Involuntary Attention and Distractibility as Evaluated with Event-Related Brain Potentials

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potentials (ERPs)

Abstract
This article reviews recent event-related brain potential
(ERP) studies of involuntary attention and distractibility
in response to novelty and change in the acoustic envi-
ronment. These studies show that the mismatch negativ-
ity, N_1 and P_{3a} ERP components elicited by deviant or
novel sounds in an unattended sequence of repetitive
stimuli index different processes along the course to
involuntary attention switch to distracting stimuli. These
studies used new auditory-auditory and auditory-visual
distraction paradigms, which enable one to assess objec-
tively abnormal distractibility in several clinical patient
groups, such as those suffering from closed-head inju-
ries or chronic alcoholism.

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Our ability to select a subset from the wealth of infor-
mation entering the sensory systems is crucial for most
activities. The human brain does not have a sufficient
capacity to allow the conscious processing of all stimulus
information that simultaneously impinges on the various
senses. Therefore, following an initial survey of the senso-
ry input, only a part of the incoming information gains
access to consciousness. This basic scheme of Broadbent's
[1958] original theory, i.e. the assumption of a large-
capacity system performing the initial processing and a
subsequent limited-capacity system for task-related eval-
uation and decision making, appears also in current theo-
ries of human attention [Cowan, 1995; Näätänen, 1992].
Versions of the basic model differ in the extent of the ini-
tial survey [early vs. late selection theories) [Treisman,
1988; Duncan, 1984] as well as in the method of selection
[for the classical treatment of the problem, see Broadbent,
1958, and Neisser, 1967]. Although other recent theories
of attention [Allport, 1993] question the existence of a
unitary system of selection, it is nevertheless important to
trace back the multitude of different forms of selection to
their neural bases.

In principle, the entry of information to the limited-
capacity system is controlled by two types of processes:
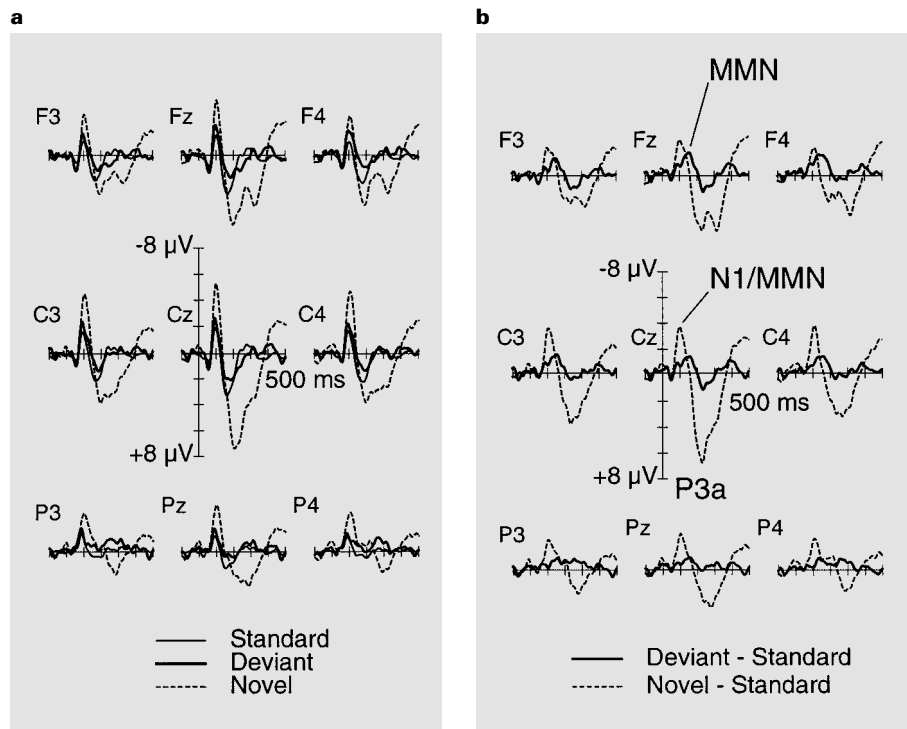active selection (focussed attention) and breakthrough of

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Fig. 1. ERPs elicited by standard and deviant tones and novel sounds (**a**), and the corresponding difference waves obtained by subtracting the standard tone ERP from that to deviant tones or novel sounds (**b**), which reveal the N_1 enhancement, the MMN and the P_{3a}. Adapted from Escera et al. [1998].

the unattended (passive attention) [James, 1890]. The first is a top-down process, in which channels of information are selected or rejected under the direction of the central mechanisms of behavior control. Certain subfunctions of the selection processes might be automatic; for example, auditory streaming is largely automatic [Bregman, 1990; Sussman et al., 1999], but, at least in ambiguous cases, it is affected by top-down control [Sussman et al., 1998]. The second is a bottom-up process that enables the conscious evaluation of those potentially important events that are not currently selected by the first mechanism. Without a good balance between the two, one cannot behave adequately in many situations. If the top-down processes dominate one's attention, one may not react to vitally important events occurring outside the focus of attention. On the other hand, if bottom-up processes can too easily catch one's attention, then one's behavior appears fragmented, making goal-directed actions less effective.

Brain injuries and neurological and psychiatric disorders, such as autism, attention-deficit hyperactivity disorder, dementia or schizophrenia, often affect the precarious balance of attentional control. Symptoms of such states are usually described in terms of distractibility. Distraction denotes the involuntary redirection of one's attention from some goal-oriented behavior to other aspects of the environment. Lack of distractibility points to the dominance of the top-down control of attention, whereas increased distractibility suggests an abnormally low threshold for the breakthrough of the unattended (in most cases irrelevant) information. Despite the obvious importance of distractibility in assessing the patients' neurological status, no generally accepted index of it has emerged in clinical practice. Currently available tests of attention focus on voluntary or controlled attention, such as different versions of the Continuous Performance Test, the Stroop test or the Paced Auditory Serial Addition Test, among others. However, whereas these tests are suitable for revealing impairment in the control of relevant stimuli, they fail to provide an indication of any subtle alteration in the passive reorienting of attention. The approach to be discussed in the present paper may lead to a set of objective measures of involuntary attention and distractibility which are applicable across a large variety of clinical populations.

The converging methods reviewed here are based on event-related brain potential (ERP) components elicited by short sounds that in some respect discriminably differ from the ongoing auditory stimulation (fig. 1). These ERP components index different processes along the course of distraction. The mismatch negativity (MMN) and N_1 mark instances when the preattentive system detected

sounds which carry previously unavailable information that may require conscious processing. The P_{3a} component, in turn, is regarded as a reflection of attention switching itself. Finally, the reorienting negativity (RON) [Schröger and Wolff, 1998a] may reflect redirecting attention back to the primary task.

The MMN [Näätänen et al., 1978; for recent reviews, see Näätänen and Alho, 1997; Näätänen and Winkler, 1999; Schröger, 1997] is elicited by incoming sounds that violate some previously invariant characteristic of an auditory stimulus sequence. The simplest paradigm in which MMN can be observed is the auditory oddball paradigm: infrequent sounds (deviants) differing in some acoustic feature from the repetitive (standard) stimulus elicit the MMN (independently of the direction of the subject's attention). It has been shown that the process generating the MMN component is initiated by a discordance ('mismatch') between the incoming sound and some memory record representing the regularities of the immediate history of auditory stimulation [for a detailed discussion, see Näätänen, 1992; Winkler et al., 1996; Winkler and Czigler, 1998]. In accordance with this account, no MMN is elicited by the repetitive stimulus itself, by infrequent sounds presented alone (i.e. in the absence of a different repetitive sound) [Näätänen et al., 1989] or by a change at the beginning of a sound sequence [Cowan et al., 1993].

One of the most important features of MMN is that it is elicited even when the subject or patient is engaged in a task unrelated to the MMN-eliciting sounds or the auditory stimulation in general [Alho et al., 1992]. Although the MMN amplitude is not fully attention independent [Trejo et al., 1995; Woldorff et al., 1991], MMN elicitation is not affected by task-related top-down processes [Alain and Woods, 1997; Näätänen et al., 1993; Ritter et al., 1999]. From these results one can conclude that incoming sounds are extensively analyzed and their regularities (including abstract ones [Paavilainen et al., 1995]) are detected even when these sounds fall outside the focus of attention. The MMN amplitude was attenuated when subjects performed a difficult primary auditory discrimination task with the target sequence presented at a very fast pace in one ear in parallel with the MMN-eliciting sequence presented in the opposite ear [Näätänen et al., 1993; Woldorff et al., 1991]. One interpretation of these results is that they reflect a state of reduced susceptibility to distraction (stimulus-initiated redirection of attention) when subjects under time pressure need to maximally focus their attention on the target sound sequence to cope with the primary task. It is possible that such highly

focussed attentional states diminish the amplitude of those MMN subcomponents [Alho, 1995] which are, presumably, involved in initiating a call for attention to deviant sounds (see in detail below).

Since the MMN is elicited when the incoming sound does not fit the series of the previous stimuli even when these stimuli fall outside the focus of the subject's attention, it marks one of those situations in which unattended sounds might carry potentially relevant information. In fact, the MMN-generating process can be regarded as an information filter: it is activated only when a sound could not be (preattentively) 'predicted' from the preceding stimulus sequence, i.e. when it carries new information. Therefore, one might suspect that the MMN-generating process could be involved in the passive (bottom-up) directing of attention [Alho et al., 1994; Knight, 1991; Näätänen and Michie, 1979; Schröger, 1996]. Indeed, the autonomic nervous system responses associated with involuntary attention switching (heart rate deceleration and the skin conductance response) tend to be elicited by the same stimulus events that also elicit the MMN [Lyytinen and Näätänen, 1987; Lyytinen et al., 1992]. Moreover, the MMN is usually followed by the P_{3a} component, an ERP sign of attention switching [Squires et al., 1975] (see below). On this basis, Näätänen [1990] proposed that the process reflected by the MMN can initiate redirecting of focussed attention to infrequent changes in the auditory background. As will be reviewed below, converging evidence shows that, although the primary generators of the MMN are located in the auditory cortex, there are also frontal sources contributing to the observable MMN response. The existence of frontal MMN generators supports the assumed role of the MMN in calling for attention [Öhman, 1979] because of the involvement of the frontal lobes in the control of the direction of attention [Fuster, 1989; Stuss and Benson, 1986]. The neural representations involved in the MMN-generating process [for a review, see Näätänen and Winkler, 1999] quickly adapt to changes in the auditory regularities. It appears that the MMN-generating process is involved in maintaining these representations by providing an error signal whenever the incoming stimulus differs from what could be extrapolated from the model of the auditory environment [Näätänen and Winkler, 1999; Winkler and Czigler, 1998; Winkler et al., 1996]. This function of the MMN is compatible with its above-described role in passive attention.

A change in a regular sound sequence is not the only situation in which the incoming stimulus may signal some potentially important change in the auditory environment. An unattended sound appearing after a relatively

Fig. 2. The location of the sources determined for the MEG counterparts of MMN (white circles) and P_{3a} (black circles) activated in the supratemporal auditory cortex of an individual subject by a frequency change occurring in a repetitive tone while the subject concentrated on watching a silent movie. The source locations are projected on a horizontal MRI slice tilted along the Sylvian fissure. Adapted from Alho et al. [1998b].

long silent period, or one having largely different acoustic features from those generally encountered in a given environment (a novel sound), is also likely to intrude to one's conscious experience. These sounds are also known to elicit a large N_1 wave. The auditory N_1 is an obligatory ERP response which is sensitive to refractoriness effects [Giard et al., 1994; Hari et al., 1982; Näätänen and Picton, 1987; Näätänen and Winkler, 1999]. A repeating sound presented at a high rate elicits a small N_1, whereas auditory events of salient features elicit N_1 waves of a considerably higher amplitude. Näätänen's [1990] model suggests that the auditory N_1 might reflect a process involved in redirecting the focus of attention to the onsets of any, especially new, events in the auditory background. This suggestion receives support from findings showing that novel sounds which elicit a large N_1 also elicit a P_{3a} (see below), indicating their potential for attention catching [Woods, 1990].

P_{3a} is regarded as an ERP sign of attention switching. It has been distinguished from P_{3b} (P_{300}) [for a review, see Donchin and Coles, 1988] by the different variables affecting its elicitation, its somewhat shorter peak latency and its different scalp topography [Ford et al., 1976; Squires et al., 1975; for reviews, see Knight and Scabini,

1998; Woods, 1990]. Whereas P_{3b} is elicited by relevant infrequent stimuli in task situations, P_{3a} can be elicited by rare or unusual stimuli even when this stimulus sequence is not attended. Whereas the P_{3b} is of maximal amplitude over parietal scalp areas, the scalp distribution of the P_{3a} has a frontocentral maximum. Findings showing prolonged reaction times (RTs) to target stimuli immediately following an irrelevant P_{3a}-eliciting novel sound support the notion that P_{3a} reflects an attention switch to these sounds [Grillon et al., 1990; Woods, 1992]. As will be reviewed below, several brain structures including the prefrontal, temporal and parietal cortices, as well as the hippocampus and the parahippocampal and the cingulate gyri, are involved in generating the P_{3a}.

Finally, the RON, recently discovered by Schröger and Wolff [1998a], might index another important stage along the full course of brain events associated with distraction: the return of focussed attention to the primary task after involuntary attention switch away from this task. This component will also be discussed later in the present review.

Cerebral Generators of MMN and P_{3a}

The MMN scalp distribution shows an amplitude maximum over the frontocentral scalp. This distribution is explained by bilateral generator sources in the auditory cortices [Scherg et al., 1989; Giard et al., 1995]. This explanation is supported by source modeling of the magnetoencephalographic (MEG) counterpart of the MMN, the MMNm, which has revealed bilateral MMNm sources in the auditory cortex on the superior plane of the temporal lobe (fig. 2) about 1 cm anterior to the source of the N_1m (the MEG counterpart of N_1), at least for the MMN/MMNm elicited by frequency changes [Alho et al., 1996, 1998b; Csépe et al., 1992; Hari et al., 1992; Huotilainen et al., 1993; Levänen et al., 1993, 1996; Levänen and Sams, 1997; Sams et al., 1991; Tiitinen et al., 1993; for a review, see Alho, 1995].
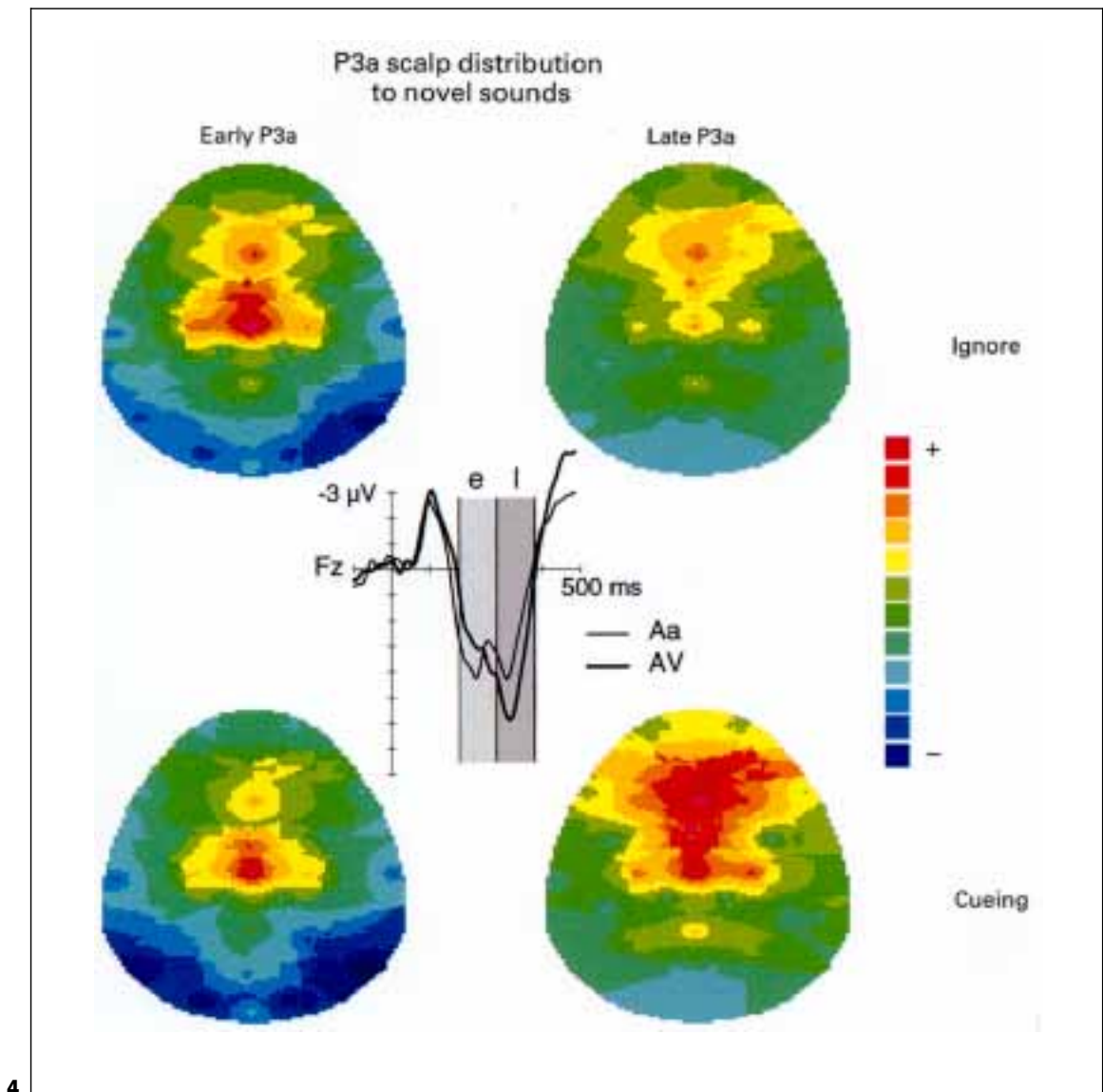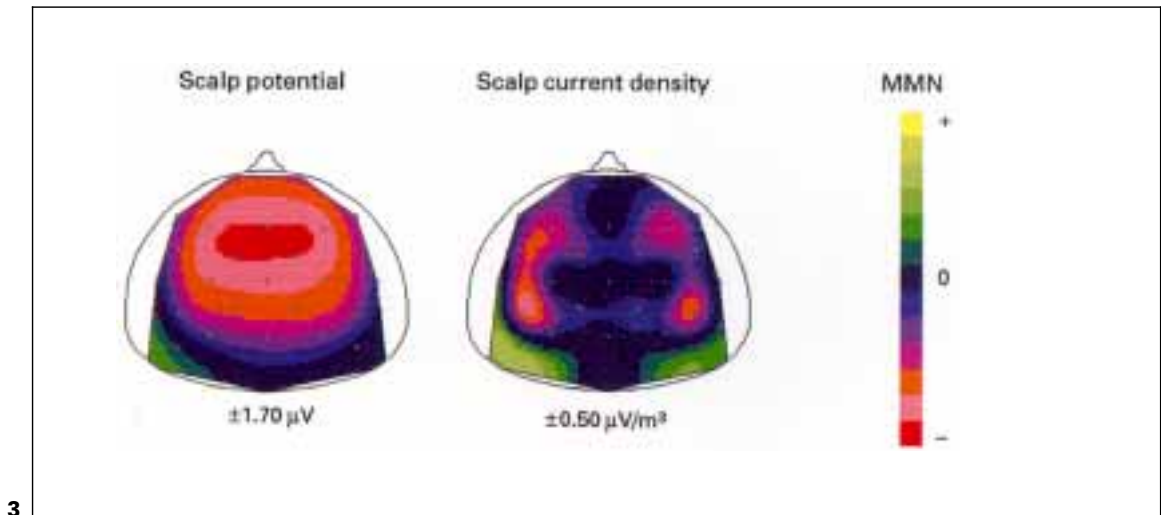
Interestingly, MMN/MMNm responses to changes in different physical features appear to be generated by at least partly different neuronal populations in the auditory cortex, as suggested by differences in MMN scalp distributions for frequency, intensity and duration changes observed by Paavilainen et al. [1991] and later confirmed with dipole source modeling by Giard et al. [1995]. Consistently with this, Levänen et al. [1996] have observed MMNm location differences for changes in tone frequency, duration and interstimulus interval. Thus, if we as-

sume that a sensory-memory trace for some auditory attribute is located where the MMN is generated by a change in this attribute [Näätänen, 1992], then these results indicate that different neuronal populations are involved in sensory-memory representations for sound frequency, intensity, duration and interstimulus interval. This proposal may also be extended to sensory-memory traces for simple versus more complex sounds, since Alho et al. [1996] observed that MMNm dipoles for frequency changes occurring in one tone of complex sounds (a 5-tone chord or melody) are located in the auditory cortex about 1 cm medial to the MMNm dipole for a similar frequency change in a simple tone. Moreover, whereas MMN and MMNm responses to changes in pure sinusoidal tones or in more complex nonphonetic auditory stimuli are elicited with larger amplitudes in the right than left hemisphere [Levänen et al., 1996; Paavilainen et al., 1991; Rinne et al., 1999a; Tervaniemi et al., 1999a], MMN and MMNm responses to phoneme changes usually get a stronger contribution from the left than right auditory cortex [Alho et al., 1998a; Näätänen et al., 1997; Rinne et al., 1999a]. Furthermore, the MMN source models of Rinne et al. [1999a] suggest that the neuronal population activated by phoneme change is located in the superior temporal cortex posteriorly (closer to Wernicke's area) to the neuronal population activated by changes in nonphonetic sounds.

The generation of MMN in the auditory cortex was also indicated by intracranial recordings in animals [Csépe et al., 1987; Javitt et al., 1996; Kraus et al., 1994] and humans [Halgren et al., 1995a; Kropotov et al., 1995; Liasis et al., 1999]. However, intracranial recordings in humans are performed in neurological, usually epileptic, patients whose brain responses to auditory stimuli may differ from those of healthy individuals. Thus, patients may show pathologically attenuated or enhanced responses, or even ones with changed source configurations. The generation of MMN in the auditory cortex is also suggested by auditory-cortex activity elicited by changes in to-be-ignored sound sequences recorded with positron emission tomography (PET) [Tervaniemi et al., 1999b], functional magnetic resonance imaging (fMRI) [Celsis et al., 1999; Opitz et al., 1999] and event-related optical signals [Rinne et al., 1999b]. Moreover, the MMN was attenuated in patients with temporal-cortex lesions [Alain et al., 1998]. Interestingly, such lesions may affect differently MMNs to different types of sound changes: in two patients with a lesion of the left posterior-temporal cortex and a speech comprehension deficit, Aaltonen et al. [1993] found no MMN to a phonetic change that elicits an MMN in healthy subjects, whereas the MMN to a change

in tone frequency appeared to be intact. This finding is consistent with the proposal discussed above that different neuronal populations generate MMNs to phoneme changes and changes in nonphonetic sounds.

The existence of MMN generators in the left and right auditory cortices was also implicated by scalp current density (SCD) maps calculated from MMN scalp potential distribution maps [Deouell et al., 1998; Giard et al., 1990; Serra et al., 1998]. However, these SCD maps also suggest that the MMN gets an additional contribution from the prefrontal cortex (fig. 3). A contribution of prefrontal neurons to MMN is also suggested by hemodynamic activity caused by stimulus changes and recorded with PET [Tervaniemi et al., 1999b] and fMRI [Celsis et al., 1999]. This frontal-MMN generator is also supported by the chaos analysis of the EEG following MMN-eliciting deviant sounds [Molnár et al., 1995], by MMN attenuation in patients with lesions of the dorsolateral prefrontal cortex [Alain et al., 1998; Alho et al., 1994] and by the MEG recordings of Levänen et al. [1996] who reported in some of their subjects an additional frontal source contributing to MMNm. The dorsolateral prefrontal cortex has an important role in the control of the direction of auditory attention [Alho et al., 1999; Knight et al., 1981]. Therefore, the prefrontal MMN subcomponent might be associated with the initiation of an involuntary attention switch towards a change in the acoustic environment [Giard et al., 1990; Näätänen, 1992]. However, an open question in the course of involuntary attention switching is the temporal dynamics of the activation of MMN sources and its relation to behavioral distraction. According to the current theoretical background, the supratemporal MMN subcomponent may be related to the memory representation of the auditory regularity involved in MMN generation (see above), whereas the frontal MMN source might generate the neuroelectric signal leading to the attention-switching response [Giard et al., 1990; Näätänen and Michie, 1979]. Consequently, the activation of the supratemporal MMN subcomponent should precede in time the activation of the frontal subcomponent, although no concluding evidence has yet been obtained. Very recently, Rinne et al. [submitted] indeed found in their MMN source current analysis that the right frontal MMN source was activated on average 16 ms later than the temporal one, whereas an opposite tendency was found by Escera et al. [in preparation], whose SCD analysis of the MMN scalp distribution suggested that the right frontal MMN source was activated about 20 ms before the supratemporal one. Escera et al. also observed a positive correlation between the activation of the left temporal

Scalp potential   Scalp current density   MMN

±1.70 µV   ±0.50 µV/m³

3

P3a scalp distribution
to novel sounds

Early P3a   Late P3a

Ignore

Cueing

-3 µV

Fz

500 ms

—— Aa

—— AV

e   l

4

MMN source and behavioral distraction, quantified as the increased number of errors in a visual discrimination task when subjects had to respond to visual stimuli following deviant, MMN-eliciting tones compared with the responses to stimuli following standard tones (for a detailed description of this distraction paradigm, see the next section). Further studies need to be conducted, however, to clarify the temporal course of the activation of the different MMN sources.

An additional contribution to MMN might originate from the parietal lobes, as hemodynamic recordings also revealed parietal-cortex activity in response to auditory stimulus changes [Celsis et al., 1999]. Furthermore, Levänen et al. [1996] found, in addition to the bilateral auditory-cortex MMNm sources, also a right parietal MMNm source. Perhaps the parietal activity elicited by auditory stimulus changes is associated with the activation of the parietal mechanisms involved in directing spatial auditory attention [Alho et al., 1999; Heilman and Valenstein, 1972; Mesulam, 1990; Posner et al., 1982].

The positive P_{3a} ERP deflection, with its amplitude maximum over the central and frontal scalp areas, often follows MMN even to small changes in to-be-ignored auditory stimulus sequences. Further, a large P_{3a} is elicited by wide changes, e.g. by complex 'novel' sounds occurring among repetitive tone pips [Woods, 1990]. This P_{3a} response might indicate the actual orienting of attention to an MMN-eliciting sound change occurring outside the current focus of attention [Sams et al., 1985; Escera et al., 1998]. Recently, Alho et al. [1998b] have located the source of the MEG counterpart of the P_{3a} response to deviant tones and novel sounds in the auditory cortex in the vicinity of the supratemporal MMNm source (fig. 2).

This finding accords with intracranial recordings of P_{3a} activity in the superior temporal cortex [Halgren et al., 1995a; Kropotov et al., 1995]. Escera et al. [1998] found that the early portion of P_{3a} has its maximal amplitude over the central midline areas, whereas the later P_{3a} portion has a more frontal scalp distribution (fig. 4). Judging from its relatively short latency, the auditory-cortex P_{3a} observed in the MEG study of Alho et al. [1998b] appears to explain the earlier part of the (auditory) P_{3a}, whereas the later, more frontal P_{3a} portion might be generated in the prefrontal cortex, as suggested by P_{3a} recordings directly from the human prefrontal cortex [Baudena et al., 1995], as well as by the P_{3a} attenuation in patients with dorsolateral prefrontal lesions [Knight, 1984]. However, several additional areas also appear to be involved, as P_{3a} activity has been recorded intracranially also from the parietal cortex, parahippocampal gyrus and anterior cingulate gyrus [Alain et al., 1989; Baudena et al., 1995; Halgren et al., 1995a, b; Kropotov et al., 1995], and as lesions of the temporoparietal junction and the posterior hippocampal region also attenuate the P_{3a} amplitude [Knight, 1996; Knight et al., 1989]. Moreover, source modeling of the scalp-recorded P_{3a} to novel sounds suggests the existence of P_{3a} main sources in the frontal and medial temporal lobes [Mecklinger and Ullsperger, 1995].

Distraction Caused by Irrelevant Novel Sounds and Sound Changes

The series of studies to be reviewed in this section provide a wealth of supporting evidence for the participation of the cerebral process involved in the generation of N_1, MMN and P_{3a} in the course from involuntary attention to behavioral distraction. In these studies, behavioral performance in a primary visual or auditory task was disrupted by unpredictable novel environmental sounds or slight sound changes occurring outside the focus of the subject's attention.

Distraction during Visual Task Performance

A recently developed paradigm [Escera et al., 1998] allows one to study the disruption of visual task performance caused by irrelevant sound changes and novel sounds. In this paradigm, the subject is instructed to discriminate two categories of visual stimuli, e.g. odd and even numbers, or numbers and letters, presented at a constant rate on a computer screen, and to press the corresponding response button as fast and accurately as possi-

Fig. 3. Scalp potential (left) and current density (right) maps, showing auditory-cortex and prefrontal sources of MMN elicited by frequency-deviant tones. Adapted from Escera et al. [in preparation].
Fig. 4. Scalp potential distribution of the early (left column) and late (right column) phases of P_{3a} in two different conditions. In the ignore condition, subjects were instructed to read a book and to ignore the auditory stimulation. In the cueing condition, subjects were instructed to discriminate visual stimuli presented 300 ms after each sound and to ignore the auditory stimulation. Note the different scalp distributions of the two P_{3a} phases. Note also that whereas the early P_{3a} phase was similar in the two conditions, the late P_{3a} phase was enhanced in amplitude, particularly over the frontal region in the cueing condition. The central curves show the P_{3a} potential at Fz in the two conditions; e = Early; l = late; Aa = ignore; AV = cueing. Adapted from Escera et al. [1998].
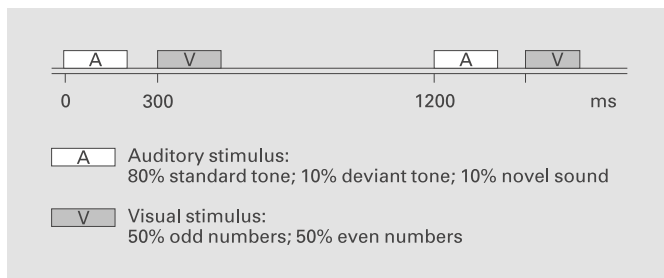
Fig. 5. An illustration of the auditory-visual distraction paradigm. Subjects are presented with equiprobable odd and even numbers, each preceded by an irrelevant auditory stimulus (interval between auditory and visual onsets, 300 ms). Auditory stimuli are randomly either standard tones (80%) or distractors (10% deviant tones; 10% novel sounds). Subjects are instructed to press the corresponding response button to odd and even numbers and to ignore the auditory stimulation. From Escera et al. [1998].

ble. An auditory stimulus is delivered shortly before each visual stimulus (for instance, 300 ms from auditory onset to visual onset; fig. 5). In most cases, the auditory stimulus is a repetitive, standard tone. In some (10–20%) unpredictably scheduled cases, however, this stimulus is replaced by a slightly different (10–15% change in frequency), deviant tone or by a natural complex sound (novel sound). The responses to the visual stimuli are classified according to the preceding auditory stimulus. The pattern of behavioral results obtained in this paradigm is illustrated in figure 6. Compared with the responses to visual stimuli that follow standard tones, visual stimuli following deviant tones and novel sounds show RTs which are about 5 and 20 ms longer, respectively [Alho et al., 1997; Escera et al., 1998; Jääskeläinen et al., 1996; Yago et al., 1999]. Interestingly, whereas the hit rate is similar after standard tones and novel sounds, deviant tones cause a hit rate decrement of about 2%, resulting from an increase in the number of erroneous decisions in the visual discrimination task [Alho et al., 1997; Escera et al., 1998; Serra et al., 1998; Yago et al., 1999].

The effects described above may not reflect truly involuntary attention, however, as subjects may have been attending to the irrelevant auditory stimuli, which occurred with a 100% probability and a fixed interval before the visual stimuli. In this case, the auditory stimuli may have acted as warning cues of the occurrence of the task-relevant stimuli, as indicated by the shorter RT when the visual stimuli were preceded by an auditory stimulus compared with when they occurred in a series with no sounds [Escera et al., 1998] (fig. 6).
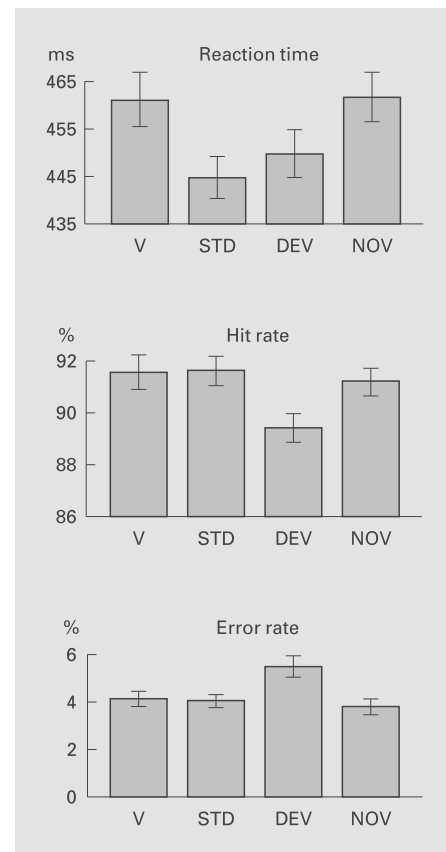

Fig. 6. The pattern of behavioral results in the auditory-visual distraction paradigm. Compared with standard tones (STD), deviant tones (DEV) and novel sounds (NOV) prolong the RT to the successive visual targets. Deviant tones also decrease the hit rate in the visual performance, due to the increase in the number of wrong responses. When sounds are omitted (V), RTs tend to be slower than when the visual targets are preceded by a standard tone, for the sounds serve as warning stimuli in the auditory-visual condition. Adapted from Escera et al. [1998].

In a subsequent experiment, attention was more effectively withdrawn from the auditory stimuli by presenting simultaneous visual warning cues informing the subject of whether a successive task-relevant stimulus would be presented or not. In this experiment, in which the occurrence of an auditory stimulus did not predict the occurrence of a subsequent task-relevant visual stimulus, making it unlikely that subjects were monitoring the auditory stream, similar behavioral distraction effects were observed [Alho et al., 1997]. Moreover, deviant tones preceding visual stimuli caused an attenuation of the occipital N_1 ERP to these visual stimuli. Cued visual stimuli are known to elicit enhanced N_1 responses due to enhanced attention to

these stimuli caused by the cue [Mangun and Hillyard, 1991]. Therefore the attenuation of the N_1 to a cued task-relevant visual stimulus caused by a preceding deviant tone appears to indicate that the involuntary switching of the subject's attention to the deviant tone interfered with the early, attentive visual processing [Alho et al., 1997]. These results strongly support the involuntary nature of the attentional mechanisms involved in the observed distraction effects.

In the auditory-visual distraction paradigm, the ERPs elicited by the auditory-visual stimulus pairs in which the tone is deviant show an MMN followed by a small P_{3a} [Alho et al., 1997; Escera et al., 1998; Yago et al., 1999]. In pairs in which the auditory stimulus is a novel sound, in turn, the ERPs show an enhanced N_1, compared with that elicited in pairs containing the standard tone, and a large, biphasic P_{3a} potential [Escera et al., 1998; Yago et al., 1999] (fig. 7). These ERP results, in combination with the behavioral results discussed above, led the authors to propose that two different attention-switching mechanisms are involved in the distraction observed during visual performance in the auditory-visual distraction paradigm. Novel sounds elicited an enhanced N_1 wave, probably caused by an enhanced supratemporal N_1 [Näätänen and Picton, 1987] or some other N_1 component such as the frontal N_1 [Giard et al., 1994], and MMN [Alho et al., 1998b] (fig. 7). This suggests that the attention-switching signal is probably triggered by a combined response of the transient-detector mechanism reflected by the N_1 [Näätänen, 1990, 1992; Näätänen and Picton, 1987] and the stimulus change detector mechanism reflected by the MMN [Näätänen, 1990, 1992], resulting in an effective attention switch as indicated by the subsequent large P_{3a} wave and the clearly delayed RT to the following visual stimulus. For deviant tones, in turn, a distinct MMN, followed by a small P_{3a} wave, was observed (fig. 7), suggesting an attention switch initiated by the stimulus change detector mechanism generating the MMN [Schröger, 1996]. This results in a less effective attention switch, as indicated by the smaller P_{3a} and the more modest behavioral effect compared with that caused by the novel sounds.

As already mentioned, the large, biphasic P_{3a} potential to novel sounds of Escera et al. [1998] had an early centrally dominant scalp distribution with polarity reversal in posterior and inferior electrodes, whereas the late P_{3a} displayed a frontal scalp maximum (fig. 4). The scalp distribution of these two P_{3a} phases is in agreement with studies suggesting a critical role of the temporal-parietal junction in the generation of the P_{3a} to auditory [Halgren
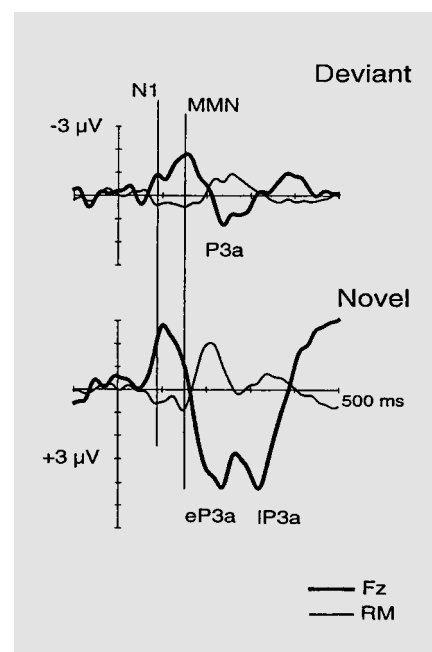

Fig. 7. The component structure of ERPs to deviant tones and novel sounds, as revealed by the ERP difference waves (deviant-standard, novel-standard) at Fz and the right mastoid (RM) referred to an electrode at the nose. Deviant tones elicit MMN and a small P_{3a}, whereas novel sounds elicit an overlapping N_1 enhancement and MMN [Alho et al., 1998b], and a large biphasic P_{3a} potential. MMN and the early part of the P_{3a} invert in polarity at the right mastoid below the auditory cortex, suggesting an auditory-cortex contribution to these responses; e = Early; l = late. Adapted from Escera et al. [1998].

et al., 1995a,b; Knight et al., 1989], somatosensory [Yamaguchi and Knight, 1991, 1992] and visual novel stimuli [Knight, 1991, 1997], and also with results suggesting a prefrontal contribution to the P_{3a} [Baudena et al., 1995; Friedman and Simpson, 1994; Friedman et al., 1993; Knight, 1984; Mecklinger and Ullsperger, 1995]. It is possible that the two phases of P_{3a} reflect two different processes in the course of involuntary attention switching, as they have different cerebral sources and react differentially to attentional manipulations. Interestingly, Escera et al. [1998] found that the early P_{3a} subcomponent was of similar amplitude irrespective of whether their subjects were reading a book or performing a visual discrimination task, whereas the late P_{3a} subcomponent was enhanced in amplitude when subjects were monitoring the auditory stimuli during the visual performance (fig. 4). As discussed above, the task-irrelevant auditory stimuli may have been to some extent attended as they cued the occurrence of a successive visual target (fig. 6). A similar atten-

Fig. 8. An illustration of the auditory-auditory distraction paradigm. Subjects are presented with equiprobable short- and long-duration tones and instructed to discriminate them. Infrequent task-irrelevant frequency deviations in these tones serve as distractors. Adapted from Schröger and Wolff [1998b].
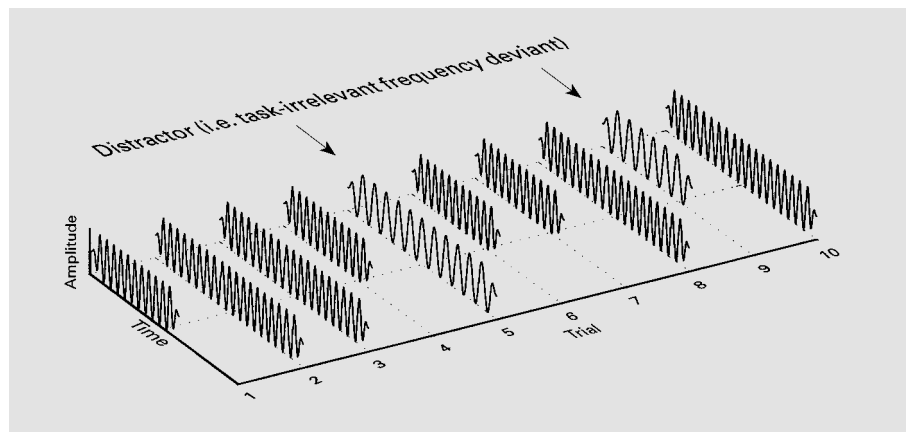
tional modulation of the P_{3a} elicited by novel sounds has already been reported [Holdstock and Rugg, 1995; Woods, 1992]. Thus, judging from its neural generators and insensitiveness to attentional manipulation, the early P_{3a} might reflect violation of a multimodal model of the external world maintained in the temporal-parietal association cortex [Yamaguchi and Knight, 1991], whereas the late P_{3a} may be more closely related to the actual orienting of attention, as indicated by its attentional dependence and prefrontal generators.

Distraction during Auditory Task Performance

The processing of task-relevant auditory information can be distracted by irregularities in task-irrelevant aspects of the acoustic input. In one type of these auditory-auditory distraction paradigms, subjects have to perform a same-different judgement on two tones (S1 and S2) separated by an interval of several seconds (delayed match-to-sample task). The interval between S1 and S2 is silent or filled with different types of intervening stimuli such as sinusoidal tones or environmental sounds. The interference in immediate memory (e.g. for tonal pitch) caused by intervening sounds has been studied as a function of several variables such as the type of intervening stimuli, particular brain lesions or age [Chao and Knight, 1995, 1997; Deutsch, 1970; Pechmann and Mohr, 1992; Semal et al., 1996]. This paradigm is suited for studying effects of task-irrelevant sounds on short-term and working memory. In another type of paradigm, subjects who presented with dichotic sounds are instructed to attend to the input of one ear and to respond to particular target sounds occurring in this ear (dichotic selective-attention task). The discrimination of targets preceded by irregular or novel sounds in the attended and even in the unat-

tended ear may be deteriorated [Schröger, 1996; Woods, 1992; Woods et al., 1993]. This paradigm is suited for studying distractibility of selective attention. In a third type of paradigm, the distracting and task-relevant aspects of stimulation appear in the same acoustic event. In this paradigm, subjects are to discriminate the duration of tones that are equiprobably of short (200 ms) or long (400 ms) duration. These tones are of the standard frequency (e.g. 600 Hz) with a high probability, or of the deviant frequency (e.g. 650 Hz) with a low probability (fig. 8), this frequency variation having no task relevance. This auditory-auditory distraction paradigm recently developed by Schröger and Wolff [1998a, b] is suited for studying distraction mediated by a sensory-memory-related mechanism. We will examine this paradigm in more detail.

The RT in the duration discrimination task is prolonged for frequency-deviant tones compared with standard frequency tones [Schröger and Wolff, 1998a, b]. Theoretically, this RT effect could be due to 'costs' in processing duration information in deviant trials, but also to 'benefits' in processing duration in standard trials. In their control condition, Schröger and Wolff [1998a] showed that the RT prolongation in deviant trials was mainly due to distraction caused by task-irrelevant frequency deviations, that is, there are genuine costs in the processing of duration information in deviant trials. In the ERPs, the present distraction effects are reflected by the MMN and P_{3a} components (fig. 9), which differ from each other with respect to their dependence on the allocation of attention to the sounds. When sounds are not attended, the moderate frequency deviations that were used in this paradigm only elicit an MMN, indicating the preattentive registration of the deviant sound, but no P_{3a}.

When sounds are in turn attended, a distinct P_{3a} is elicited by frequency deviations, although the MMN is not augmented relative to the MMN in the ignore condition [Schröger et al., submitted; Schröger and Wolff, 1998b]. One may assume that an attention switch indicated by P_{3a} is elicited in this case because task-irrelevant sound information cannot be easily disregarded when the sound carries task-relevant information also (see below). This hypothesis is supported by the subjects' self-report stating that they often felt distracted from the duration discrimination task by frequency deviations when sounds were attended, whereas they did not feel distracted by these frequency deviations when ignoring the sounds.

Notably, in the present paradigm, P_{3a} is followed by a frontocentrally distributed negativity at the 400- to 600-ms range. Since this negativity was confined to conditions in which subjects discriminated long sounds from short ones but did not occur when frequency deviations were task relevant nor when sounds were ignored, it was suggested to reflect the reorienting of attention towards task-relevant aspects of stimulation following distraction [Schröger and Wolff, 1998b]; therefore, this negativity was termed RON. In a recent study comparing the present auditory-auditory distraction paradigm with its visual analog, a RON was also observed, indicating that this component is not specific to the auditory modality [Berti and Schröger, in press]. SCD maps for RON reveal bilateral frontal sinks around FC1 and FC2 electrodes, suggesting frontal generators, and complex current fields of lower amplitudes over the centroparietal regions [Schröger et al., submitted].

It has been shown in several visual and auditory studies that distractors are more effective if task-relevant and distracting information is carried by the same object or perceptual group than if distracting information appears in a different object [Alain and Woods, 1993, 1997; Baylis and Driver, 1992; Bregman and Rudnicky, 1975; Driver and Baylis, 1991; Jones and Macken, 1993; Kramer and Jacobsen, 1991]. That is, large distraction effects are to be expected if a deviation occurs in a task-irrelevant dimension of a task-relevant sound, e.g. in the frequency of the sound of a duration discrimination task. Indeed, the above-discussed auditory-auditory distraction paradigm, in which distracting and task-relevant events occur in the same to-be-attended stimuli, yields larger behavioral distraction effects than the auditory-visual [Escera et al., 1998] or the other types of auditory-auditory distraction paradigms [Schröger, 1996] in which distractors occur within the to-be-ignored stimulus sequence. Importantly, each subject studied in the paradigm with distracting and
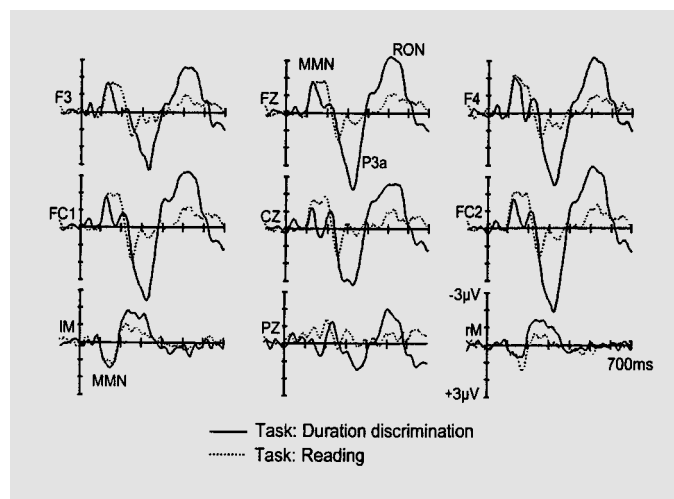

Fig. 9. Typical ERP difference waves (calculated by subtracting ERPs to tones of standard frequency from those to tones of deviant frequency) obtained with the auditory-auditory distraction paradigm. During the duration discrimination task, MMN, P_{3a} and RON are elicited. When subjects are instructed to read a book of their own choice and to ignore the auditory stimuli, only MMN is elicited. Adapted from Schröger et al. [1999].

target events occurring in the same stimulus showed a behavioral effect of distraction [e.g. Jääskeläinen et al., 1999; Schröger et al., submitted; Schröger and Wolff, 1998a, b; Berti and Schröger, 1999]. Moreover, in this paradigm, the test-retest replicability of the RT prolongation and of the MMN, P_{3a} and RON is rather high, with product-moment correlations for those parameters measured in two sessions separated by 25 days being 0.77 for MMN, 0.88 for P_{3a}, 0.81 for RON and 0.90 for the RT prolongation [Schröger et al., submitted].

Due to the large and consistent distraction effects when distracting stimulus changes occur in a task-irrelevant attribute of the target sounds, considerably smaller stimulus changes can be used as distractors in this paradigm than in the traditional distraction paradigms. In the above-mentioned dichotic selective-attention type of paradigm, widely deviant distractors such as dog-barking or telephone-ringing are required in order to produce clear behavioral distraction effects when the distractors are presented in the to-be-ignored ear. With widely deviant distractors, it is likely that distraction is triggered by a transient-detector mechanism activated by firing patterns of neural populations specifically responding to the features of the infrequently presented distracting sound, as these neurons are less refractory than those specifically re-

sponding to the repetitive (standard) acoustic input [Nää-tänen and Picton, 1987]. However, as already reviewed, distraction can also be mediated by the memory-based mismatch mechanism which can detect irregular events within regular stimulation by comparing the current stimulus with the representation of the invariances inherent in the recent stimulation [Näätänen, 1992; Öhman, 1979; Schröger, 1997; Sokolov, 1975]. In order to study distraction mediated exclusively by this change detector mechanism, distractors should then be physically close to non-distractors.

Use of ERPs in Clinical Research of Involuntary Attention and Distractibility

The distraction paradigms reviewed in the preceding section offer valuable objective tools for investigating the neural mechanisms of involuntary attention and their disorders. The main advantage of these paradigms is that they provide, in a reliable way, behavioral measures of distraction and electrophysiological indices of the underlying cerebral processes. A limitation, however, is that patients are required to perform a highly demanding main task, precluding the examination of widely impaired subjects. In this case, an alternative may consist of instructing the patients to ignore the auditory stimuli and to concentrate on reading a book or watching a silent video movie, excluding the behavioral measures. This would yield MMN and P_{3a} components, although the results may be different in comparison with the active condition, at least for P_{3a} (see the previous section). Future research in this direction will clarify to what extent a passive version of the distraction paradigms reviewed here provides reliable indices of involuntary attention.

In a study of patients with closed-head injuries, Kaipio et al. [1999] reported MMNs to deviant tones similar to those in control subjects but an enhanced late subcomponent of P_{3a} to novel sounds, suggesting a 'normal' activation of the change detector mechanism associated with MMN but a stronger attention-switching response to large changes in the unattended acoustic environment. Consistently with this, Polo et al. [1998] reported similar MMNs but enhanced P_{3a} responses to deviant tones in a group of chronic abstinent alcoholics. Both studies indicate a functional dissociation between the neural processes involved in MMN and P_{3a} generation: the MMN generator process may be related to triggering a call for attention [Öhman, 1979], and this call may result in a more or less effective attention switch reflected by the P_{3a} component. These results also indicate the utility of recording ERPs (MMN and P_{3a}) to deviant tones and novel sounds in an attempt to identify particular attention deficits in different clinical populations.

In a preliminary report, Polo et al. [1999] found an enhanced P_{3a} to novel sounds in chronic alcoholics, which was due to an enhanced left frontal amplitude of the later P_{3a} phase. This finding might provide the physiological substrate of the abnormally strong reactivity to irrelevant stimuli as a common problem in alcoholic patients [DeSoto et al., 1985; Fein et al., 1990; Hansen, 1980] and suggests the involvement of certain left prefrontal areas, in addition to the right prefrontal cortex, in P_{3a} generation. Several functional neuroimaging studies have indicated the involvement of the left prefrontal cortex in memory encoding of novel stimuli [Berns et al., 1997; Tulving et al., 1994]. Thus, in the Polo et al. [1999] study, the observed enhanced P_{3a} resulting from a left prefrontal contribution may indicate enhanced memory encoding of novel sounds in chronic alcoholics, as suggested by the (small) parietal P_{3b}, a scalp signature of memory updating [Donchin and Coles, 1988], elicited in the patients after the P_{3a}.

Increased involuntary attention switch in chronic alcoholics, as indicated by the enhanced P_{3a} to deviant tones and novel sounds, suggests increased distractibility in alcoholism. Thus, in addition to clinical symptoms, experimental behavioral evidence of increased distractibility in chronic alcoholics should be expected. Ahveninen et al. [submitted], using the auditory-auditory distraction paradigm described above, found prolonged RTs after deviant stimuli in abstinent chronic alcoholics. This RT prolongation was larger in alcoholics than in age-, sex- and education-matched controls, supporting the hypothesis of increased distractibility in alcoholics. Furthermore, the RT prolongation correlated positively with the MMN amplitude (r = 0.7), indicating that the abnormal attentional reactivity of chronic alcoholics to irrelevant acoustic changes was accompanied by an increased response of the change detector mechanism reflected by the MMN.

There is currently a lack of instruments capable of revealing deficits in the brain's ability to move attention from a main task to unexpected potentially relevant stimuli occurring outside the focus of attention. Such an instrument appears to be provided by the above-discussed paradigms, which may become also a useful tool to prove 'reduced' attention-switching capabilities. Jääskeläinen et al. [1999], using occasional distracting frequency changes in target tones of a duration discrimination task, found that a moderate dose of alcohol (0.3 g/kg, corresponding

to about 0.04% blood alcohol concentration) reduced the RT prolongation observed after the distracting events relative to a placebo condition. Furthermore, similar results, with the auditory-visual distraction paradigm, were obtained by Jääskeläinen et al. [1996] who found that during a mild ethanol intoxication (0.05% blood alcohol concentration), the hit rate reduction observed in distracting trials was significantly smaller than during a placebo condition. Taken together, these results suggest that acute alcohol challenge, even at a very small dose, suppresses the attention-capturing effect of deviant sounds, indicating a detrimental influence of alcohol on the neural mechanisms of involuntary attention. These detrimental effects may result in damage and subsequent adaptive changes caused by long-term alcohol consumption, which may, in turn, explain the abnormal attention reactivity to irrelevant stimuli observed in chronic alcoholics. It is, however, an open question how these short-term effects of alcohol intoxication relate to the abnormal attention reactivity to irrelevant stimuli observed in chronic alcoholics [Ahveninen et al., submitted; Polo et al., 1998, 1999; see Ahveninen et al., in press].

Another area in which the paradigms reviewed may provide insightful information is the study of children and adolescents with attention, language or learning disabilities. There is a relatively extensive ERP literature in the area of attention in these children, but mainly focussed on selective and voluntary attention. In children with attention-deficit hyperactivity disorders, some authors have suggested a deficit in preferential processing of attended stimuli as opposed to an inability to block irrelevant stimuli [Satterfield et al., 1990, 1994]. However, some recent results showing an attenuation of the MMN elicited by deviant tones suggest the dampening of mechanisms of involuntary attention [Winsberg et al., 1993; Kemner et al., 1996]. Also in adolescents, Lähteenmäki et al. [in press] found similar MMNs but reduced P_{3a} to deviant tones in survivors to childhood leukemia, suggesting that the P_{3a} amplitude might be used to evaluate the deteriorating effects of prophylactic CNS radiotherapy in child cancer patients on attention functions, possibly explaining their learning disabilities. These results strongly encourage the use of the new distraction paradigms in future research in infants, children and adolescents.

Concluding Remarks

The studies reviewed in the present article shed some light on the brain mechanisms of involuntary attention

and distractibility, indicating that the MMN, N_1, P_{3a} and RON components of the ERP mark different cerebral processes in the course of distraction. The MMN and N_1 mark those instances when the preattentive system detects sounds which may carry new, potentially relevant information. A small P_{3a} elicited by slightly deviant sounds and a larger P_{3a} elicited by complex novel sounds probably reflect an actual switching of attention to unattended stimuli. The RON, in turn, might reflect the return of attention to the primary task after an involuntary attention switch. The above-reviewed studies also suggest a complex cerebral circuitry, including the supratemporal auditory cortex and the temporoparietal and prefrontal cortices as well as some other brain areas, such as the cingulate cortex and the hippocampus, underlying involuntary attention.

The auditory-visual and auditory-auditory distraction paradigms discussed above have been developed only recently. In these paradigms, the performance in an auditory or visual task is disrupted by the occurrence of an irrelevant auditory (distracting) event, i.e. a deviant or novel sound, preceding task-relevant stimuli. These tests provide objective measures of distraction, e.g. an increase in RT or a decrease in the hit rate, for task-relevant stimuli immediately following the distracting events. In addition, the simultaneous recording of ERPs during performance in these distraction paradigms allows one to test the functional integrity of the underlying cerebral processes. Although the distracting effects yielded by the auditory-auditory distraction paradigm are larger than those obtained with the auditory-visual distraction paradigm, both tests provide reliable measures of distractibility. These measures can now be, as reviewed above, used to reveal attentional dysfunctions at the group level in several clinical populations and might provide, in the near future, a new tool for the evaluation of attentional integrity in individual patients.

Acknowledgements

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