3a is an index of attention switching. However, although a relatively small frequency change was used, it is likely that the change-related response elicited by the task-irrelevant frequency changes consisted of both N1 enhancement and MMN (as suggested by the ERPs presented in their Fig. 3). Thus, their results are consistent with the new interpretation of the role of P3a based on the present results: P3a is not a general index of attention switching but rather is related to attention switching triggered by the N1 mechanism. Note that it is assumed that the N1 and MMN mechanisms can, but do not always, produce attention shift and thus that P3a does not always follow observation of enhanced N1 and MMN (Näätänen, 1992).

The present study is based on the model of auditory change detection and involuntary attention (Näätänen, 1992). The effects of variation in irrelevant sounds on task performance have also been investigated in other theoretical contexts (Dyson and Quinlan, 2004; Jones et al., 1992; Melara et al., 2005). For example, according to the changing-state hypothesis (Jones and Macken, 1993; Jones et al., 1992), changes in discretely presented irrelevant tones impair performance (more errors) in a visually presented serial-recall memory task. The effect of irrelevant sound changes on task
performance is explained in the level of working memory: it is assumed that the preattentive processes in which auditory information is segmented interfere with memory of order cues. According to the present approach, preattentive processing of auditory information involves two different preattentive change detection mechanisms, which may trigger involuntary attention switching so that attention-controlled processing of task-relevant information is interrupted for an instant. Thus, the different approaches explaining interference of irrelevant auditory information with the processing of relevant information are based on different experimental paradigms. Therefore, further research is needed before an integration of these theories can be provided.

In conclusion, the behavioral and ERP results of the present study indicate that task-irrelevant intensity increments and decrements are processed differently by the brain. The results are consistent with the model of involuntary control of attention proposed by Näätänen (1992) in which the N1 and MMN mechanisms are assumed to be two separate routes from unattended auditory processing to involuntary switching of attention. However, the results were inconsistent with the general view of the P3a. Future experiments should carefully address the question of whether P3a may be regarded as a general index of attention elicited when any obtrusive auditory sound change is detected or whether P3a is only generated in conditions which also elicit enhanced N1.

The present results also underline the importance of carefully considering the acoustic parameters used in studies of the mechanisms underlying involuntary control of attention (see Rinne et al., 2005).

4. Experimental procedures

4.1. Subjects

Eighteen right-handed healthy subjects (22–30 years old; 9 male) with no hearing impairment or history of neurological or psychiatric problems participated in the study. Prior to the experiment, participants gave informed consent. The data of 4 participants were excluded from the analysis due to high overall error rate (over 50%) in the behavioral task.

4.2. Stimuli

Stimuli were harmonic complexes with fundamental frequencies 186 Hz (harmonics with equal intensity at 372, 558, 744 and 930 Hz, “low pitch”) or 196 Hz (392, 588, 784 and 980 Hz, “high pitch”). Low and high pitch sounds were presented randomly with equal probabilities. Sounds were presented with a standard intensity of 60 dB HL (above subjective hearing threshold) on 82% of trials. On other trials, sound intensity was either decreased or increased (−9, −6, −3, +3, +6, or +9 dB; P = 0.03 for each) relative to the standard intensity. The duration of all sounds was 100 ms with 5 ms rise and fall times. The sound onset-to-onset interval was 1 s, and sounds were presented diotically (identically to the two ears).

4.3. Behavioral task

Subjects performed a forced-choice discrimination task. They were instructed to press one button when hearing a high pitch sound and another when hearing a low sound while ignoring the infrequent changes in sound intensity. The experiment was divided into eight blocks (12 min each). Subjects were allowed to have short breaks between the blocks.

4.4. Data acquisition and analysis

Continuous EEG (sampling rate 500 Hz, the common reference electrode was attached to the tip of the nose) was recorded with a 64-channel electrode cap. EEG epochs starting 200 ms before and ending 800 ms after each sound onset were analyzed. Epochs with extracerebral artifacts (amplitude changes >100 μV on any electrode) and the first five epochs of all blocks were excluded from further data processing. EEG was digitally filtered (bandpass 1–20 Hz). Seven classes of responses were separately averaged according to stimulus intensity: standard sounds and 6 different intensity changes. The baseline for the waveforms was defined as the mean voltage in the 200 ms period preceding the sound onset. To estimate the response to infrequent intensity changes, the standard waveform was subtracted from each infrequent sound waveform.

Hit rates (HRs) and mean reaction times (RTs) were calculated separately for each stimulus type. Responses occurring between 200 and 1100 ms after stimulus onset were accepted in the analysis. For each subject, difference in performance between each task-irrelevant intensity change and standard sound was computed.

4.5. Behavioral control

In order to examine the dependency of frequency discrimination on sound intensity, a separate control condition (N = 12, three subjects did not participate in the main experiment) was conducted several months after the main experiment. The task and the sounds were the same as above. However, in the control experiment, the sounds were presented in constant-intensity blocks of 6–10 sounds (51, 54, 57, 60, 63, 66, or 69 dB above subjective threshold; 160 sounds for each intensity level). The blocks were presented in random order, except that the intensity difference between two successive blocks was 9 dB or less. The two first sounds of a block were not included in the analysis.

Acknowledgments

Supported by the Academy of Finland (grants #201160, #202562, #207180, #1200522). We thank Dr. G. Christopher Stecker for comments on the earlier version of the manuscript.

References


Butler, R.A., 1968. Effect of changes in stimulus frequency and
intensity on habituation of the human vertex potential.


621 Dyson, B.J., Quinlan, P.T., 2004. Stimulus processing constraints
in audition. J. Exp. Psychol. Hum. Percept. Perform. 30,
1117–1131.

mechanisms of involuntary attention to acoustic novelty and

attention and distractibility as evaluated with event-related

event-related brain potential (ERP) sign of the brain’s

memory-based comparison of sound intensity. Audiol.
Neurotol. 8, 338–346.

626 Jones, D., Macken, W., 1993. Irrelevant tones produce an irrelevant
speech effect: implications for phonological coding in working

627 Jones, D., Madden, C., Miles, C., 1992. Privileged access by
irrelevant speech to short-term memory: the role of change
state. Q. J. Exp. Psychol. 44A, 645–659.

628 Knight, R.T., Scabini, D., 1998. Anatomic bases of event-related
potentials and their relationship to novelty detection in

629 Korzyukov, O., Alho, K., Kujala, A., Gumenyuk, V., Ilmoniemi, R.J.,
responses of the human auditory cortex generated by
sensory–memory based processing of tone–frequency changes.

Deviant auditory stimuli activate human left and right auditory

masking of auditory lateralization and pitch judgments.

632 Melara, R.D., Chen, S., Wang, H., 2005. Inhibiting change: effects of
memory on auditory selective attention. Cogn. Brain Res. 25,
431–442.

equation describing frequency discrimination as a function of
frequency and sensation level. J. Acoust. Soc. Am. 73,
2117–2123.

634 Näätänen, R., 1992. Attention and Brain Function. Lawrence

635 Näätänen, R., Picton, T., 1987. The N1 wave of the human electric
and magnetic response to sound: a review and an analysis of
the component structure. Psychophysiology 24, 375–425.

636 Näätänen, R., Winkler, I., 1999. The concept of auditory stimulus
representation in cognitive neuroscience. Psychol. Bull. 6,
826–859.

637 Näätänen, R., Sams, M., Alho, K., Paavilainen, P., Reinikainen, K.,
Sokolov, E.N., 1988. Frequency and location specificity of the
Neurophysiol. 69, 523–531.

638 Näätänen, R., Paavilainen, P., Alho, K., Reinikainen, K., Sams, M.,
1989. Do event-related potentials reveal the mechanism of the
98, 217–221.

Näätänen, R., Jacobsen, T., Winkler, I., 2005. Memory-based or
affect processes in mismatch negativity (MMN): a review of
the evidence. Psychophysiology 42, 25–32.

Mismatch negativity: different water in the same river. Audiol.
111–139.

640 Rapin, I., Schimmel, H., Tourk, L.M., Krasnegor, N.A., Pollak, C.,
1966. Evoked responses to clicks and tones of varying intensity
in waking adults. Electroencephalogr. Clin. Neurophysiol. 21,
335–344.

641 Rinne, T., Degerman, A., Alho, K., 2005. Superior temporal
and inferior frontal cortices are activated by infrequent
sound duration decrements: an fMRI study. Neuroimage
26, 66–72.

duration and location deviants: a behavioral and event-

repetition vs. response change modulates behavioral and
electrophysiological effects of distraction. Cogn. Brain Res. 22,

frequency discrimination and event-related potentials.

Cortical activity elicited by changes in auditory stimulus: different
carriosphor for the magnetic N100m and mismatch

646 Scherg, M., Vajsar, J., Picton, T.W., 1989. A source analysis of the
late human auditory evoked potentials. J. Cogn. Neurosci. 1,
336–355.

647 Schröger, E., 1996. A neural mechanism for involuntary attention
shifts to changes in auditory stimulation. J. Cogn. Neurosci. 8,
527–539.

effects of task-irrelevant sound change: a new distraction

cortical potentials during an auditory signal detection task
Perform. 1, 268–279.

involuntary attention switching in the auditory modality.

651 Tiitinen, H., Alho, K., Huotilainen, M., Ilmoniemi, R.J., Simola, J.,
Näätänen, R., 1993. Tonotopic auditory cortex and the
magnetoencephalographic (MEG) equivalent of the mismatch

scales of adaptation in auditory cortex neurons. J. Neurosci. 24,
10440–10453.

653 van der Molen, M.W., Keuss, P.J., 1979. The relationship between
reaction time and intensity in discrete auditory tasks. Q. J. Exp.
Psychol. 31, 95–102.

and reorientation in children: a behavioral and ERP study.
NeuroReport 15, 1358.

elderly subjects: an event-related brain potential study.