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Alexandra Muller-Gass

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Abstract

The main interest of this dissertation was to examine the role of attention in early auditory processing using event-related potential (ERP) recording techniques. The Mismatch Negativity (MMN), a component of the ERP, is an index of early auditory deviance detection. In the present research, the MMN was used to probe the extent to which auditory stimuli were processed when these stimuli were or were not within the focus of attention. Four experiments were carried out. The aim of Experiments 1 and 2 was to investigate whether the demands of common diversion tasks modulated the MMN. In these experiments, subjects were instructed to ignore the auditory sequence and engage in tasks that varied in the amount of attention required to complete them. The results of Experiment 1 indicated that the MMN elicited by small frequency deviants was sensitive to the nature of the task (although this effect could not be clearly related to attention). In contrast, the MMNs elicited by small intensity deviants in Experiment 2 did not vary based on the diversion task demands. A limitation of Experiments 1 and 2 was the absence of an independent measure of task demands. This limitation was addressed in Experiments 3 and 4. A visual discrimination task was employed that permitted quantification of task demands. The visual task was either easy or difficult to perform. Hence, in Experiments 3 and 4, the extent to which the attentional demands of the visual task affected the passively-elicited MMN could be more rigorously examined. Importantly, the MMNs elicited by small frequency and intensity deviants were not significantly modulated by task difficulty, in spite of a wide variation in performance measures between the easy and difficult visual tasks. Experiments 3 and 4 also investigated whether the direction of attention had an effect on the MMN. Subjects were subsequently asked to divide their attention between the visual and auditory channels and to detect all visual and auditory deviant stimuli. This allowed a comparison of the MMN when it was elicited by stimuli within or outside the focus of attention. The results of Experiment 3 indicated that the frequency MMN was unaffected by the direction of attention; the intensity MMN, however, was larger during active attention of the auditory sequence. The attentional modulation of the intensity but not frequency MMN may be due to specific deviant features being more sensitive to the effects of attention. Alternatively, these results could be explained by the difference in perceptual discriminability of the intensity and frequency deviants from the standard (the frequency deviants were detected more accurately and more rapidly than the intensity deviants). Experiment 4 tackled this issue by increasing the discriminability of the intensity deviant while decreasing the discriminability of the frequency deviant. The results showed that the frequency MMN was significantly affected by the direction of attention, whereas the intensity MMN was not. Together, the results suggest that the attentional modulation of the MMN may be limited to the processing of small stimulus changes. Attention may be viewed as a means to sharpen the memory trace of the attended stimuli and consequently enhance the processing of small auditory changes. This explanation would also be consistent with the present findings that the passively-elicited MMN is insensitive to variations in visual task difficulty.

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I dedicate this thesis to my mother, a truly exceptional person. You have taught me the most important lessons, not the ones leading to a Ph. D., but those that keep me on the road to happiness. Thank you for your faith in me, your nurture, your love.

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CHAPTER 1

GENERAL INTRODUCTION

The gift of hearing in humans enables us to locate objects at a distance, a fundamental ability that has high survival value. This sense is also the foundation of communication, a function that facilitated the development of culture and civilization. An understanding of how sound is transformed into our experience of it that is, how we perceive sound, remains an elusive research problem. In this thesis, a contemporary model of auditory representation[1] (Näätänen, 1990; Näätänen, 1992; Näätänen & Winkler, 1999) serves as the context for exploring how attention modulates our experience of the acoustic environment.

While the general structure of Näätänen's model resembles some of the earlier auditory processing models, its unique value comes from the extensive electrophysiological evidence that supports its claims. In this model, a particular emphasis is placed on the role of attention in sensory and post-sensory auditory analyses. Importantly, Näätänen maintains that the obligatory stimulus-elicited sensory processes leading to the stimulus representation are not altered by the direction of attention. This view has been referred to as a theory of *strong-automaticity*, that is, a theory according to which basic sensory processing cannot benefit from attentional resources (Hackley, 1993).

Näätänen's position on the automaticity of basic sensory processing has met with some resistance. This controversial issue has been the focus of several recent event-related potential (ERP) studies. The present thesis extends this research by examining the effects of visual task demands on the mismatch negativity (MMN). The MMN is a component of the auditory ERP that is very informative about the actual flow and extraction of sensory information. It reflects

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[1] An adaptation of Näätänen's (1990) auditory information processing model appears as Figure 1.

the outcome of pre-conscious detection of change, and can be used to probe the sensory memory on which this detection relies.

In Section 1 of the Introduction, Näätänen's model of auditory information processing will be outlined. This includes the proposed phases involved in basic sensory analysis as well as the mechanisms leading to the psychological experience of sound. Following this, alternative views on automaticity in sensory and post-sensory processing will be presented briefly. As Näätänen has based his model primarily on ERP evidence, the ERP technique is introduced in Section 2. The main auditory ERP components that lend support to Näätänen's claims are described in Section 3. Finally, Section 4 more directly addresses the central question of this thesis, by providing the relevant literature review on the effects of attention on the MMN.

1. Näätänen's Model of Auditory Processing

1.1. Basic Sensory Processing: The Feature-Detector and Sensory Memory Mechanisms

Sound reaches the ear as a pressure wave. In the auditory periphery, sound is transduced from mechanical energy into a neural signal. According to Näätänen's model, during the initial phase of auditory processing, this neural activity rapidly changes as the features of the auditory stimulus (e.g. frequency, intensity, duration) are extracted (see [1] in Fig. 1). Because the stimulus information is in continual transformation, Näätänen has suggested that the form of sound information in this phase can best be described as an *afferent activation pattern* — as opposed to a more stable information trace. Before the outputs of the feature extraction processes can be integrated into a single memory structure, it is conceived that they are buffered in the auditory system (see [2]). This is because the extraction of some features may be complete, while other feature-extraction processes are still in progress. Hence, this second phase of processing, in which the information is said to be stored as *feature traces*, temporally overlaps with the feature-extraction phase. The phases relating to feature analysis are performed by the Permanent Feature-Detector system. Näätänen proposes that this system subsequently forwards the feature information to sensory memory.

In the initial short phase of sensory memory lasting 150-200 ms from stimulus onset, the feature traces are thought to be integrated into a functionally unified memory trace that contains all sound features (see [3]). Importantly, Näätänen suggests that temporal integration of sensory information, relating the stimulus to its auditory context, also occurs during this short phase. As such, the time separating the incoming stimulus from the preceding stimulus, and the features of concurrent or preceding stimulation are encoded together with the incoming stimulus. The form of the stimulus information resulting from this phase of processing has been termed the *stimulus representation* and is considered the outcome of a completed sensory analysis. The auditory stimulus representation provides the sensory-specific contents for sound perception. In Näätänen's model, the emergence of the stimulus representation does not imply, however, conscious sound perception. The circumstances under which conscious perception occurs are described in the following sub-section (Section 1.2. Selection and Conscious Perception).

Näätänen cautions that the short sensory memory store, in which the stimulus representation is formed, should not be regarded as "pure" memory (i.e. not fixed) — as it still is an "on-going" process. However, the subsequent long phase of sensory memory that resembles what has been called echoic memory (Neisser, 1967), long auditory store (Cowan, 1984) or synthesized store (Massaro, 1975) can be characterized as "pure" memory (see [4]). The long auditory store holds the sensory representation of past acoustic stimuli. Each stimulus representation is stored for approximately 10-20 s after which it will fade and vanish unless the stimulus is repeated. The content of the long auditory store is therefore in constant flux, with new representations being added and older ones disappearing.

The basic sensory processing described in this section is said to be obligatory and automatic, that is it is fully completed whether the subject attends to the auditory stimulation or not (for this reason, Näätänen calls this mode of processing *task-independent*). In Näätänen's model, attention, whether active or passive, only affects the probability that a stimulus will enter the limited capacity system and ultimately, be consciously perceived.

1.2. Selection and Conscious Perception

At any one time, an individual may be faced with a multitude of stimulus input impinging on the sensory receptors. Only a small portion of this input is relevant. Rapid processing of the most biologically relevant information is critical for survival. Rapid processing of the most task-relevant information and the disregarding of task-irrelevant information is critical for performing goal-directed behaviour. The restriction of cognitive processes to only a small subset of the available inputs or tasks is "*for the purpose of improving the speed or accuracy of the processes*" (Luck & Vecera, 2002, p.238). The cognitive operations that allow the relevant stimuli to attain conscious perception are collectively known as attention. Attention can be "controlled" either internally (self-directed or voluntary) or externally (captured or involuntary). Attention that is self-directed is called *active* whereas attention that is captured by external stimuli is called *passive* (James, 1890). Although both active and passive attention may be differentially controlled, both provide a means of allowing the observer to become aware of what is relevant (Hopfinger, Buonocore, & Mangun, 2000).

Näätänen proposes two routes by which external auditory stimuli that are potentially relevant may capture attention (i.e. passive attention) and become consciously perceived: (1) a Transient-Detector mechanism and (2) a Change (mismatch) Detector mechanism. These attention-capture mechanisms do not require the subject to be actively attending to the auditory environment. Nonetheless, the likelihood of attention being captured by a stimulus is, in part, dependent on the direction of attention. Näätänen's model also includes a third route to conscious perception, the Temporary Feature-Recognition system, which enables selection of task-relevant among task-irrelevant stimuli and requires active voluntary attention. Importantly, the basic sensory analysis is unaffected by whether or not the voluntary selection mechanisms are activated. That is, selective attention does not influence the extent of elaboration of the basic sensory analysis received by either task-relevant or -irrelevant stimuli.

1.2.1. Attention Capture: The Transient- and Change-Detector Mechanisms

As described above, basic sensory analysis is initiated in Näätänen's model via the Permanent Feature-Detector system. Following feature extraction, a separate task-independent system may be activated by certain stimulus features (see [5]). This system, the Transient-Detector system, detects certain transient aspects of the auditory stimulation, such as abrupt onsets of discrete stimuli, offsets of long-duration stimuli, and energy or qualitative changes in continuous stimulation. The Transient-Detector system automatically generates an attention-trigger signal upon the occurrence of such stimulus events (see [6]) — but it does not mediate qualitative aspects of these events, that is, it does not participate in the analysis of the stimulus *per se*. The strength of this interrupt signal depends on the properties of the stimulus and on the momentary excitability of the Transient-Detector system. A loud and abrupt signal will, for example, generate a stronger interrupt signal than a weak and gradual sound. This interrupt signal must exceed some variable threshold (see [7]), the latter being primarily determined by the direction and intensity of attention, in order for an attention switch to occur (see [8]). The nature of the task in which a subject's attention is engaged and the extent to which the task engages cognitive resources (i.e. task load) will thus affect the success of a transient event in causing an attention switch. When attention is captured, the subject may detect the occurrence of the eliciting (i.e. current) stimulus (see [9]). However, only the complete information corresponding to the previous stimulation (see [10]), and to those stimuli in the immediate acoustic past (in the long auditory store) (see [11]) has access to the limited-capacity system, is evaluated for its significance and may then subsequently be consciously perceived. This is because the Transient-Detector System operates in parallel with feature analysis and sends an interrupt signal prior to the emergence of the representation of the eliciting stimulus. For example, it is possible to behaviourally detect the occurrence of a stimulus before the emergence of the stimulus representation; the precise features of the incoming stimulus are thus unavailable at that time. This has been called *responding to something happening* (Näätänen, 1975).

Näätänen's model also proposes a second route through which sensory information may automatically elicit an attention-switch process. Unlike the Transient-Detector System, this route requires feature analysis to be complete and depends on the contents of sensory memory. It elicits an interrupt signal in response to another common event in acoustic input: a change in repetitive, homogeneous discrete stimuli.

When an identical discrete stimulus is presented repetitively, its representation in the long auditory store is strengthened, and a solid memory trace for this stimulus is established. With each subsequent stimulus presentation, a comparison process takes place between the well-established memory trace and the representation of the incoming stimulus. If the memory trace and representation of the incoming stimulus are identical (i.e. match), the memory trace becomes more vivid but no response is elicited. On the other hand, if they are not identical (i.e. mismatch) acoustic change is detected (see [12]). It should be emphasized that in Näätänen's model this detection occurs pre-attentively. An interrupt signal is then automatically sent to the executive mechanisms (see [13]). Similar to the Transient-Detector signal, the strength of the interrupt signal issued by the Change-Detector mechanism primarily depends on the properties of the incoming stimulus, that is, the extent of deviance of the incoming stimulus when compared to the standard stimulus. The attention switch occurs (see [8, 10, 11]) when the strength of the signal exceeds the variable attention-dependent threshold (see [7]), and conscious perception may subsequently follow.

Hence, it appears that basic sensory analysis automatically initiates attention capture processes, by means of two different mechanisms, in response to transient aspects or change in sensory input. Acoustic change is thus biologically relevant whereas constancy is not. As previously mentioned, the likelihood of an attention-switch, however, depends on the direction and intensity of attention. Therefore when attention is anticipatorily directed to the auditory stimulation even the onset of a weak stimulus or a slight acoustic change may be consciously detected. On the other hand, such stimuli would not be perceived when attention is intensively focused elsewhere; albeit, under these circumstances, a very obtrusive transient aspects or change in the auditory stimuli may nevertheless trigger an attention switch. During such involuntary "attentional glimpses", all sensory information from the immediate acoustic past enters the limited capacity system and is evaluated for its urgency and significance to the organism. If it corresponds to nothing urgent or significant, it is not further processed, and attention is quickly re-directed to the previous activity (e.g. task). If the contents of the sensory memory reveal something of interest, for example one's own name, this information is likely to be consciously perceived. The passively-elicited attention may subsequently result in active attention to the auditory stimuli. Näätänen's model thus accommodates the phenomenon of the *breakthrough of the unattended* without having to posit late-selection (i.e. automatic semantic activation). However, if the demands of a to-be-attended task are less than maximal or during periods when attention is "wandering", the sensory information of the to-be-ignored input is likely to make contact with its semantic codes. This may give the impression that semantic activation is fully automatic.

1.2.2. Selective Attention: The Feature-Recognition Mechanism

Basic sensory analysis, initiated via the Permanent Feature-Detector system, is called *task-independent* processing because all stimuli are processed without bias, whether task-relevant or not. A second mode of sensory processing, one that is *task-dependent*, operates in parallel with basic sensory processing. The task-dependent mode of processing, conducted by the Temporary Feature-Recognition system, is called upon when a task requires rapid selection of some stimuli for further processing and the rejection of others. An example of such a task is the classic dichotic listening situation, in which subjects must attend to the stimuli in one ear (attended channel) while ignoring those in the other ear (unattended channel). In order to do this type of selection, the feature(s) differentiating relevant from irrelevant stimuli must first be defined — in the example above, ear of delivery would be the defining feature — and a memory trace of these features must be established (see [14]). This, in turn, requires that a solid stimulus representation corresponding to the relevant stimulus be present in the long auditory store. Näätänen has labelled this memory trace: the *attentional trace*. As there are often short delays between the presentations of the relevant stimulus, the existence of the attentional trace is crucially dependent on the voluntary maintenance of the corresponding mental image. This is achieved through the effortful process of rehearsal (see [15]). Despite these maintenance efforts, the trace may vanish if the subject is momentarily distracted by internal thoughts or by external events, such as those causing an attention switch to the irrelevant input. In this case, the attentional trace may be retrieved only if the corresponding stimulus has its representation in sensory memory. It is therefore important that the representation of the relevant stimulus be frequently activated.

Whereas the set-up and maintenance of the attentional trace is a controlled process, requiring cognitive effort, the actual selection process is an automatic process, not requiring effort. The selection of relevant among irrelevant incoming stimuli, achieved through a memory comparison with the attentional trace, is performed by the Temporary Feature-Recognition system. The purpose of the sensory analysis within the Temporary Feature-Recognition system is to determine if the incoming stimulus possesses the critical feature(s) of the to-be-attended stimulus. Each incoming stimulus makes contact with the attentional trace (see [16]) and a comparison (matching) process between the features of these two stimuli is initiated (see [17]). The matching process terminates only when sufficient information has accrued to reveal a difference between the current stimulus and the to-be-attended stimulus. Thus, the more similar these latter stimuli are, the longer the matching process continues until a difference is detected. This process is therefore longest for a perfect match whereas it ceases rapidly when the incoming stimulus is very distinct from the to-be-attended stimulus.

The Temporary Feature-Recognition system thus allows for rapid and efficient selection of matching stimuli for further processing, whereas mismatching stimuli are rejected (i.e. cease to be processed). The matching stimuli gain access to the limited-capacity system for further processing or response, depending on the task instructions. A matching stimulus may immediately trigger a sequence of prepared processes (see [18]), following which a response to a pre-determined target may be released (see [19]). When no prepared processing is readily available, the response to the matching stimulus involves long-term memory (LTM) search and evaluation (see [20]). On the other hand, the stimuli that do not correspond to the attentional trace usually will not gain access to the limited capacity system, and as such are not consciously perceived. An exception to this may occur when the basic task-independent processing of these rejected stimuli — which takes place whether the stimulus matches or mismatches the attentional trace — sufficiently triggers the mechanisms causing an involuntary attention switch to the representation of these stimuli. For example, a very loud stimulus may not match any relevant stimulus feature of the to-be-attended stimulus and would thus be rejected from further processing in the Temporary Feature-Recognition system. Still, it might be consciously perceived through the operation of the Transient-Detector and/or the Change-Detector systems.

1.3. Different Perspectives on Automaticity in Information Processing

The concept of attentional selection presumes that the capacity to process information is limited. If processing capacity were unlimited, there would be no need for such selection. Some stimuli will hence advance further in the chain of processing from stimulus to response, but at the expense of other stimuli. When is processing narrowed from many to a single channel? Two extreme and opposing views emerged during the 1950s and 1960s. These are often called the early- and late-selection theories.

1.3.1. Automaticity of Semantic Activation

Broadbent's (1958) early-selection theory purported that all stimuli are registered in sensory storage where they receive a primitive feature analysis. Most of these stimuli are denied, however, a more complete physical and semantic analysis. On the other hand, Deutsch and Deutsch's (1963) late-selection theory proposed that all stimuli are fully physically and semantically analyzed and that selection must occur because the observer is unable to respond concurrently to all stimuli. Other researchers adopted an intermediate position concerning the fate of the unattended. For example, Treisman (1969) suggested that all stimuli would enter the limited-capacity system, albeit unattended stimuli would take an attenuated form. Only if the semantic content of the unattended input is significant will the subject become aware of it. Importantly, on the issue of automaticity, Treisman takes the stance that semantic activation does not require attention but may lead to an attentional shift (Treisman, Squire, & Green, 1974). In this regard, Näätänen's model of selective attention has more in common with the early selection models because " *(...) according to the model, semantic processing would not occur in the complete absence of attention in audition*" (Näätänen, 1990, p.262). Attention (active or passive) is necessary for the recognition of meaning.

1.3.2. Automaticity of Sensory Processing

In contrast to semantic activation, Näätänen's position on the automaticity of basic auditory sensory processing is more in line with the late-selection theories. He suggests that all auditory stimuli are fully analyzed for their sensory content and represented in sensory memory, whether the stimuli are attended or not. Moreover, the quality, quantity or decay of this information within sensory memory does not depend on the direction or extent of attention. Selective auditory attention is based on a separate parallel matching process instead of a selective facilitation or inhibition of the basic sensory analysis. Therefore, although selection of relevant stimuli may occur very early in sensory processing — prior to the completion of the basic sensory analysis — this selection does not influence the operation and outcome of the basic sensory analysis.

Näätänen's view on basic sensory processing has thus been dubbed a *strong-automaticity theory* (Hackley, 1993). Attentional theories in which the sensory processing of attended stimuli is facilitated (resulting in enhanced stimulus representations) or the processing of unattended stimuli is suppressed (resulting in degraded stimulus representations) are referred to as *gain theories* by Näätänen (1986). Different gain theories suggest that this facilitation or inhibition occurs at different levels in sensory processing. According to the extreme view of gain theory, the Peripheral-Gating theory, the very earliest sensory analyses are affected by attention; unattended stimuli can be filtered or gated soon after transduction (in the inner ear, peripheral auditory nerve, or at the first central synapses) via descending neural pathways (Hernández-Péon, Scherrer, & Jouvet, 1956). Others have suggested that very early sensory analyses are indeed strongly automatic; however, possibly even before the sensory information reaches the cortex there may be a switch to weak automaticity in sensory processing (Hackley, 1993; Woldorff, Hansen, & Hillyard, 1987; Woods, 1990). The view of a transition between strong to weak automaticity implies that unattended stimuli continue to be processed but in degraded form relative to attended stimuli. This point of view is different from the Broadbent (1958) position, which suggests that the initial feature analysis of unattended stimuli is strongly automatic but eventually, unattended stimuli will be completely rejected. Rather, it is consistent with Treisman's (1969) position that unattended stimuli are attenuated but not completely rejected.

2. Bioelectrical Recordings in the Study of Information Processing

Most psychological models of information processing have been developed on the basis of results from behavioural experiments, relying on an overt response. The accuracy and speed of responding are often used infer the extent to which a channel has been processed. One of the problems with strict behavioural/performance methodology is that the researcher has access only to present behaviour (the "response"). The researcher must then infer the extent of cognitive processing that has preceded the response. There are additional methodological problems in the study of attention and automaticity. It is difficult to infer the extent of processing in an unattended channel on the basis of an absence of a behavioural response. For example, a failure to respond does not mean that the subject was not conscious of the unattended channel. Some researchers thus require some form of response to certain stimuli in the unattended channel. This, however, will draw attention to the channel that should be ignored, contaminating the results. Thus, many scientists now employ neurophysiological measures, such as event-related potentials (ERPs), to complement the performance measure. ERPs have the advantage that they provide a real-time measure of information processing that occurred prior to, at the time of, and following presentation of a stimulus (Coles, Smid, Scheffers, & Otten, 1995). They can thus be used as an index of the extent of processing in an unattended channel (i.e., automatic processing) in the absence of a behavioural response.

2.1. The Electroencephalogram

Although it was H. Berger (1929) who first succeeded in recording human electrical brain activity, it was R. Caton who made the following discovery in 1875: "*feeble currents of varying direction pass through the multiplier when the electrodes are placed on two points of the external surface, or one electrode on the grey matter, and one on the surface of the skull* ". The weak electrical activity of the human brain can be detected by means of electrodes placed on the scalp. The continuous recording of the voltage fluctuations in this electrical activity is called the electroencephalogram (EEG). The voltage fluctuations are due to changes in arousal and activity level, and are commonly used as markers for various global brain states. The absence of the EEG for several hours has been used as an indicator of "brain death". The EEG reflects the summation of the activity — excitatory and inhibitory postsynaptic potentials — generated by a multitude of simultaneously active neurons in the cerebral cortex (Nunez, 1981). Raw EEG data are thus not useful in the investigation of specific neural processes as these make a relatively minute contribution to the total voltage. Not until 1951, when G. D. Dawson developed an EEG averaging technique, would the study of stimulus-specific neural processing be possible.

2.2. Event-Related Potentials

The neural activity generated by the onset of a particular stimulus, movement or thought, the event-related potential (ERP), is not discernable against the noisy background EEG. This is because the amplitude of the ERP "signal" is generally much smaller than the background EEG "noise". Signal averaging techniques are used to enhance the amplitude of the signal and reduce the amplitude of the background noise. The amplitude of background noise is assumed to be random. Sometimes it is positive-going; sometimes it is negative-going. The summation of an infinitely large number of random noise trials will tend to zero. On the other hand, the amplitude of an ERP is assumed to be constant and invariant. The average of a constant is, of course, the constant. The ERP signal thus becomes enhanced relative to the background EEG noise by the averaging process. The resulting signal-to-noise ratio (S/N) is dependent on the amplitude of the ERP signal, the background EEG noise and the number of times the event is repeated (i.e. trials). Therefore, if the ERP signal under study is of small amplitude or the EEG is very noisy, numerous same stimulus trials would be necessary.

The ERPs recorded on the surface of the scalp are also the result of electrical activity that is generated by different populations of neurons. For ERPs, however, this activity is related to the processing of a particular repetitive event, either external or internal to the organism. This event-related electrical activity summates and is propagated through brain tissue, bone and scalp. For summation and conduction to occur, these neurons must be activated synchronously and must have similar orientations (Coles, Gratton, & Fabiani, 1990). The ERP waveform hence reflects only a sample of the electrical activity — primarily postsynaptic potentials generated at the dendrites of cortical pyramidal cells — elicited by the processing of the event. It is thus possible that some information processing will not be detected by means of ERP recordings. Consequently, null effects should be interpreted with caution (Eimer, 1998).

2.2.1. ERP Deflections, Peaks or Waves

In the averaged ERP, voltage (μV) is plotted as a function of time (ms). The ERP waveform appears as a series of deflections, peaks or waves. These can be described in terms of observed characteristics such as polarity (positive or negative), sequence and peak latency (ms). If a peak is positive-going, it will be given the label P; if negative-going, the label will be N. The polarity label is followed by a number that represents either the ordinal position of the peak, the latency at which it typically occurs, or the latency at which it actually occurs. For example, the third positive peak in the waveform might be — and most often is — labelled P3. This deflection often attains its peak amplitude around 300 ms following stimulus onset, and therefore is sometimes referred to as P300 even if this number does not correspond to the actual latency in a specific study. Alternatively again, P3 may be called, for example, P600 or P800 when the third peak in a specific study actually occurs at 600 ms or 800 ms, respectively.

The individual deflections that are visible in the scalp-recorded ERP waveform may result from the temporal summation of electrical activity from various intra-cranial neuronal processes and reflects various information-processing functions. A distinction was therefore introduced between an ERP deflection (or peak, wave) and an ERP component.

2.2.2. ERP Components

An ERP deflection may represent the summation of several functionally and structurally distinct ERP components. Näätänen and Picton (1987) define the ERP component as: "*The contribution to the recorded waveform of a particular generator process, such as the activation of a localized area of cerebral cortex by a specific pattern of input (...) Whereas the peaks and deflections of an EP*[2] *can be directly measured from the average waveform, the components contributing to these peaks can usually be inferred only from the results of the experimental manipulation*" (Näätänen & Picton, 1987, p.376). This definition suggests that an ERP component is elicited by a specific neural process having a specific neural source or generator (i.e. functionally and anatomically distinct neuronal population). Donchin and colleagues (Donchin, Ritter, & McCallum, 1978) define a component in a slightly different way: "*Functionally different [neuronal] aggregates need not be anatomically distinct neuronal populations. But it is assumed that neuronal aggregates whose activity will be represented by an ERP component have been distinctly affected by one or more experimental variables*" (Donchin et al., 1978, p.353). While the Näätänen and Picton definition places particular emphasis on a component's distinct intracranial generation, the Donchin et al. definition places more emphasis on the component's functional role. Even so, in both definitions the ERP

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[2] ERPs are sometimes called EPs, which stands for evoked potentials. Often, the pre-cortical evoked responses are labeled EP, as in BAEP for brainstem auditory evoked potential, while the cortical ones are labeled ERPs.

component is clearly of greater value for psychological research than the ERP deflection that is observed on the scalp.

A more precise ERP nomenclature has also been introduced to distinguish among the various components that contribute to a scalp-recorded peak. The component label often refers to its underlying function or to the scalp location at which the component — but not necessarily the deflection — is maximal. For example, the N2 deflection (i.e. second peak in the waveform) may be comprised of various components, such as an N2b, an attention-dependent component and the mismatch negativity (MMN; or the N2a), a component elicited by a change in discrete auditory stimulation. The MMN, in turn, may also consist of two subcomponents: the supratemporal MMN, which has been associated with the actual change detection process, and the frontal MMN that is believed to reflect a call for attention following the detection of change.

Different strategies have been adopted to disentangle the various overlapping components that may contribute to an observed peak deflection. Each component has a characteristic voltage distribution across the scalp because of the specific neuroanatomical locus and orientation of its generator(s). The scalp distribution of an ERP deflection thus provides critical evidence of the underlying ERP components. Consequently, it is imperative to record ERPs at multiple scalp sites (with some labs employing as many as 256 electrodes). Particular emphasis should also be placed on the experimental design of a study. Certain experimental manipulations may affect particular components but not other overlapping components. Thus, the relative contribution of each component within a peak may change across experimental condition. However, determining which of the overlapping components is affected by a particular manipulation is not always easy. Therefore, many studies simply report the experimental effect on the ERP deflection, and this effect must consequently be interpreted with caution.

The sequence of ERP components that follows a stimulus is commonly believed to reflect the sequence of sensory and cognitive processes that are triggered by the onset of the stimulus or the preparation for a response. The amplitude and latency of the inferred component is therefore used as an index of the magnitude and timing, respectively, of a given process. ERP components are conveniently classified as being exogenous — primarily affected by the physical parameters of the stimulus, or endogenous — primarily affected by the internal psychological state. Exogenous ERP components are considered to be obligatory (that is, elicited without and despite intent; Posner, 1978) and occur shortly, usually within 250 ms, following stimulus onset. On the other hand, endogenous ERPs are determined by the interaction between the person and the eliciting event. Hence, the endogenous ERP components are informative about cognitive processes whereas the exogenous components mainly reflect sensory processes (Coles et al., 1990). However, the distinction between these two types of ERP components is not always straightforward, especially in the time range between 100 and 300 ms following stimulus onset (van Boxtel, 1998).

ERPs can be recorded in all modalities (auditory, visual, somatosensory, olfactory, gustatory). The exogenous ERPs are often modality-specific. The main focus in this thesis is on auditory processing and therefore the description of ERP paradigms and components will be limited to those related to the auditory modality.

2.3. Auditory ERP Paradigms

This sub-section describes the tasks and terminology used in the study of attention, automaticity and the detection of acoustic deviance.

2.3.1. The Oddball Paradigm

The most widely employed auditory ERP paradigm is undoubtedly the so-called *oddball task*. Typically, in this paradigm, two stimuli are presented in random order, one of which occurs less frequently than the other. The frequent stimulus is called the *standard*, whereas the infrequent stimulus is called the *deviant*[3]. Additional infrequent stimuli may also be include in the oddball paradigm, such that, for example, one standard, and two different deviants are presented in the same sequence.

In the *active* oddball task, the subject is required to discriminate the deviant(s) from the standard by noting the occurrence of the deviant(s) – for example, by pressing a button or keeping a mental count. The behavioural response of a subject to such an irregular event serves as the primary indicator of a conscious detection of change. When subjects are asked to note the occurrence of the deviants, these stimuli are referred to as *targets*. When two (or more) infrequent stimuli are included in an otherwise homogeneous sequence, some deviants may be targets, while others are non-targets; the targets are said to be *task-relevant*, while the deviant non-targets are *task-irrelevant*. On the other hand, in the *passive* oddball task, all — standard and deviant — auditory stimuli are non-targets and task-irrelevant.

2.3.2. Selective Attention Paradigms

Selective attention paradigms are primarily used in ERP research to study distraction of task performance by task-irrelevant stimuli and to determine the time at which relevant and irrelevant stimuli are processed differently (Näätänen, 1990). In selective attention tasks, subjects are presented with two (or more) concurrent stimulus inputs (or *channels*) and instructed to restrict processing to only one of them. Often the subject is asked to detect a target occurring at rare times in the attended channel. The overt response to the target serves as behavioural evidence that the subject was, in fact, attending to the designated channel. The different stimulus channels may arrive via the same or different modalities. Selective attention is called *intramodal* when both the to-be-attended and to-be-ignored channels are presented in the same modality (e.g., auditory). The classical example of an intramodal task is the dichotic

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[3] The deviant stimulus may be called a *novel* stimulus when it is widely different from the standard stimulus, as would be the case if a rare environmental sound (e.g. animal sound or telephone ring) is presented among repetitive pure tones.

listening situation, in which subject attends to the input in a designated ear while "ignoring"[4] the input in the opposite ear. The task-relevant and task-irrelevant channels may alternatively arrive via the same ear, and be differentiated by some stimulus feature. For example, subjects may be asked to attend to high-pitched tone in order to detect occasional decrements in its intensity while "ignoring" low pitched tones. Selective attention is called *intermodal (*or *crossmodal)* when the attended and the "ignored" channels are in different modalities. For example, subjects may be asked to perform a visual discrimination task while ignoring all auditory stimuli.

2.3.3. Divided Attention Paradigms

A means to test the extent to which different tasks compete for the limited resources is the use of the so-called *divided attention paradigm*. The divided attention paradigm provides useful information about an individual's processing limitations and the extent to which different tasks can be performed concurrently without penalty (Luck & Vecera, 2002). Similar to selective attention, divided attention is also studied by presenting the subject with at least two stimulus channels. In divided attention tasks, all channels, however, contain relevant information and must be attended. In this paradigm, the subject may initially be asked to perform a single, *primary* task; subsequently, another *secondary* task may be imposed. If the two tasks compete for the same resource, performance on the primary task will deteriorate. If, on the other hand, one task is carried out automatically (without using available resources), then performance on the primary task will not suffer.

3. Auditory ERPs and Näätänen's Model of Information Processing

This section serves both to introduce the most common ERP components elicited in studies of auditory processing, as well as to exemplify how Näätänen has used ERPs as support

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[4] Subjects may actually be unable or unwilling to ignore this input although they are instructed to do so. This input is also called *unattended* or *task-irrelevant*.

for the phases and mechanisms proposed in his complex psychological model of auditory information processing. Central to Näätänen's model is that basic sensory processing is strongly automatic, the outcome of which is unaffected by the direction and intensity of attention. The literature addressing the automaticity of sensory processing will be reviewed separately, in Section 4 (The Effects of the Direction and Intensity of Attention on the MMN).

3.1. Basic Sensory Processing: The Feature-Detector and Sensory Memory Mechanisms

According to Näätänen, basic sensory analysis is said to proceed through three temporally overlapping phases. These phases were primarily distinguished on the basis of ERP data suggesting three forms of auditory sensory information: an ever-changing afferent activation pattern, more durable feature traces and finally, a complete stimulus representation (Näätänen & Winkler, 1999). In contrast to the activation pattern, the neuronal populations underlying the feature traces must retain for a short time the stimulus-specific information. In contrast to the stimulus representation, the neuronal populations underlying the feature traces do not represent the combination of these features and the temporal aspects of stimulation that are present in perception and accessible to top-down mechanisms. Stimulus effects on various ERP components suggest that they may serve as indexes of these forms of sensory information.

The earliest human auditory EEG responses, the brainstem responses (BAEPs) and the subsequent middle-latency responses (MLRs) are obligatorily elicited by the occurrence of a discrete auditory stimulus. They are a series of small-amplitude deflections occurring within 10-50 ms after stimulus onset. They represent the activity of auditory centers from the peripheral auditory nerve, the brainstem relay centers, the thalamus and the primary auditory cortex (Näätänen & Picton, 1987). The various BAEPs and MLRs are the result of multiple temporally overlapping neural generators. While the generators of these ERPs show some frequency-specificity, they do not retain the stimulus-specific information for longer than a tenth of a second. This can be observed as minimal rate-of-presentation effects on the BAEPs and MLRs, with identical stimuli presented at very rapid rates resulting in similar peak amplitude than when presented at slower rates (Picton, Champagne, & Kellett, 1992; Picton, Stapells, & Campbell, 1981). The neural circuits underlying the BAEPs and MLRs thus recover their pre-stimulus excitability almost immediately, that is, they have very short refractory periods. Näätänen and Winkler (1999) suggest that these ERPs are generated by the rapidly changing neural activity of the feature extraction phase. In order to index the more durable feature traces of the eliciting stimulus, the ERP component must be attenuated with rapid repeated presentation of a similar stimulus. This is because the underlying neural circuits would be in a state of refractoriness for a while after the offset of the stimulus, and therefore unable to fully respond to a similar stimulus.

The first deflection of the longer latency auditory potentials is the N1 wave[5], peaking at about 100 ms following stimulus onset. The N1 wave and its components have been extensively reviewed by Näätänen and Picton (1987). N1 is a transient response to a relatively abrupt change in energy impinging on the ear. Such changes include the onset and offset of stimulus energy, a change in environmental energy (i.e. intensity) of a continuous stimulus, and also a purely qualitative (e.g. frequency) change of a continuous stimulus. The N1 wave is composed of several anatomically and functionally distinct components. Some of the N1 sources are believed to be located in the auditory cortex on the supratemporal plane (N1b or supratemporal component), in the auditory association cortex and the superior temporal gyrus (N1c), and perhaps also in the frontal lobe. The N1 wave is usually measured at the fronto-central sites on the scalp, where the negativity is maximal. At interstimulus intervals (ISIs) below 5 s., the anterior-superior orientation of the supratemporal component contributes

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[5] The P1deflection, peaking at about 50 ms, immediately precedes the N1 deflection. P1 may be considered as part of the middle (as it is here) or long latency ERPs. P1 is a small amplitude wave with a very short refractory period.

heavily to this frontal negativity on the scalp. It can also be distinguished from the other N1s by its topography; the supratemporal N1 inverts in polarity at sites below the Sylvian fissure[6].

The fronto-central N1 wave is extremely sensitive to the rate of stimulus presentation, that is, it is attenuated with stimulus repetition within a period extending up to about 10 s (Hari et al., 1987). The N1 refractory period is partially specific to the stimulus, revealing frequency and location N1-specificity (Näätänen et al., 1988). The recovery of the N1 thus depends on the time elapsed since the last stimulus, but also on the dissimilarity of the present and previous stimulus. This stimulus-specific refractoriness pattern suggests that at least some of the neuronal elements underlying the N1 may be involved in the mnemonic retention of certain stimulus features. Based on findings of electrical and magnetic ERP studies, Näätänen and Winkler (1999) proposed that it is the supratemporal N1 sub-component that may index the feature traces.

The supratemporal N1 probably does not index, however, the auditory stimulus representation. While some of the neuronal elements involved in the generation of the supratemporal N1 may encode certain stimulus-specific information, most of these elements respond to a wide variety of stimuli and therefore do not retain the individuality of the stimulus. For example, the N1 refractoriness pattern is generalized to many different stimuli; N1 will be attenuated following the presentation of a similar, but also a different stimulus in a homogeneous sequence (Butler, 1968). Furthermore, different types of acoustic stimuli, as disparate as a simple tone or an animal sound, elicit a similar supratemporal N1, when transient aspects of the stimulation (i.e. extent and slope of energy change) are controlled (Gaillard & Lawson, 1984). As such, a number of neuronal elements underlying the supratemporal N1 are believed to subserve a transient detection function, providing information about stimulus

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[6] The site of inversion provides a critical means to determine the intra-cranial source of the ERP component.

onsets — and sometimes offsets — rather than about specific stimulus features. Secondly, the temporal stimulus features are not encoded in these neuronal elements. For example, N1 amplitude increases with increasing stimulus duration but only up to durations of approximately 30-50 ms (Kodera, Hink, Yamada, & Suzuki, 1979). Finally, while studies have shown that the N1 response may at times correlate with perceived pitch, the information encoded in the neurons generating this response is not available to perceptual mechanisms (Winkler, Tervaniemi, & Näätänen, 1997).

N1 is followed by the P2 deflection, peaking at 175-200 ms from stimulus onset. P2 often co-varies with N1 along many stimulus dimensions, and thus these waves are often referred to as the N1-P2 complex. In early studies, the overall N1-P2 potential was noted to be maximal at the vertex (top) of the scalp. For this reason, it was also called the vertex potential. P2 also has a long stimulus-specific recovery period but does not accurately index the individuality of the eliciting stimulus. More recent studies have indicated that the scalp distribution of P2 is different from that of N1, indicating different intra-cranial neural generators within the auditory cortex (Paavilainen et al., 1991).

A negative wave peaking around 150-300 ms, the N2, may follow the P2 deflection. N2 is most prominent when the eliciting stimulus is an infrequent deviant in a sequence of frequent homogeneous standard stimuli. Näätänen, Simpson and Loveless (1982) demonstrated that this deviance-related negativity is comprised of at least two sub-components. One of these, the mismatch negativity (MMN; or N2a) component, peaking approximately 150-200 ms from stimulus onset, was first described by Näätänen and colleagues (Näätänen, Gaillard, & Mäntysalo, 1978). The fronto-central scalp distribution and lateral-inferior (below the Sylvian fissure) polarity inversion of the MMN has been explained by source activity in the supratemporal plane of the auditory cortex — slightly anterior to N1 sources (Scherg, Vasjar, & Picton, 1989). In addition, a frontal generator for the MMN has been proposed and confirmed on the basis of different imaging techniques (Giard, Perrin, Pernier, & Bouchet, 1990; Opitz et al., 2002). The frontal and temporal MMN generators appear to have distinct functional roles (Rinne et al., 2000). The MMN is elicited following the occurrence of an infrequent deviant stimulus, independently of whether or not the subject is actively attending to the MMN-eliciting stimuli. In contrast, the N2b component is primarily associated with active stimulus discrimination. Therefore it can best be observed when the subject is actively attending to the eliciting deviant stimulus, whether this stimulus is a target or not. Nevertheless, the N2b can also be evoked without active attention when stimulus deviance is very wide (Näätänen et al., 1982). The MMN and N2b may overlap temporally and spatially, making the components difficult to discern. The N2b, however, usually peaks somewhat later, around 200-300 ms from stimulus onset. Furthermore, it is maximal at central areas of the scalp and does not invert in polarity at sites below the Sylvian fissure, as its generators are probably located outside the auditory cortex.

The MMN is thought to be generated by a discriminative process utilizing the neuronal traces of *both* the deviant *and* standard stimuli. This is because the MMN is only elicited when a sound deviates from the preceding homogeneous standard sounds. It is not elicited by presenting an infrequent stimulus without the frequent intervening standard stimuli (Näätänen et al., 1989). The most convincing evidence, however, comes from studies showing that an MMN may be elicited by a stimulus identical to all others in the sequence but presented somewhat earlier (i.e. shorter ISI; Näätänen et al., 1993a), as well as by the omission of a stimulus in a repetitive sequence (Yabe et al., 1998). This argues against the MMN being generated by the deviant stimulus activating new afferent elements (i.e. those not activated by the standard stimulus). The MMN is thus considered to be a response to auditory stimulus change, that is, it represents the relation between present and previous stimulation, rather than to the incoming stimulus *per se*. This component can best be seen in a difference waveform, by subtracting the ERP response to the standards from the response to the deviants. Both the standard and deviant stimuli elicit the exogenous N1-P2 complex. The deviant, in addition, also elicits the MMN, which may overlap and summate with the N1-P2 complex. In most MMN studies, the physical features of the deviant stimulus are quite similar to those of the standard. For this reason, the N1-P2 complex elicited by standard and deviant stimuli is essentially identical. Processing that is common to both standard and deviant stimulus (as reflected in the N1-P2 complex) is removed by the subtraction process, leaving only the MMN.

The traces underlying the MMN encode both static stimulus features and temporal characteristics of the stimulation. The MMN component can be elicited by a variety of auditory stimulus changes, including tonal frequency (Sams, Paavilainen, Alho, & Näätänen, 1985), intensity (Näätänen et al., 1987), spatial location (Paavilainen, Karlsson, Reinikainen, & Näätänen, 1989), duration (Näätänen, Paavilainen, & Reinikainen, 1989), interstimulus interval (Böttcher-Gandor & Ullsperger, 1992), rise time (Lyytinen, Blomberg, & Näätänen, 1992) and complex stimulus features such as phonemes (Sams, Aulanko, Aaltonen, & Näätänen, 1990) or spectrotemporal sound patterns (Schröger, Näätänen, & Paavilainen, 1992). Therefore almost any discernible change may elicit the MMN. The scalp topography may be different depending on the type of deviant employed, suggesting that the locus of the neural generator may vary with the nature of the sound (e.g. simple, complex, phonemic; Alho et al., 1996) or the stimulus feature (e.g. frequency, intensity, duration; Giard et al., 1995) eliciting the MMN. Alternatively, the difference in scalp topography may reflect the activity of stimulus-independent MMN generators, sensitive to the ease of discrimination of the deviant from the standard (Picton et al., 2000).

The MMN has proven to be an exquisitely sensitive index of the perceptual detection of change, suggesting that the information encoded by the memory traces underlying the MMN corresponds to that in perception. There is evidence that the MMN is elicited by subtle stimulus changes that approximate perceptual discrimination thresholds (Lang et al., 1990). The MMN is not elicited, however, by a change that cannot be detected behaviourally (Winkler et al., 1997). Furthermore, the amplitude of the MMN parallels to a certain extent the magnitude of sound change. As the deviant becomes more difficult to discriminate from the standard, the MMN amplitude decreases (Muller-Gass, Marcoux, Logan, & Campbell, 2001). A positive correlation has also been established between the latency of the MMN to the deviant sound and the speed (RT) of the behavioural discrimination (Novak, Ritter, Vaughan, & Wiznitzer, 1990). Together, this evidence suggests that the MMN provides a means to probe the accuracy of the auditory stimulus representations on which it relies.

This conclusion is further supported by the correspondence between the memory system involved in MMN generation and the long phase of sensory memory. For the MMN to be elicited, the well-formed auditory representation of the standard stimulus must be part of this long auditory store. A deviant presented up to 10 s following a standard stimulus may still elicit a MMN; following this time period, the memory trace of the standard may be too degraded (Sams, Hari, Rif, & Knuutila, 1993). ERP studies suggest that the memory trace lasts about 4 s using electrical recordings (Böttcher-Gandor & Ullsperger, 1992) and about 10 s using magnetic recordings (Sams et al., 1993). Consistent with this, behavioural studies of the long phase of sensory memory suggest that the duration of the memory trace may be between 10 and 20 s (Cowan, 1984). Schröger (1997) presented results from a study that indicate that the representation of the standard is not yet established in the long auditory store after 120 ms. In this study, the MMN was not elicited by a deviant stimulus, preceded by three standard stimuli, if the time between stimulus presentations was less than 40 ms. Consistent with this, the transfer of information to the long auditory store has been estimated to require between 150-200 ms. Näätänen (1985) suggests that the MMN is generated by the deviant stimulus establishing its own trace in the sensory memory system, probably at the transition of sensory information from short to long auditory store. This suggestion is in accordance with reports that MMN typically develops around 100 ms after the onset of the deviant stimulus and usually peaks between 150-200 ms, the time corresponding to the end of the short phase of sensory memory (Schröger, 1997).

3.2. Selection and Conscious Perception

3.2.1. Attention Capture: The Transient and Change Detector Mechanisms

According to Näätänen's model, task-independent sensory processing has, in addition to the extraction of sensory information, a second function: triggering attention switches to unexpected and potentially significant changes in the environment (similar to the orienting response, Sokolov, 1963). Such switching of the focus of attention may be crucial for the survival of higher animals (Pavlov, 1927). The mechanisms responsible for this passive attention function are partially separate from those involved in sensory analysis. As mentioned, Näätänen proposes two routes by which unattended information may reach consciousness: (1) a Transient-Detector mechanism and (2) a Change-Detector mechanism. These two mechanisms are similar in that they are responsive to change in auditory stimulation, and automatically generate an interrupt signal in order to control the direction of attention.

Näätänen suggests that the Transient-Detector system is activated by rapid onsets and offsets of stimulus energy and indexed by N1. More specifically, he proposes that the transience detection function is probably subserved by the neuronal elements underlying the supratemporal N1 component [7]. The amplitude of the N1, believed to reflect the strength of the interrupt signal, is affected by the "obtrusiveness" of the stimulus, that is, by the rate of stimulus presentation and by the extent and the slope of the energy change (Näätänen & Picton,

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[7] Näätänen however acknowledges that the frontal N1 generator may also be a good candidate for this function, as suggested by Giard et al. (1994).

1987). A loud and sudden sound elicits a large N1, particularly if it follows a long silent period.

The Change-Detector system, indexed by the MMN, is activated by an unexpected change in a repeating sequence of discrete stimuli. Current evidence suggests that the supratemporal (sensory-specific) MMN sub-component is involved in the actual pre-perceptual detection of stimulus change, whereas the frontal MMN sub-component is associated with the attention switch to stimulus change. Giard et al. (1990) suggested that the auditory MMN process might lead to a "call" from the pre-attentive mechanism (Öhman, 1979) to focal attention, and this "call" is a function of the frontal MMN generator. This is supported by findings that the activity of the frontal MMN generator emerges after the onset of the activity of the temporal MMN generator (Rinne et al., 2000), and by the involvement of the frontal lobes in the control of the direction of attention (Stuss & Benson, 1986). The strength of the MMN signal is primarily affected by the extent of deviance and the probability of deviance occurrence. A large change elicits a large MMN, particularly if the deviant is rare and the time between deviants is long.

The proposal that N1 and MMN processes are involved in redirecting the focus of attention to new events in the auditory background is supported by findings that sounds eliciting large N1s or MMNs also typically elicit a large P3a, an ERP component proposed to be a manifestation of attention capture. The family of ERP components called P3 is usually elicited by infrequent stimuli that are personally or physically salient. Although the various P3s do appear to be independent components, they share a common functional significance: awareness that a rare event has occurred. Conscious awareness of the rare event may be a consequence of voluntary choice (active attention) or because of an involuntary intrusion (passive attention). The P3b (or P300), maximal at parietal scalp sites, is generated by a rare designated target stimulus when this target has been actively detected. As it co-occurs with the

N2b, these components are often referred to as the N2b-P3 complex. The P3b is commonly thought to index the updating of working memory. The working memory for the standard stimulus is well-formed because it is presented frequently. On the other hand, the memory for the rarely presented target is poor. Upon its presentation and detection, the memory for the target must be updated (Donchin & Coles, 1988). The peak latency of P3b is often used as an index of stimulus classification time, independent of processes that are related to the motor response initiation and production. In contrast, the P3a is maximal at fronto-central sites and is elicited earlier (250-300 ms) than the P3b. It can best be observed following a non-target[8] deviant or novel[9] stimulus, whether the auditory stimulation is attended or not. Thus, the P3a may or may not be preceded by the attention-dependent N2b.

The suggestion that P3a is related to attention switching was first made by Squires, Squires and Hillyard (1975), although no evidence for this was provided at the time. Support for the functional significance of P3a has mainly come from studies of distraction. Distraction refers to the involuntary switching of attention from a goal-related behaviour to the disturbing event. For example, Grillon and colleagues (1990) reported delayed reaction times (RT) to targets following infrequent non-target novel sounds relative to frequent non-target sounds. This result implies that the target stimuli received less attention when preceded by the novel stimuli because these novel stimuli were more distracting, that is, they engaged additional processing resources, than the frequent stimuli. Importantly, the novel stimuli also elicited a large P3a. Woods (1992), using a dichotic listening task, further demonstrated that the P3a elicited by such non-target novel sounds was larger when presented in the attended ear compared to when presented in the unattended ear. The RT prolongation to targets following

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[8] Presentation of a target stimulus may also elicit a P3a component, but the fronto-central P3 is difficult to observe at the scalp due to the overlap with the much larger parietal P3b.

[9] The fronto-central P3 following a non-target novel stimulus may have different characteristics than that elicited by a non-target deviant. It is sometimes called a novel-P3 (Courchesne, Hillyard, & Galambos, 1975).

the novel sounds was also greater when P3a was larger, that is when presented in the attended sequence. When the P3a-eliciting stimuli are to-be-ignored, its amplitude is usually larger when the diversion task is less demanding (Sams et al., 1985). Consistent with this, Harmony et al. (2000) reported an inverse relation between P3a and the demands of the primary visual task. This supports the assumption of Näätänen's model that in order for an attention-switch to occur, the interrupt signal must exceed a variable threshold, determined, at least in part, by the direction and intensity of attention.

Recent convincing evidence for a link between N1/MMN, P3a and behavioural distraction derives from studies by Schröger and colleagues using an auditory-auditory[10] distraction paradigm and by Escera and colleagues using an auditory-visual[10] distraction paradigm. In Escera's paradigm, subjects are asked to perform a visual categorization task while ignoring the auditory stimuli. Each visual stimulus is preceded by an auditory stimulus, which is either a frequent standard tone, a rare deviant tone or a rare novel tone. Escera and colleagues (Escera, Alho, Winkler, & Näätänen, 1998) reported that RTs to visual targets increased following novel sounds relative to standard and deviant sounds. These novel sounds elicited an enhanced N1, most likely including an MMN-overlap, and a large dual-component P3a. The accuracy of detection of the visual targets did decrease following presentation of the deviant tones, although RT was not prolonged. These deviant tones elicited a MMN followed by a small P3a. The different behavioural and ERP patterns generated by the novel and deviant stimuli were proposed as evidence for two different attention-triggering mechanisms. One of these, the Transient-Detector mechanism is activated by widely deviant stimuli with corresponding non-refractory neurons, such as novel sounds, and indexed by N1. In contrast,

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[10] Auditory-auditory paradigm denotes that the distracter stimuli are auditory stimuli and the task-related stimuli are also auditory stimuli. This is in contrast to the auditory-visual paradigm, in which the task-related stimuli are visual stimuli.

the Change-Detector is a memory-based mechanism activated by any irregular stimulus, such as a deviant or novel stimulus, within a homogeneous sequence and indexed by the MMN.

In Schröger's recent auditory-auditory distraction paradigm, the distracter stimuli are embedded within the task-relevant auditory sequence. Subjects are asked to discriminate between equally probable, randomly presented short and long duration auditory stimuli. Occasionally, the frequency of one of the stimuli changes, although this is irrelevant to the duration classification task. This paradigm was designed to investigate distraction mediated exclusively by the Change-Detector mechanism. In order to do so, distracters (the frequency deviants) should be physically similar to the non-distracters (the frequency standards)[11]. Indeed, Schröger and associates (Schröger, Giard, & Wolff, 2000; Schröger & Wolff, 1998) demonstrated that under such conditions, even very small frequency deviants resulted in prolonged RTs compared to non-distracter targets having the standard frequency. These task-irrelevant deviants also elicited a MMN and P3a, implicating the memory-dependent Change-Detector mechanism in the elicitation of involuntary attention shifts.

Interestingly, Schröger et al. (1998) also reported a late fronto-central negativity elicited between 400-600 ms following the attended but task-irrelevant frequency deviants. This negative ERP response, labelled the *reorientation negativity* (RON) was interpreted as reflecting the process of reallocation (or reorientation) of attention back to the task-relevant stimuli after momentary distraction. This is supported by the fact that when all auditory stimuli were task-irrelevant and the subject engaged in reading, neither P3a nor RON was elicited following the small frequency deviants, although the MMN was generated. Furthermore, a RON was also evident following the distracter stimuli presented in the auditory-visual

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[11] As Schröger (1996) cogently notes, the extent of distraction is a function of the channel separation of task relevant and irrelevant aspects of the stimulation. When the distracter stimulus is task-irrelevant but part of the task-relevant stimulus stream, its disruptive effect on task performance is greatest. In this case, the distracter stimulus can be a small deviant, and the distraction effect can be solely attributed to the operations of the Change-Detector mechanism.

paradigm (Escera, Yago, & Alho, 2001). A larger RON was reported following the more distracting novel sounds — also eliciting a larger P3a — when compared to that following the deviant tones.

3.2.2. Selective Attention: The Feature-Recognition Mechanism

In selective attention paradigms, as in any daily goal-directed activity, the relevant stimulus channel is selected for attention, while other stimulus inputs are task-irrelevant and thus, to be ignored. The mechanism involved in this selection and the time point at which relevant and irrelevant information are treated differently has been the subject of much debate. Näätänen's model proposes that a memory trace — present in the long auditory store — for the features of the relevant auditory stimulus is actively maintained and compared to the features of the incoming stimulus. A matching process is automatically initiated, and the irrelevant channel stimuli are rejected as soon as their features are identified as failing to match those of the attentional trace.

Näätänen suggests that this matching process generates a slow endogenous ERP wave, called the Processing Negativity (PN). According to his attentional-trace theory, both the to-be-attended and the to-be-ignored stimuli undergo this matching process and therefore both these stimuli would be predicted to generate this attention-dependent negativity. However, the PN (and the matching process) elicited by the to-be-ignored stimuli should terminate before that elicited by the to-be-attended stimuli. Support for this comes from a number of selective listening studies (Alho, Sams, Paavilainen, & Näätänen, 1986b; Michie, Solowij, Crawford, & Glue, 1993) reporting that, indeed, the attended stimuli generate the largest-amplitude and longest-duration PNs, and the to-be-ignored stimuli generate some PN, which is larger in amplitude and longer in duration the more the to-be-attended and the to-be-ignored stimuli are similar (i.e. difficult to discriminate). No PN is elicited, however, by the first few stimuli at the beginning of the selective attention task (Hansen & Hillyard, 1988) or when the silent intervals between relevant stimuli are very long (Alho et al., 1990). This is consistent with Näätänen's suggestion that the maintenance of the attentional trace depends on the corresponding trace being present in sensory memory.

In order to reveal the selective attention effect, the standard ERP evoked in the "ignore" condition is often subtracted from that evoked in the attended condition, resulting in the Negative Difference (Nd) wave. As such, the Nd wave reflects the additional processing that is received by an attended channel, relative to an ignored channel. This wave consists of separate early (between 50-200 ms) and late (between 300-500 ms) negative components, which are probably generated in auditory and frontal cortices, respectively (Näätänen, 1990)[12]. According to Näätänen, the early Nd is caused by an early PN component, indexing the matching process. Similarly, Näätänen suggests that the late Nd, which has been much less studied than its earlier counterpart, is caused by a late PN component. The late PN component may be related either to further processing after the initial stimulus selection, an arousal response following the occurrence of the relevant stimulus or the effortful maintenance of the attentional trace (Näätänen & Michie, 1979; Näätänen & Picton, 1987). An alternative interpretation proposes that the late Nd is primarily caused by an endogenous positivity (therefore not a PN) elicited by the irrelevant stimuli and related to an active suppression of the processing of these stimuli (Michie et al., 1993).

It is Näätänen's interpretation of the early Nd, however, that has been of more controversial nature. The early Nd was actually first demonstrated by Hillyard and colleagues (Hillyard, Hink, Schwent, & Picton, 1973). They employed a dichotic listening task in which

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[12] Most of the ERP studies on auditory attention have examined *intramodal* selective attention. In *intermodal* selective attention studies, an early Nd has also been reported for standard ERPs during attention to auditory stimuli as compared to those recorded during visual attention. In contrast to intramodal stimulus selection, this early Nd was usually followed by a positive displacement (Pd) and, furthermore, the late Nd was typically very modest if not absent. These results suggest that at least partly different mechanisms are involved in intermodal and intramodal selection (Alho, 1992).

the attended channel was easily distinguished from the unattended channel on the basis of physical location (ear of delivery) and the stimuli were presented very rapidly. In this study, the negative displacement occurred at the latency of the exogenous N1. It was hence understood to be a genuine attention-related enhancement of N1, coming to be called the "N1 effect". The N1 effect was interpreted in terms of a selective tonic facilitation of the attended input. The attended channel is essentially amplified relative to the unattended and this causes the increase in the amplitude of N1. This interpretation is supported by a parallel enhancement of the exogenous N1 with visual spatial attention (Mangun, Hansen, & Hillyard, 1987). In contrast, Näätänen's model suggests that selective attention does not affect the initial stimulus-elicited obligatory processes; instead the selection of stimuli is realized by means of a matching process that generates an endogenous ERP. Näätänen's most compelling argument remains that the early Nd does not necessarily occur at the latency of the exogenous N1 components. When this is the case, it does not significantly affect the amplitude of the N1 peak but instead may appear to attenuate the amplitude of the later P2 deflection. Such a late onset of the early Nd has been demonstrated in studies employing long ISIs (around 800 ms), a condition in which a rapid selection is not required (Näätänen et al., 1978). Moreover, the early Nd may develop later when to-be-attended and to-be-ignored stimuli are similar because more time is needed in order to reject the to-be-ignored (Alho et al., 1986b; Michie et al., 1993).

Clearly, these opposing views have very different implications for the nature of the processes underlying selective attention and for the outcome of basic sensory analysis. In 1999, when Prof. R. Näätänen was asked to confer the prestigious Award for Distinguished Contributions to Psychophysiology on Prof. S. Hillyard, he spoke amicably of this "quarter-century quarrel": " *The battle [over the nature of the selective-attention effect on the auditory N1] was intense but always fair, and it was never clear which side was going to win as the situation continually evolved. When we in Helsinki believed that at last we were able to deliver* *the final blow, we very soon noticed that we had become the target of an even stronger hit, and so the "missiles" crossed the Atlantic Ocean in both directions several times (...) One day during this fight, the PN dared to show up in Steve's laboratory (...) and we in Helsinki were not able to annihilate the N1 effect of selective attention (...) Now that the fighting has finally stopped and the dust has settled to the ground, we can see that both their N1 effect from 1973 and our PN from 1978 have survived. That is, selective attention can produce both types of effects on the auditory N1, and these effects can even occur in parallel and in good peace.*" (Näätänen, 2000, p. 269-270).

Näätänen and associates still insist that the early Nd heavily reflects the PN, which is elicited under a wide variety of circumstances and therefore serves as a general index of auditory selective attention (Näätänen, Alho, & Schröger, 2002). They do acknowledge, however, that the early Nd may partly reflect the attentional modulation of the auditory N1 under certain circumstances — e.g. fast rate of presentation and large physical differences, circumstances that also facilitate selective attention. Nevertheless, they maintain that selective attention, while possibly leading to a modest but genuine N1 modulation, does not affect the elaboration (quantity and quality) of the basic sensory analysis. This is because: " *(...) the relationship of all these ERP components [BAEPs, MLRs and N1] to sensory information extracted by the auditory system from the stimulus is unclear; these components usually serve only as an index of stimulus detection, not as an index of the accuracy of processing and discrimination of different auditory stimulus features. Fortunately, there is one component in the ERP that is highly informative about the actual processing of unattended input. This component is the mismatch negativity (MMN)*" (Näätänen et al., 2002, p.607). The effects of attention on the MMN will be examined in the subsequent section.

4. The Effects of the Direction and Intensity of Attention on the MMN

In Näätänen's model, the sensory processes leading up to the formation of the stimulus representation are characterized as being strongly automatic. This is because basic sensory analysis is conceived to be performed in an unbiased manner, unaffected by the operation of selective attention mechanisms. Accordingly, the MMN should be independent of the direction and intensity of attention. The ERP findings that originally led Näätänen to this conclusion are detailed in the present section. Subsequently, a review of more recent research that has questioned the validity of this claim is presented. This research has focused on how the direction of attention and the intensity of attention affect the morphology of the MMN. The direction of attention refers to whether the channel in which the MMN-eliciting stimuli occur is attended or ignored. When this critical channel is to-be-ignored, the subject is typically instructed to engage in a task that diverts attention away from the MMN-eliciting stimuli. The intensity of attention refers to the extent to which this diversion task requires attentional resources (i.e. focus). According to Näätänen (1992), a high-load task optimizes selective attention and minimizes attention "wandering" (also referred to as "leakage" by Alain and Woods, 1997) to the to-be-ignored channel. In contrast, during a task that requires sub-maximal focus (i.e., a low load task), selective attention may not be necessary and subjects may potentially attend to both to-be-attended and to-be-ignored stimuli.

4.1. The Early MMN Studies

In the late 1970s and early 1980s, Näätänen and colleagues reported findings from several experiments in which the MMN appeared to be uninfluenced by the direction of attention. In the first of these (Näätänen et al., 1978), subjects were instructed to attend to the stimuli presented in one ear and ignore those presented in the other ear. The stimuli were randomly presented to each ear. These included a frequent standard and, in separate conditions, an infrequent intensity increment or an infrequent frequency increment. The subject's task was to silently count the deviant stimuli occurring in the designated ear. In another condition, the subjects were asked to attend to the channel they had previously ignored and to ignore the channel they had previously attended. Critical to studies of selective attention, the ERPs elicited by physically identical stimuli could then be compared when they were to-be-attended and when they were to-be-ignored. Thus, differences in processing can only be attributed to an endogenous factor, attention, since the physical, exogenous attributes of the stimulus were identical in each condition. In such dichotic listening situations, the requirement of the task (e.g. the counting of the rare target occurrences) also helps to divert attention away from the to-be-ignored channel. Näätänen et al. (1978) reported that the additional negativity generated by the deviants relative to the standard stimulus (Deviance-Related Negativity, DRN)[13] was similar whether subjects attended to the channel in which these stimuli were presented or whether they ignored it. Based on this finding, they concluded that the processes underlying the MMN are "*largely automatic, beyond the control of will, instruction, etc. (...)*" (Näätänen et al., 1978, p. 327).

In a subsequent dichotic listening experiment, Näätänen, Gaillard and Mäntysalo (1980) facilitated selective attention by increasing the separation between attended and ignored channels. The channels could be differentiated not only on the basis of location (ear of delivery) but also on the basis of the frequency of the stimuli. Again, the DRN was not significantly different whether it was elicited by to-be-attended stimuli, or by the same stimuli when they were to-be-ignored. Further support for the attention-independence of MMN came

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[13] As described in Section 3, a deviant stimulus in an otherwise homogenous sequence may elicit additional ERP components or enhanced components relative to the standard stimulus ERP. For example, when the deviant is widely different from the standard, the N1 may be enhanced and contribute to the additional negativity elicited by the deviant relative to the standard (the DRN). Also, when the stimuli are attended, the deviant stimulus typically elicits an N2b in addition to the MMN and both contribute to the DRN. Therefore, under these circumstances (large deviants or attended conditions), one cannot assume that the DRN is solely composed of the MMN. However, when the deviant is very similar to the standard, and these stimuli are to-be-ignored, the DRN is usually only composed of the MMN. Therefore, both the terms DRN and MMN will be employed in this thesis to refer to the additional negativity elicited by the deviant relative to the standard.

from a study by Sams, Alho and Näätänen (1984). In one condition, subjects were instructed to count the rare frequency deviants and, in another, to ignore the auditory stimulation and read a book. The DRNs in both attend and ignore conditions were of equal amplitude during the latency window in which the MMN typically occurs (150-200 ms).

In other studies (Näätänen, Sams, Järvilehto, & Soininen, 1983; Sams et al., 1985) the DRN appeared slightly larger when elicited during attend compared to ignore (reading) conditions. This effect was attributed, however, to an early N2b overlapping the MMN when the stimuli were to-be-attended. In an early review article, Näätänen and Gaillard (1983) clearly outlined the position assumed by Näätänen's group: " *Hence, it is concluded that the MMN occurs independently and unmodified by attentional and perceptual factors (...) When task-related differences in the [DRN] exist, we attribute them to the presence/absence of the N2b. There is of course a serious risk of circularity here (...)*" (Näätänen & Gaillard, 1983, p. 134).

4.2. Divergent Positions: Woldorff et al vs. Näätänen et al

The early studies demonstrating that the MMN could be elicited in the absence of active attention lent considerable support to Näätänen's claim that basic auditory sensory analysis operates independently of attention. This was, of course, based on the assumption that the auditory stimuli could indeed be ignored. Woldorff and Hillyard (1990), however, remarked that in the early experiments of Näätänen and colleagues, attention may not have been very selectively focused. Most of these studies employed a relatively slow rate of stimulus presentation (e.g. ISI over 800 ms in Näätänen et al., 1980; Näätänen et al., 1978; Sams et al., 1984), which is generally not conducive for selective attention. Furthermore, Woldorff, Hackley and Hillyard (1991) suggested that the reading task employed by Sams et al. to divert attention from the auditory stimuli did not require sufficient focused attention.

Hence, according to these authors, these experiments did not serve as a strong test of the independence of the MMN from attentional influences.

4.2.1. The Woldorff et al. (1991) Study

Woldorff et al. (1991) employed a dichotic listening task similar to that used by Näätänen et al. (1980). They facilitated the rapid and early selection of stimuli by distinguishing to-be-attended from to be-ignored channels on the basis of obvious location and pitch cues. In addition, Woldorff et al. (1991) also optimized selective focusing of attention by presenting the stimuli at very rapid and variable rates, as well as by making the target discrimination task relatively difficult (hit rate of 70 - 80%). Subjects were required to detect (by button-pressing) an infrequent small intensity decrement in the designated ear. Under these conditions, the amplitude of the DRN elicited by the unattended stimuli was substantially smaller compared to the DRN elicited by the attended stimuli. In fact, the amplitude of MMN in the unattended condition was not larger than the zero baseline level. The authors insisted that the difference between the DRN evoked in attended and ignored channels could not simply be explained by the contribution of an overlapping N2b. They pointed out that the MMNs obtained in previous studies to similar unattended stimuli were much larger than those obtained in their study. This difference would unlikely be due to an N2b, as this component is attention-dependent. Woldorff et al. concluded that under conditions of highly-focused attention, processing in the unattended channel is degraded or gated very early in sensory processing[14]. "*The modulation of the MMN observed here suggests that the processes of auditory feature analysis and mismatch detection (and their electrophysiological index, the MMN) may be*

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[14] Differences between attended and ignored channel ERPs started as early as 20 ms (P20-50 wave) following stimulus onset, suggesting that auditory information processing is influenced by attention before the time of elicitation of the MMN (100-200 ms). Both the P20-50 and the N1 were larger when elicited by attend-channel stimuli compared to ignored-channel stimuli.

"weakly automatic", not requiring attention for their occurrence but subject to attenuation when attention is strongly focused on another input channel." (Woldorff et al., 1991, p.41).

4.2.2. Näätänen's Reply

In a commentary to Woldorff et al., Näätänen (1991) argued that most of the attentional effect reported by these authors was almost certainly due to an enhancement (N2b) in the attended channel rather than a strict attenuation of the MMN in the unattended channel. This suggestion was made based on the considerably larger DRN in the attended condition at central (where N2b is usually maximal) than frontal (where MMN is usually maximal) electrode sites. Näätänen nevertheless conceded that the MMN may indeed have been somewhat attenuated by attention being strongly focused on another auditory channel, but that this attentional reduction was substantially more modest than claimed by Woldorff et al. (1991). This acknowledgement was made primarily because Näätänen's own research group had at the time replicated this attentional suppression of the MMN to intensity deviants. This finding was discussed in the commentary to Woldorff et al. and later published in a separate empirical article (Näätänen et al., 1993b).

The Näätänen et al. (1993b) study also promoted rapid stimulus selection through the use of a large channel separation (location and distinct pitch cues), a fast rate of stimulus presentation and a difficult target detection task. The auditory stimulus sequence presented in each channel included a standard stimulus, a small frequency deviant and a small intensity deviant. In one condition, subjects were instructed to attend to the input delivered to a designated ear and count the designated deviant feature. The input to the opposite ear was to-be-ignored. In another condition, subjects were instructed to ignore the auditory stimuli and read a book. The DRNs elicited by the small frequency and intensity deviants were largest when these stimuli were delivered to the attended ear (whether they were designated as a target or not) and significantly smaller when they were delivered to the unattended ear. Näätänen et al. (1993b) insisted that the main component of the DRN modulated by the direction of attention was the N2b based on the timing and scalp distribution of this enhancement.

Perhaps the more important finding in this study was uncovered from a comparison between the two unattended conditions, that is, when subjects' attention was diverted away from the to-be-ignored channel by the reading task compared to when subjects ignored stimuli occurring in one ear during the dichotic listening task (and counted targets occurring in the opposite ear). These will be described as the ignore-reading and the ignore-counting conditions, respectively. The frequency and intensity MMNs were found to be larger in the ignore-reading relative to the ignore-counting condition, although this difference failed to reach significance for the frequency MMN. As the authors pointed out, an N2b overlap cannot easily explain the larger MMN during the ignore-reading task. The N2b is not typically elicited in unattended conditions, unless stimulus deviance is very wide. In this study, the extent of both frequency and intensity deviance was quite small. On the basis of this evidence, the authors conceded that, as had been previously suggested by Woldorff et al, the amplitude of the MMN might indeed be attenuated under conditions of strongly-focused attention. Presumably, attention was very strongly focused on the input delivered to the opposite ear in the ignore-counting condition whereas attention was less intensively focused on the reading during the ignore-reading condition.

Where the positions taken by Woldorff et al. and Näätänen et al. diverge is in the interpretation of this attention-related effect, each interpretation having very different theoretical implications in terms of the automaticity of basic sensory processing. As previously stated, Woldorff et al. concluded that their data provided evidence that the processing of stimuli can be attenuated or gated at an early sensory level when attention is highly focused elsewhere. Näätänen et al. however disagreed, pointing to the small but significant frequency MMN elicited in the ignore-counting condition, under conditions of highly-focused attention.

They argued that if an MMN, even a much attenuated one, were elicited under such conditions then a well-formed representation of the standard and of the incoming deviant stimulus must have been present within sensory memory. In order for these representations to emerge, prior sensory processing (feature analysis, encoding and integration) must have been completed. According to this view, the mere elicitation of the MMN implies an accurate sensory processing of the to-be-ignored stimuli[15]. Näätänen et al. further hypothesized that the signal generated by the MMN "computational" process (the deviance detection process) is subsequently amplified. It is probably this MMN "activational" process (the amplification process) that is affected by attentional demands. "*In this case, sensory information would be fully processed even in the absence of attention, whereas the assumed alarming, attention-switching function of the MMN system might be dampened because of the attenuated amplification of the mismatch signal generated by the computational system*" (Näätänen et al., 1993b, p.447-448).

4.2.3. The Woldorff et al. (1998) Study

The purpose of this second Woldorff et al. study (Woldorff et al., 1998) was to further examine the assertion made by Näätänen et al. (1993b) that the major component being modulated by the direction of attention was not actually the MMN but rather the N2b. The experimental design was similar to that employed by Woldorff et al. (1991). The attended channel was distinguished from the unattended channel by location and pitch cues. Again, stimuli were presented very rapidly. Subjects were to detect (by button-pressing) small intensity decrements in the designated ear and ignored tones delivered to the other ear. In this study, both electrical (EEG) and magnetic (MEG) activity was recorded in order to determine

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[15] A non-significant MMN was obtained to the intensity deviants in the ignore-counting condition. Näätänen et al. however downplay this finding. " it *would be very hard – and unparsimonious – to explain how the basic sensory processing, that leading to the development of initial stimulus representations of one [frequency] but not of another [intensity] basic attribute of the same auditory stimulus could be modulated by attention (and at the same time).*" (Näätänen et al., 1993b, p.449).

the neural sources of the attention-sensitive DRN. A major advantage of the MEG technique is that it reflects cortical activity better than the EEG, which is also sensitive to more distant far-field sources. Furthermore, whereas the EEG is sensitive to dipoles that have either a tangential or a radial orientation, the MEG is not sensitive to radial sources. Näätänen (1990) suggested that the N2b may not be well registered by the magnetic recordings because it presumably reflects the activity of a radially oriented source. The ERP results of the Woldorff et al. (1998) study were in accordance with the findings of Näätänen et al. (1993b) and Woldorff et al. (1991). The DRN to unattended intensity deviants was substantially attenuated compared to that elicited to attended intensity deviants. The magnetic DRN was similarly modulated by the direction of attention. Importantly, the attention-sensitive component of the magnetic DRN had neural sources localized near the superior temporal plane in the auditory cortex, that is, in the vicinity of the primary MMN neural generators. The authors suggested that these MEG findings provide support for the proposal that the auditory MMN generator itself can be influenced by attention. These results strengthened their belief that the early sensory processing leading up to and including mismatch detection is gated when strongly-focused attention is required in a different channel. As for the alternative interpretation put forward by Näätänen et al. (1993b), the authors offered the following comments: "*These proposals of Näätänen and associates, which would sustain the concept of strong automaticity of sensory mismatch analyses and MMN generation, seem debatable on several grounds. First, it seems circular to argue that an equality of MMN amplitude in attended and unattended channels constitutes evidence for a strong automaticity of the sensory and computational analyses (e.g., Näätänen, 1992), whereas a greatly reduced MMN to unattended-channel deviants – even to the point of nonsignificance – does not weigh against such automaticity but rather is attributed to an attention effect on a separate amplification process (e.g., Näätänen et al., 1993). Following this line of reasoning, it is not clear what kind of electrophysiological evidence would be* *required to disconfirm the concept of strongly automatic sensory analysis. In fact, this two-stage amplification/computational model seems very difficult to test experimentally unless clear operation definitions were formulated for the hypothesized amplification and computation systems and a linkage established between those systems and separate subcomponents of the MMN (...)*" (Woldorff et al., 1998, p. 289-290).

4.2.4. Summary

The position taken by Woldorff and colleagues regarding the DRN modulation with the direction of attention is that this effect can be attributed to a genuine MMN difference. From this, they conclude that the sensory information used in the MMN generation is degraded when subjects' attention is strongly focused away from the eliciting stimuli. Näätänen's group, on the other hand, insists that the larger DRN in the attended compared to the unattended condition is due to the elicitation of an additional negative wave, the N2b. This alternative explanation for the attention-sensitive DRN is not incongruent with Näätänen's proposal that the processes leading up to the MMN elicitation are performed in an unbiased fashion, independent of task. Nevertheless, based on the DRN modulation with variations in the intensity of attention, Näätänen et al. conceded that the MMN amplitude may be larger when subjects are sub-maximally focused compared to when they are strongly focused away from the eliciting stimuli. They attribute this effect to the operations of the MMN generator process itself (its amplifying system). As such, the quality and quantity of sensory information arriving at the MMN generator is unchanged by the nature of the task; only the output of the generator process may vary depending on the availability of attentional resources. In other words, according to Näätänen and colleagues, the threshold of MMN elicitation is unaffected by task demands whereas the amplification of the MMN may, under highly focused attention, be affected. Unfortunately, it is not at all clear how the operations of the computational and amplification systems can be distinguished on the basis of scalp recordings. Näätänen's group has, to date, not further elaborated on this issue.

4.3. Review of MMN Studies on the Direction and Intensity of Attention

Many other research groups have joined the debate surrounding the effects of attention on the MMN. These studies examined the modulation of the MMN with the direction and/or the intensity of attention. This subsection reviews the findings from these studies.

4.3.1. Direction of Attention

As mentioned, the studies on the direction of attention contrast a condition in which the MMN-eliciting stimuli are attended (whether these stimuli are targets or non-targets) with a condition in which the same MMN-eliciting stimuli are "ignored". When the MMN-eliciting stimuli are to-be-ignored, the attended channel may be auditory or visual, that is the task may require intramodal or intermodal selection, respectively.

The studies of *intramodal* selective attention have generally distinguished attended and unattended auditory channels on the basis of obvious physical cues, most notably location (Alain & Woods, 1997; Alho, Woods, & Algazi, 1994; Arnott & Alain, 2002; Näätänen et al., 1993b; Paavilainen, Tiitinen, Alho, & Näätänen, 1993; Szymanski, Yund, & Woods, 1999; Woldorff et al., 1998; Woldorff et al., 1991). Other studies have differentiated the attended and unattended auditory channels by presenting multiple frequency streams (Alain & Woods, 1994) or a mixture of narrative and tone bursts (Trejo, Ryan-Jones, & Kramer, 1995). Regardless of the feature distinguishing attended and unattended channels, most studies have observed that the DRN elicited in the attended auditory channel is larger than that of the unattended auditory channel (however, see Alho et al., 1994 for non-significant results).

Studies of *intermodal* selective attention differentiate between attended and unattended channels on the basis of stimulus modality. Thus, when the MMN-eliciting auditory stimuli are to-be-ignored, subjects might engage in some visual distraction task such as, for example, reading (Alain & Woods, 1997; Gomes et al., 2000; Näätänen et al., 1993b; Paavilainen et al., 1993; Schröger, 1995), a visual discrimination task (Alho et al., 1994; Alho, Woods, Algazi, & Näätänen, 1992; Dittmann-Balcar, Thienel, & Schall, 1999; Woods, Alho, & Algazi, 1992) or a video game (Gomes et al., 2000; Kramer, Trejo, & Humphrey, 1995; Woods et al., 1992). Again, most of these studies have shown that the DRN is modulated by attention; the DRN is larger when subjects attend the eliciting auditory stimuli compared to when they engage in a visual distraction task (however, see Alho et al., 1994 and Gomes et al., 2000[16] for non-significant results and Dittmann-Balcar et al., 1999[17] for contradictory results). Finally, a study by Oades & Dittmann-Balcar (1995) contrasted a condition in which subjects were to attend to the MMN-eliciting stimuli with a condition in which subjects simply sat passively (non-task condition) and ignored these same stimuli. Results from this study are in agreement with those generally reported by the intramodal and intermodal studies.

The effect of the direction of attention on the DRN is thus quite robust. In addition to the diversity of auditory and visual diversion tasks employed by these studies, the attention effect has also survived a large variety of deviant stimulus features. These have included a frequency change (Alho et al., 1992; Kramer et al., 1995; Näätänen et al., 1993b; Oades & Dittmann-Balcar, 1995; Paavilainen et al., 1993; Trejo et al., 1995; Woods et al., 1992), an intensity change (Alain & Woods, 1997; Näätänen et al., 1993b; Szymanski et al., 1999; Woldorff et al., 1998; Woldorff et al., 1991), a duration change (Alain & Woods, 1994; Arnott & Alain, 2002), and more complex changes such as a pattern deviant(Alain & Woods, 1997), a

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[16] While Gomes et al. did not obtain significant DRN difference between attended and ignored conditions with adults, they did report that the attention effect was significant for children when employing a very small frequency change.

[17] In this study, there was a trend toward a smaller MMN when subjects attended the eliciting stimuli compared to when they ignored them and engaged in a visual diversion. Subjects were however required to complete the visual discrimination tasks prior to engaging in the auditory discrimination tasks. There is evidence that the amplitude of the MMN may significantly decrease over the recording period (Gomes et al., 2000; Lang et al., 1995). Hence, the lack of randomization of the visual and auditory conditions may have confounded the attention effect found in this experiment.

two-dimensional deviant (Schröger, 1995) and a phoneme deviant (Szymanski et al., 1999). Furthermore, stimulus presentation rates have ranged from less than every 200 ms (Woldorff et al., 1991) to more than every 1200 ms (Oades & Dittmann-Balcar, 1995). Finally, the attention effect has been demonstrated whether the attended deviants were designated as targets or non-targets.

As previously discussed, the significance of the DRN differences has been much debated (Näätänen et al., 1993b; Woldorff et al., 1998). The results of studies on the direction of attention are therefore often interpreted with considerable caution. Several researchers maintain that the DRN modulation cannot be entirely explained by an overlap with the N2b, basing their claim on the timing and topography of this additional negativity. The onset of the attention effect was visible at an early latency (Alain & Woods, 1997; Alain & Woods, 1994; Gomes et al., 2000; Szymanski et al., 1999) and a similar attention effect was observed at the mastoids (Alain & Woods, 1997; Gomes et al., 2000; Schröger, 1995), where the MMN inverts in polarity. Furthermore, as Gomes et al. (2000) pointed out: "*if N2b was responsible for the increased amplitude of the MMN, the effect should be greater for the easy [larger] deviant than for the hard [smaller], given the better detection of easy than hard deviants*" (Gomes et al., 2000, p.814). Indeed, several studies have demonstrated that the attentional effect on the DRN is limited to that elicited by deviant stimuli closely resembling standard stimuli, that is when deviance is small (Alho et al., 1992; Gomes et al., 2000; Woods et al., 1992).

The studies reviewed above have not indisputably established, however, that the direction of attention significantly affects the MMN. This would require a means of clearly dissociating the contribution of the MMN and N2b to the DRN. Nevertheless, they certainly "*throw into question the view that the MMN represents an automatic process…*" (Alain & Woods, 1994, p.513).

4.3.2. Intensity of Attention

The N2b overlap and summation with the MMN remains a major obstacle to the understanding of the effects of attention. Any comparison of attend and ignore conditions will be confounded by the fact that attention to an auditory channel results in the elicitation of the N2b. Studies that have examined the effects of the intensity of attention have taken a different approach. They avoid having the subjects attend to the auditory channel in which the MMN-eliciting stimuli are presented. Instead, two or more diversion tasks are employed, one of which is presumed to demand a greater focusing of attention to successfully complete. The more difficult task thus requires more stringent selective attention. In contrast, during an easier task, selective attention may not be necessary, possibly allowing for the subject to sample and process the task-irrelevant auditory stimuli. In this way, any DRN modulation with attentional demands cannot be attributed to the N2b process because attention is never directed to the auditory channel in which the MMN-eliciting stimuli are presented.

A first group of studies, including the previously described Näätänen et al. (1993b) study, have investigated whether the early processing of unattended auditory stimuli differed between conditions of attention to an auditory channel and attention to a visual channel (Alain & Woods, 1997; Alho et al., 1994; Paavilainen et al., 1993). These studies will thus be described as auditory-visual diversion studies. A second group of studies have compared unattended auditory processing while subjects engaged in visual tasks that varied in nature and/or level of difficulty (Alho et al., 1992; Dittmann-Balcar et al., 1999; Harmony et al., 2000; Kathmann, Frodl-Bauch, & Hegerl, 1999; Kramer et al., 1995; Otten, Alain, & Picton, 2000). These will thus be described as visual-visual diversion studies.

4.3.2.1. Auditory-Visual Diversion Studies

In this group of studies, subjects are asked to ignore the MMN-eliciting stimuli while, in separate conditions, engaging in either an auditory or a visual diversion task. Alain and Woods (1997) examined attention effects on the MMN elicited by changes in an auditory pattern. The auditory pattern consisted of two tones regularly alternating in frequency. Occasionally, the low or high frequency tone was repeated, breaking the alternating pattern. Subjects discriminated these pattern deviants in the designated ear while ignoring the similar tone sequence in the opposite ear. In a separate condition, they were instructed to ignore the auditory stimuli while reading a book. Similarly to the results reported by Näätänen et al. (1993b), the MMN elicited during the reading condition was significantly larger than that elicited in the unattended ear during the auditory discrimination task. This attention effect began as early as 120 to160 ms but was not visible at the mastoid sites. Alain and Woods speculated that this attention effect "*may be explained by assuming that there was more "leakage" of participant's attention toward the irrelevant auditory stimuli during reading than during the active listening task (i.e., the larger MMN amplitude during reading resulted partly from attentive processing of the patterns). Alternatively, the small MMN observed in the unattended ear condition may reflect an active inhibition of unwanted auditory input.*" (Alain & Woods, 1997, p.539).

Interestingly, in a second experiment conducted by Alain and Woods (1997) no significant differences were found when comparing the MMN elicited by unattended stimuli during the dichotic listening task and the reading task. The tone sequences presented in this second experiment were similar to those used in the previous one. The stimuli, however, were presented more rapidly. Also, the intensity of the stimuli was lowered by 10 dB. The authors noted that the MMN to pattern-deviant stimuli was smaller during the reading condition in Exp. 2 when compared to Exp. 1. They suggested that the changes to the stimulus parameters (for example, softer stimuli) may have made the auditory stimuli easier to ignore during reading in Exp. 2.

Alho et al. (1994) and Paavilainen et al. (1993) also contrasted unattended auditory processing during a dichotic listening task with that accomplished during a visual task. In both studies, frequency deviants were presented among standard stimuli at rapid rates. During the visual task, subjects were asked to detect an infrequent visual target (Alho et al., 1994) or read a book (Paavilainen et al., 1993). Results showed that the MMN elicited by to-be-ignored stimuli during the auditory discrimination task was similar to that elicited by the same deviant stimuli during the visual distraction task.

4.3.2.2. Visual-Visual Diversion Studies

In these studies, subjects are instructed to ignore the MMN-eliciting stimuli and, in separate conditions, engage in visual tasks that vary in nature and/or difficulty. Task load can be manipulated either by *qualitatively* changing the nature of the processing demands or by varying *quantitative* demands placed on processing associated with the task (Handy, 2000). An assumption is made concerning the extent of selective attention required to successfully complete each task. When possible, this assumption is supported by behavioural measures of task performance.

The Alho et al. (1992) study was the first to systematically examine the influence of visual processing load on the MMN elicited by to-be-ignored stimuli. They achieved this by manipulating the discriminability of the visual targets, which were either made slightly or markedly shorter than a standard vertical grating. In separate conditions, subjects were to detect the large or small visual deviants while ignoring the auditory stimuli. The hit rates were approximately 0.8 and 0.6 for the easy and difficult tasks, respectively. The auditory stimuli, including a standard 1000 Hz tone and two deviant tones (1050 Hz and 1500 Hz), was presented at rates between 200 and 400 ms. The MMNs elicited by both the large and small frequency deviants, however, were unaffected by variations in the difficulty of the visual task. The authors suggested that these results are at odds with the notion that the MMN requires covert attention to the eliciting stimuli, as the subjects' resources were presumably fully consumed during the difficult visual discrimination task. Dittmann-Balcar et al. (1999)

similarly examined the effects of task difficulty on the MMN. Subjects were asked to ignore the auditory stimuli and discriminate the smaller target circle infrequently presented among the larger standard circle. In separate conditions, this discrimination was easy, medium and difficult, more specifically, the target circle was 70%, 85% or 92% of the standard circle size. Hit rates for these tasks were not reported. A standard 100 ms-tone and the deviant 50 ms-tone were presented slowly, with an ISI of 1000 ms. In accordance with the results of Alho et al. (1992), the MMN to the duration change did not significantly vary with task difficulty.

Otten et al. (2000) postulated that a simple visual target detection task, as employed by Alho et al. (1992) and Dittmann-Balcar et al. (1999), may not have been sufficiently taxing to interfere with the processing of task-irrelevant auditory stimuli. Subjects may have been able to divert attention to the auditory stimuli in between the presentation of the visual stimuli, particularly in the Dittmann-Balcar et al. study in which visual stimuli were presented quite slowly. In addition to an easy visual categorization task, Otten et al. (2000) therefore employed a more demanding task requiring the visual information to be continuously maintained in working memory. The visual stimuli were digits between 1 and 9 presented in red or green color. During the easy task, the color of the digits was incidental and subjects were instructed to categorize each stimulus as being above or below 5. The hit rate of 0.95 reflected the ease of this task. During the difficult task, the color of the digit determined if subjects were to categorize the current or the immediately preceding digit as being above or below 5. This task therefore required subjects to hold the last presented digit in memory. The hit rate was 0.83 for trials that required the preceding digit to be categorized and 0.93 for those requiring categorization of the current digit. The to-be-ignored irrelevant auditory stimulus sequence was composed of standard 1000 Hz tones and deviant 1250 Hz tones. The auditory stimuli were presented, in separate conditions, at ISIs of 500 and 1500 ms. At fronto-central sites, the MMN was not reliably affected by the demands of the visual task. Based on this finding, the authors suggested that the degree to which attention is paid to the visual domain probably does not have an effect on the pre-conscious detection of acoustic change.

Another study that examined the processing of unattended tones during a more complex visual diversion task was conducted by Kramer et al. (1995). Subjects were asked to perform a radar-monitoring task that involved the detection and appropriate response to various hostile and friendly targets. This task consisted of periods that were judged to be low and high in processing demands. The task-irrelevant auditory sequence was composed of a standard 1500 Hz tone and two large frequency deviants (1000 and 2000 Hz). These auditory stimuli were presented with an ISI of 700 ms and were mixed with communication and radar sounds. In contrast to Otten et al., the amplitude of the MMN significantly decreased with the increase in demands of the radar-monitoring task. This result led Kramer et al. to propose that: "*the effectiveness of the MMN generator was sensitive to the availability of attention or processing resources. As additional resources were required for the radar-monitoring task, fewer resources were available for the operation of the MMN generator, thereby resulting in a reduction of its effectiveness (...) attentional resources which are not being used in the service of the primary task are re-directed, in a stimulus-driven or bottom-up fashion, to the processing of the [task-irrelevant auditory stimuli]*" (Kramer et al., 1995, p.97-98).

Finally, studies by Kathmann et al. (1999) and Harmony et al. (2000) compared the MMN elicited by unattended stimuli during different tasks that presumably required greater or lesser focus to complete. In the Kathmann et al. (1999) study, subjects were instructed to ignore all auditory stimuli and were assigned to one of two task conditions. One group of subjects was asked to perform a simple visual target detection task. They were required to count the number of occasional vertical gratings presented among the standard horizontal gratings. This task was quite easy, as evidenced by a 0.95 correct detection rate. The other group was asked to sit passively, having no cognitive task to perform. "*The first condition is* *expected to force the subjects to actively ignore the auditory stimuli relevant for the MMN generation, the latter one may allow for some attention allocation to the tones without actively discriminating them*" (Kathmann et al., 1999, p.318). The to-be-ignored auditory stimuli, presented with ISI of 500 ms., consisted of a standard tone (800 Hz , 50 ms), a frequency deviant (880 Hz) and a duration deviant (100 ms). No differences in MMN following either deviant were reported between the two task groups. The authors concluded that the MMN to frequency and duration changes is not significantly influenced by the withdrawal of attentional resources. A similar conclusion was drawn by Harmony et al. (2000), employing a small frequency deviant. In this study, subjects were involved in two different tasks that were presumed to vary in terms of attentional demands. For the easy task, a stimulus AAAAA was presented and subjects were asked to verbally respond "A" within the 8 s following stimulus onset. During the difficult task, the stimulus also consisted of 5 uppercase letters; these letters when reordered formed a word. Subjects were instructed to decode and verbalize this word within 8 s following stimulus onset. The to-be-ignored auditory standard (1000 Hz) and deviant (1050 Hz) were presented with an ISI varying from 550 to700 ms. There were no task effects on the MMN in the 100-150 ms latency range.

4.3.2.3. Conclusion

The studies of the intensity of attention, while generally avoiding the problem of the N2b overlap, have certainly not been successful in demonstrating a robust effect of attention on the MMN. The Näätänen et al. (1993b) study reported a significant effect of the intensity of attention on the MMN to a small intensity change but not to a small frequency change. Based on this, it was suggested that the *intensity* MMN may be more susceptible to the effects of attention. Curiously, the studies of the intensity of attention have almost exclusively employed small (Alho et al., 1994; Alho et al., 1992; Harmony et al., 2000; Kathmann et al., 1999; Paavilainen et al., 1993) or large (Alho et al., 1994; Alho et al., 1992; Kramer et al., 1995;

Otten et al., 2000) *frequency* deviants. The lack of an attention effect in these studies may further be due to an insufficiently wide difference between the demands imposed by the easy and difficult tasks. For example, in the Kathmann et al. (1999) and Otten et al. (2000) studies, both "easy" and "difficult" tasks were easily completed, as evidenced by hit rates between 0.83 and 0.95 in the difficult condition. In contrast, in the Alho et al. (1992) study, "easy" and "difficult" tasks were difficult to complete, both tasks having hit rates below 0.8. It is quite possible that a wider range in task difficulty would be required in order to elicit measurable differences in the MMN. Clearly, the question concerning the effect of the intensity of attention on the MMN has not yet been fully addressed.

5. The Present Thesis

"*Although the MMN is most often recorded when participants pay attention to visual information and ignore the auditory stimuli, the effects of visual attention on the MMN have received scant emphasis*." (Otten et al., 2000, p.875). The primary focus of interest in the present thesis is the extent of processing of unattended auditory inputs, as indexed by the MMN, with variations in visual task demands. Although Näätänen's model postulates that the processing leading up to the MMN is task-independent, recent findings have put into question the veracity of this claim. Näätänen's own results have suggested that an increase in the focus required by the distraction task will result in a decrease in the resources available for the processing of the task-irrelevant auditory stimuli, as evidenced by an attenuated MMN (Näätänen et al., 1993b). The degree to which the task-irrelevant auditory stimuli are processed may therefore depend, already at an early stage, on the degree to which attentional resources are available beyond those necessary for processing task-relevant stimuli.

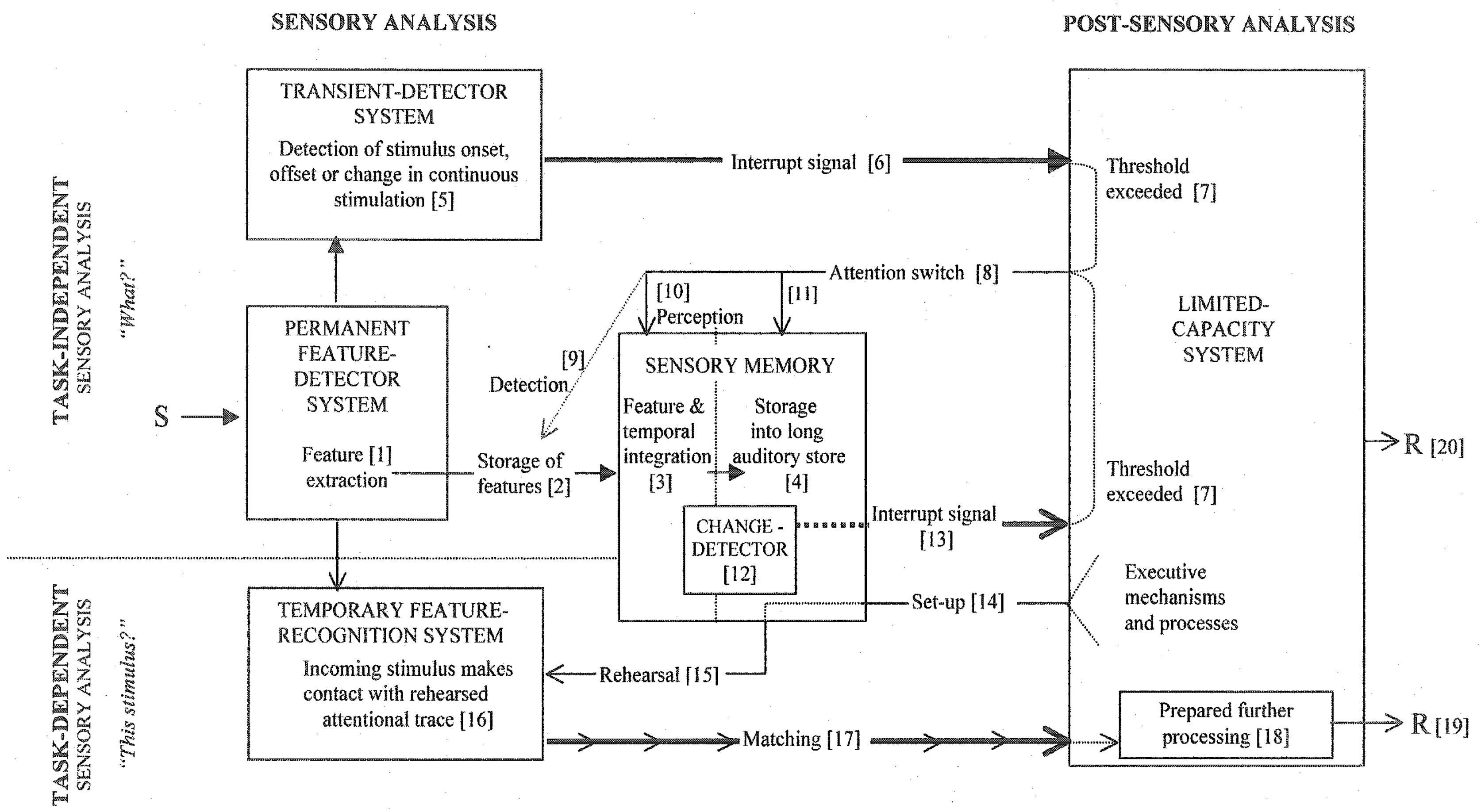
The thesis consists of four experiments. In Experiments 1 and 2, the effects of the diversion task on the MMN are addressed from a methodological standpoint. In most MMN studies, subjects are asked to engage in a visual diversion task. The nature of this task is, according to Näätänen's model and most MMN researchers, considered incidental and therefore the task is rarely well defined. At times, the subjects may even be asked to select their choice of diversion task or may not be required to perform any specific cognitive task. This approach would only be reasonable if the MMN were indeed independent of task demands. However, as suggested by some of the findings presented here, a task requiring a greater need for selective attention may lead to a smaller MMN. The first two experiments examine the effect of commonly-employed diversion tasks on the MMN to small changes in frequency (Experiment 1) and intensity (Experiment 2). In these experiments, subjects were not required to make an overt behavioural response. This is consistent with the large majority of MMN studies. A limitation of these experiments is that the absence of an independent measure of performance does not allow for quantification of task demands. This limitation is overcome in Experiments 3 and 4, in which a visual discrimination task is employed. Subjects are asked to overtly respond to infrequent changes in the visual stimulus, yielding the critical independent performance data.

In addition, in Experiments 3 and 4 the effect of visual attention on the MMN is more rigorously tested, by maximizing the likelihood of finding an effect of task demands. First, the need for selective attention is optimized by presenting both auditory and visual stimuli at rapid rates. Second, in contrast to previous studies, Experiments 3 and 4 were designed to assure a *large* separation in terms of performance between the "easy" and "difficult" tasks. As such, the "difficult" task was expected to maximally tax subjects' resources and required stringent selective attention. In contrast, during the "easy" task, when attention need not be as strongly focused, selective attention may not be necessary. Finally, we examined the effect of visual attention load on the MMN to both a *frequency* and *intensity* change. The effect of visual processing load on the MMN elicited by intensity deviants has not been examined. This is surprising in light of the common and long-held belief that "*unlike the frequency MMN, the MMN for intensity change is clearly prone to attentional influences*" (Schröger, 1997, p.254).

The notion that the MMN to an intensity change is more susceptible to the effects of attention is primarily based on the results reported in Näätänen et al. (1993b). These authors nevertheless cautioned that "*because the intensity deviants were markedly more difficult to detect than were the frequency deviants, the deviant attribute and discriminability were confounded*" (Näätänen et al., 1993b, p.441). This issue is also addressed in the present thesis. In Experiment 3, the standard, the frequency deviant and the intensity deviant are identical to those presented in Näätänen et al. (1993b). In Experiment 4, the discriminability between standard and deviant is enhanced for the intensity deviant and reduced for the frequency deviant.

The issue of the attentional modulation of the MMN is of great theoretical importance. The MMN serves as a probe of the accuracy of the stimulus representation on which the MMN generation depends. If the MMN were found to be affected by attentional demands, then the most parsimonious conclusion would be that mechanisms of attentional selection act very early on auditory processing, prior to the formation of the stimulus representation. This conclusion would obviously be at odds with Näätänen's theory of task-independent auditory processing, as well as other late-selection theories. Furthermore, the issue of the attentional modulation of the MMN is also of practical importance, in view of the increasing use of the MMN in clinical applications (Näätänen, 2003). "*(...) in many cases the patient cannot, or will not, be fully cooperative, making the control of his/her attention impossible. Only an attention-independent physiological measure could, in principle, serve as a pure index of the quantity and quality of sensory information contained by central-level sound representations*" (Näätänen & Alho, 1997, p.342)

Adaptation of Näätänen's 1990 Model of Auditory Processing



CHAPTER 2

"...and were instructed to read a self-selected book while ignoring the auditory stimuli": THE EFFECTS OF TASK DEMANDS ON THE MISMATCH NEGATIVITY

1. Introduction

The MMN has proven to be an exquisitely sensitive index of the perceptual detection of change (Näätänen, 1992). It is usually elicited by rare changes in the physical properties of repetitive auditory stimuli. The MMN is believed to reflect the outcome of a sensory memory comparison involving the well-formed representation of the frequently occurring standard stimulus and that of the incoming deviant stimulus (Novak et al., 1990). According to this view, the MMN can serve to probe the accuracy of the stimulus representations on which the generation of the MMN depends. A central feature of the MMN is that it may be evoked whether or not subjects attend to the auditory stimulation. Importantly, in Näätänen's model of auditory processing (Näätänen, 1990; Näätänen, 1992), attention does not affect the basic sensory processing leading to the generation of the MMN. As such, the quality and quantity of sensory information included in the stimulus representation is independent of the requirements of the task. The model further suggests that attention to the MMN-eliciting stimuli only affects the likelihood that these stimuli will be consciously perceived. In contrast to this view, gain theories propose that the processing leading up to the MMN may be facilitated by directing attention to these stimuli and inhibited by directing attention to a demanding task in a different channel (Woldorff et al., 1987; Woods, 1990).

In the classical MMN paradigm, the subjects are asked to read a book while ignoring the auditory stimuli. The purpose of the reading task is to ensure that the subject's attention is diverted away from the MMN-eliciting stimuli. Attention to these stimuli causes other deviant-related ERP components to be elicited, most notably a later negative wave, the N2b, and a parietal positivity, the P3b. The N2b may overlap both temporally and spatially with the MMN, making the MMN difficult to discern. There are many variations of the reading paradigm and the attentional demands required by each of these may well differ. According to Näätänen's model and to many MMN researchers, the extent of engagement in the diversion task during MMN recording is incidental. Consequently, the subject's task is not often clearly defined. At times, the subjects may even be asked to select their choice of diversion task. Furthermore, verification that the subject actually engaged in the diversion task is not often performed. This approach would be reasonable if the MMN were indeed independent of task demands.

The extent to which the processes leading to the generation of the MMN are task-independent remains unclear. Several studies have examined this issue through a manipulation of the direction of attention, that is, by making the channel in which the MMN-eliciting stimuli are presented both task-relevant and task-irrelevant. In these studies, the MMN often appears to be larger when subjects attend to the auditory stimuli compared to when they ignore them. Such an effect has been demonstrated with changes in frequency (Alho et al., 1992; Kramer et al., 1995; Näätänen et al., 1993b; Oades & Dittmann-Balcar, 1995; Paavilainen et al., 1993; Trejo et al., 1995; Woods et al., 1992), intensity (Alain & Woods, 1997; Näätänen et al., 1993b; Szymanski et al., 1999; Woldorff et al., 1998; Woldorff et al., 1991), duration (Alain & Woods, 1994; Arnott & Alain, 2002), and more complex changes such as a two-dimensional deviant (Schröger, 1995), a pattern deviant (Alain & Woods, 1997) and a phoneme deviant (Szymanski et al., 1999). However, the N2b overlap and summation with the MMN when the channel is designated as task-relevant remains a major obstacle to understanding the effects of task demands in these studies.

An alternate approach to studying the task-related effects on the processes leading to MMN elicitation has been to vary the nature and/or difficulty of the diversion task during passive MMN recording. In this way, the N2b process is less likely to contaminate the MMN results because attention is not actively directed to the auditory channel in which the MMN-eliciting stimuli are presented. Typically, in these studies, one diversion task will be assumed to require more strongly-focused attention than another. When a task is very demanding, attentional selection of relevant over irrelevant stimuli is necessary in order to maintain performance. In contrast, when a task requires sub-maximal focus, it is possible that attention may wander to the to-be-ignored auditory channel.

In some studies, performance on the diversion task has been used as an index of the attentional demands of the task (Alho et al., 1992; Dittmann-Balcar et al., 1999; Kramer et al., 1995; Otten et al., 2000). When the task is difficult (usually reflected in poor performance), it is assumed that the subject must be more attentive to the task than when the task is easier. Alho et al. (1992) were the first to systematically examine the influence of visual processing load on the MMN elicited by to-be-ignored stimuli. They achieved this by manipulating the discriminability of visual targets from visual standard stimuli. The MMNs elicited by both a large and a small frequency deviant were unaffected, however, by variations in the difficulty of the visual task. Dittmann-Balcar et al. (1999) similarly examined the effects of visual task difficulty on the passively-elicited MMN. In accordance with the results of Alho et al. (1992), the MMN to a duration change did not significantly vary with task difficulty. Otten et al. (2000) postulated that a simple visual target detection task, as employed by Alho et al. (1992) and Dittmann-Balcar et al. (1999), may not have been sufficiently taxing to interfere with the processing of task-irrelevant auditory stimuli. Subjects may have been able to divert attention to the auditory stimuli in between the presentation of the visual stimuli. In addition to an easy visual categorization task, Otten et al. therefore employed a more demanding task requiring the visual information to be continuously maintained in working memory. Again, the MMN to a large frequency change was not reliably affected by the demands of the visual task. Kramer et al. (1995), however, did find an effect of task demands on the MMN. Subjects were asked to perform a radar-monitoring task that included periods judged low and high in processing demands. The amplitude of the MMN to the large frequency deviants significantly decreased with an increase in demands of the radar-monitoring task. This result led Kramer et al. to propose that: "*the effectiveness of the MMN generator was sensitive to the availability of attention or processing resources. As additional resources were required for the radar-monitoring task, fewer resources were available for the operation of the MMN generator, thereby resulting in a reduction of its effectiveness*" (Kramer et al., 1995, p.97).

Other studies have simply varied the nature of the diversion task (and presumably the attentional demands of the task) without providing independent evidence of task load (Alain & Woods, 1997; Alho et al., 1994; Harmony et al., 2000; Kathmann et al., 1999; Näätänen et al., 1993b; Paavilainen et al., 1993). In a study by Kathmann et al. (1999), subjects were instructed to ignore all auditory stimuli and were assigned to one of two task conditions. One group of subjects was asked to perform a simple visual target detection task. The other group was asked to sit passively, having no cognitive task to perform. No differences in MMN following either a small frequency deviant or a duration deviant were found between the two task groups. Non-significant task effects were also reported by Harmony et al. (2000). In one task in this study, the stimulus AAAAA was presented and subjects were asked to verbally respond "A". In another task, the stimulus also consisted of 5 uppercase letters; these letters when reordered formed a word. Subjects were asked to decode and verbalize this word. There were no task effects on the MMN elicited by a small frequency change in the 100-150 ms latency range. Alho et al. (1994) and Paavilainen et al. (1993) contrasted the MMN elicited by to-be-ignored stimuli while subjects either performed a discrimination task in another auditory channel or attended to a visual channel. During the visual task, subjects were asked to detect an infrequent visual target (Alho et al., 1994) or read a book (Paavilainen et al., 1993). Results showed that the MMN elicited by unattended frequency deviants during the auditory discrimination task was similar to that elicited by the same deviant stimuli during the visual distraction task. In contrast, Näätänen et al. (1993) and Alain and Woods (1997) reported differences between the MMN elicited in the unattended channel during dichotic listening and that elicited during a reading task. Näätänen et al. (1993) showed that the MMN elicited by to-be-ignored intensity deviants was significantly larger when subjects were reading compared to when they were counting targets presented to the opposite ear[18]. This difference was attributed to the greater attentional focus presumably required by the counting task relative to the reading task which lead to the dampening of the MMN process. Alain and Woods (1997), using auditory pattern stimuli, also found significant differences between the MMN elicited by to-be-ignored stimuli during a dichotic listening task and that observed during reading. They suggested that the larger MMN during reading was possibly due to "leakage" of the subject's attention toward the irrelevant auditory stimuli. Alternatively, they proposed that the smaller MMN in the unattended channel during the dichotic task may be explained by inhibition of this auditory input. Interestingly, when Alain and Woods (1997) replicated this experiment using a similar auditory pattern but with stimuli that were of lower intensity, shorter duration and presented more rapidly, the MMN difference between the two conditions disappeared. They suggested that the stimuli during this second experiment may have been easier to ignore during reading.

The effects of the nature and the difficulty of the diversion task on the MMN therefore remain equivocal. In many studies, the MMN appears to be unaffected by manipulations of the diversion task. Nevertheless, others have reported a modulation of the MMN with the diversion

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[18] Moreover, Näätänen et al. (1993) reported that while the MMN to the unattended frequency deviants was also larger in the reading compared to the counting condition, this difference failed to reach significance.

task and have interpreted this effect as being related to the presumed attentional demands of these tasks (Alain & Woods, 1997; Kramer et al., 1995; Näätänen et al., 1993b). One of the factors that may contribute to the inconsistencies in these attempts to establish the influence of attention on the MMN is the lack of control over the reading task. An observation made in our laboratory while conducting MMN studies is the absence of conformity in the subjects' cognitive activities following the instruction to "*read a self-selected book while ignoring the auditory stimuli*". It was noted that while some subjects leisurely read a book of general interest, others actively studied course material or alternatively again, did not read at all. The purpose of the present study was to determine the effects of such common variations in the reading task on the morphology of the MMN. In separate conditions, subjects were asked to either read a text while being informed that they would subsequently be queried about this reading, read a text that would not be followed by query, or simply sit passively and not read. It was assumed that the reading task followed by query would require that the subject pay more attention to the task than when it did not involve a subsequent query, whereas the passive non-task condition made no attentional demands[19]. Based on previous findings, it is expected that if the diversion task has an effect on the MMN, its amplitude will vary inversely with the presumed attentional demands of the diversion task.

2. Experiment 1: Effects of task demands on the frequency MMN

2.1. Methods

2.1.1. Subjects

Twelve university students (10 women and 2 men) with self-reported normal hearing and no history of neurological or psychiatric problems volunteered to participate in this study. Subjects were between the ages of 18 and 29 years (M = 22.2, SD = 3.5). Written informed

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[19] Of course, the subject may be engaged in other non task-related cognitive activity during these conditions.

consent was obtained prior to the study and an honorarium was offered as compensation. This study was conducted following the guidelines of the Canadian Tri-Council (Medical, Natural and Social Sciences) on ethical conduct for research involving humans.

2.1.2. Stimuli

A single auditory stimulus condition was used involving 2 stimuli differing in frequency: 1000 Hz standards and 1050 Hz deviants. All stimuli were 80 dB SPL tone pips having a total duration of 55 ms and a rise/fall time of 5 ms. A constant ISI (onset-to-onset) of 600 ms was employed. Stimulus probability was 0.85 for the standards and 0.15 for the deviants. A deviant was presented, on average, every 4 s. The order of the presentation of the stimuli was pseudo-randomized. Deviants were separated by at least three standards in the train of stimuli.

2.1.3. Procedure

During the EEG recording session, subjects were seated in a sound attenuated room. The auditory stimuli were presented binaurally via insert earphones (EAR 3A). In separate conditions, subjects were instructed to engage in four different diversion tasks. In each condition, they were asked to ignore the tone pips. The order of conditions was counterbalanced across subjects. A total of 1000 trials were presented per block. Two blocks of stimuli were presented in each task condition (i.e., a total of 2000 trials consisting of 1700 standards and 300 deviants).

In the *Experimenter-Selected Reading with Query* condition, subjects were instructed to read an experimenter-selected text and were informed that they would later have to recall specific information from this reading. Experimenter-selected readings consisted of both short stories and magazine articles of general interest. The length of text assured that subjects would continue reading until the end of the stimulus presentation session. Following this session, subjects were asked to complete a test that consisted of four short answer questions. Subjects were required to correctly answer 3 out of 4 questions in order for the condition to be included for further analysis. All subjects fulfilled this requirement.

In the *Experimenter-Selected Reading* condition, subjects were again instructed to read a text chosen by the experimenter but were informed that they would not have to recall any information from this reading. Readings given during the *Experimenter-Selected Reading with Query* and the *Experimenter-Selected Reading* conditions were counterbalanced across subjects to ensure that any difference between conditions was not due to the reading material per se.

The *Self-Selected Reading* condition corresponded to the traditional MMN task and required that the subjects read a text of their choice. No control was placed on the type of reading material, which typically included textbooks related to classroom learning and magazines of interest to the subject. It was stressed, however, that subjects should not study during this condition. In the *Passive* condition, subjects were instructed to sit passively and keep their eyes open. Eye movements were monitored to verify that subjects were engaged in reading or remained alert, depending on the condition.

2.1.4. EEG/ERP recording

EEG activity was recorded from 5 channels (Fz, Cz, Pz, FC3, FC4) using tin electrodes attached to an electrode cap (ECI). Two additional channels were recorded from individual tin cup electrodes placed on the left and right mastoids (M1, M2). The nose served as a reference. A vertical EOG was recorded from electrodes placed at the infra- and supra-orbital ridges of the right eye. A horizontal EOG was recorded from electrodes placed at the outer canthus of each eye. The ground electrode was attached to the forehead. Inter-electrode impedances were below 5 kOhms.

The physiological signals were digitized continuously at a 256 Hz sampling rate using a 12-bit analogue-to-digital (A/D) converter and stored on hard disk for later off-line analysis. The analogue high frequency filter was set at 30 Hz and the time constant at 2 s. Eye movement and blink artifact were corrected using an algorithm operating in the time and frequency domain (Woestenburg, Verbaten, & Slangen, 1983). The continuous data were subsequently reconstructed into discrete trials or "sweeps". The sweep time was 700 ms, which included a 100 ms pre-stimulus baseline period. In each condition, the single-subject ERPs were averaged separately for standard and deviant stimuli across the stimulus blocks. ERP averages were then digitally low-pass filtered using an inverse FFT algorithm with a 20 Hz high frequency cutoff.

2.1.5. Data analysis

The average of all data points in the 100 ms pre-stimulus interval served as a baseline from which ERP waveforms were measured. Latency windows for peak measurements were determined from grand averages. For the standard ERPs, the peak amplitude and latency of N1, P2 and N2 were scored at Fz. Difference waveforms were obtained by subtracting point-by-point the standard from the deviant waveforms for each condition, at each electrode site. From these difference waveforms, peak measurements were made for the MMN at Fz, FC3, FC4, M1 and M2.

Many laboratories employ a mean amplitude measurement of the MMN (see, for example, Alho et al., 1989) because it often appears as a long-lasting slow wave rather than as a sharp peak. Hence, an analysis of mean amplitude values, computed by averaging all data points within a fixed interval, was also performed. The difference waveforms at Fz and M1 were subdivided into twelve consecutive 50 ms latency intervals starting at stimulus onset. The interval analysis included components often occurring after the MMN, such as a fronto-central positive wave (P3a) and a late negative slow wave.

For effects with more than one degree of freedom, the original degrees of freedom are reported along with the Huynh Feldt coefficient (ε) and the corrected probability. The Tukey

Honestly Significant Difference test was used as a post-hoc procedure following significant effects ($p < .05$).

2.2. Results

2.2.1. Standard and deviant ERPs

Grand-average ERPs elicited by the standard and the frequency deviant in each of the four experimental conditions are illustrated in Figure 1. In all conditions, the standard waveforms mainly consisted of N1, P2 and N2 deflections, peaking at 93, 151 and 269 ms, respectively. Peak amplitude and latency of these deflections were subjected to one-way repeated measures ANOVAs with task as the within-subject variable. The latency of N1, P2 and N2 did not significantly differ between conditions, $Fs < 1$. Furthermore, there was no significant effect of task on either N1 or N2 amplitude, $Fs < 1$. Task did significantly affect, however, the amplitude of P2, $F(3,33) = 3.1$, $p < .04$, $\varepsilon = 1.0$. Post-hoc tests indicated that P2 was significantly larger when the task involved reading followed by query ($M = 1.77\ \mu V$, $SD = 1.03\ \mu V$) than when subjects were asked to sit passively ($M = 1.27\ \mu V$, $SD = 0.82\ \mu V$).

ERPs to the deviant stimuli showed a negative deflection overlapping the N1-P2 waveform. This negativity was most pronounced at fronto-central sites and inverted in polarity at the mastoids.

----------Insert Figure 2.1 about here---------

2.2.2. Difference (deviant - standard) waveforms

As can be seen from the difference waves in Figure 2, a prominent MMN, peaking at approximately 180 ms following stimulus onset, was elicited in all conditions. Peak amplitude and latency of the MMN at Fz were analysed using one-way repeated measures ANOVAs. Longer MMN latencies were obtained in the passive condition ($M = 194$ ms, $SD = 18$ ms) than in either of the 3 reading conditions ($M = 177$ to 183 ms, $SD = 17$ to 18 ms), but the difference failed to reach significance, $F(3,33) = 2.7$, $p < .07$, $\varepsilon = 1.0$. There was a significant task effect on MMN peak amplitude, $F(3,33) = 3.0$, $p < .05$, $\varepsilon = 1.0$. The post-hoc analysis indicated that amplitude was significantly larger in the reading-query condition (M = -2.70 µV, SD = 1.12 µV) than in the self-selected reading condition (M = -1.70 µV, SD = 1.14 µV).

In order to examine frontal hemispheric differences, the peak amplitude of the MMN was also measured at left (FC3) and right (FC4) hemispheres. ANOVAs with two within-subjects variables (task, electrode site) were carried out on these data. As can be observed in Figure 2, the peak amplitude of the MMN did not significantly differ between FC3 and FC4, $F < 1$. Again, a significant main effect of experimental condition was found, $F(3,33) = 4.5$, $p < .01$, $\varepsilon = .99$. The MMN amplitude was significantly larger when the task involved experimenter-selected reading followed by query compared to that obtained in either the experimenter-selected reading, the self-selected reading or the passive conditions.

The MMN usually shows a polarity inversion at the mastoid sites. For this reason, the maximum positive peak in the MMN time window was quantified at M1 and M2. The peak amplitude and latency data at these sites were also subjected to two-way repeated measures ANOVAs. While the MMN did invert in polarity in all conditions, the peak amplitude pattern observed at frontal sites did not emerge at the mastoids, $F < 1$. Peak amplitude and latency did not significantly differ between left and right mastoid sites, $Fs < 1$.

----------Insert Figure 2.2 about here---------

The mean amplitudes at Fz and M1 for each of the twelve 50 ms time intervals are presented in Table 1. The mean amplitudes of each interval were analyzed using ANOVAs with task as the within-subjects variable. The results from the interval analysis are in accordance with those obtained from the peak analysis. No significant task effects were found in any of the intervals at M1. The effect of task was significant at Fz in the 150-200 ms interval, the interval that included the MMN, $F(3,33) = 3.2$, $p < .04$, $\varepsilon = 1.0$. Again, post hoc analyses indicated an enhanced negativity in the reading-query condition when compared to the self-selected reading condition. A significant effect of task was also present in later intervals extending from 400 to 600 ms, $F(3,33) = 3.1$ to 3.7, $.02 < ps < .04$, all $\varepsilon s = 1.0$. In these intervals, the mean amplitude of this negative wave obtained during the self-selected reading task was significantly smaller than that observed in the other conditions. This negativity inverted in amplitude at the mastoids.

----------Insert Table 2.1 about here---------

2.3. Discussion

In all task conditions, the ERP waveform elicited by the frequently-presented standard stimulus mainly consisted of a N1-P2-N2 complex, whereas the ERP to the rare frequency deviant featured an additional negativity overlapping these deflections. This additional negativity can best be seen in the difference waveform, computed by subtracting the standard from the deviant ERP. The deviance-related negativity (DRN) thus represents the processing of the deviant stimulus in relation to the standard stimulus. A prominent DRN, peaking at approximately 180 ms, was evoked by the small frequency change in all task conditions. This wave was most pronounced at frontal and central sites and inverted in polarity at the mastoids. These characteristics are consistent with those of the MMN. It is unlikely that the N2b contributed to the DRN. In Ignore conditions, the N2b is usually elicited in response to large deviants and peaks later, about 250 ms after onset of the deviant (Näätänen et al., 1982). It is also unlikely that an enhanced deviant N1 contributed to the DRN. The standard and deviant stimuli were separated by only 50 Hz. Exogenous ERP components such as the N1 should therefore have been essentially identical for the two stimuli.

The present experiment demonstrated that the processing of a small frequency deviant presented among homogeneous standard stimuli may be affected by the demands of the task. At Fz, the MMN was significantly larger when subjects read experimenter-selected material and were aware of a subsequent query compared to when they read self-selected material and were not queried. At left and right fronto-central sites, the MMN was significantly larger in the reading with query condition compared to all other task conditions. These findings are counterintuitive in light of previous studies proposing that the amplitude of the MMN to unattended stimuli is either unchanged (e.g. Otten et al., 2000; Paavilainen et al., 1993) or smaller (e.g. Alain & Woods, 1997; Näätänen et al., 1993b) when the diversion task requires greater attention. It would be difficult to argue that the condition showing the largest MMN, the reading with query condition, required *less* focus than the other tasks, although in the absence of independent behavioural measures it is unclear what the subjects were actually doing during each condition. Most notably, during the condition in which subjects were not required to perform any specific task, their attention may have been focused on internal thoughts (instead of re-directed to the to-be-ignored auditory stimuli).

Interestingly, the pattern of MMN results at frontal sites was not paralleled at the mastoid sites, where no significant task effects were found. A similar disassociation between the MMN effects at frontal and mastoid sites has previously been reported (Deouell & Bentin, 1998; Jääskeläinen et al., 1996; Sussman & Winkler, 2001). These authors suggested that the activity recorded at the mastoid mainly indexes the temporal MMN subcomponent whereas both the temporal and frontal MMN sources contribute to the activity recorded at frontal sites. The temporal MMN subcomponent is believed to reflect the actual detection of change. The frontal MMN subcomponent likely represents a call for attention switching. It is thus possible that task demands mainly modulated this alerting and attention-switching function of the MMN. Caution should nevertheless be heeded in interpreting scalp distribution differences.

Dissociating frontal and temporal contributions to the MMN might be accomplished by source dipole analysis, requiring the addition of several other EEG recording sites. Furthermore, a later positive wave, the P3a, was difficult to observe following the MMN. The P3a is considered by many authors to reflect the actual attention switch (Escera et al., 1998).

A significant task effect was also found on a late (400-600 ms) long-lasting negativity observed in the difference waveform. This later DRN was maximal at frontal sites and inverted in polarity at the mastoids. It was apparent in all conditions except when the MMN was smallest, in the self-selected reading condition. A similar late negativity following the MMN to unattended stimuli was originally reported by Näätänen (1982) and proposed to reflect "sensitization processes" following a stimulus change with the function of preparing for possible future change detection. Although it has subsequently been obtained in several other studies (Alho et al., 1994; Alho et al., 1992; Otten et al., 2000), very little is known about this wave. Alho et al (1992) indicated that the late DRN was unaffected by the difficulty of the visual diversion task, whereas Otten et al. (2000) obtained a larger late negativity when the visual diversion task was less demanding.

The results of the present experiment further suggest that, in addition to deviance processing, the processing of the standard stimulus was also affected by task demands. The standard ERP waveform showed differences among the task conditions, as early as 150 ms after stimulus onset. The P2 deflection elicited by the standard stimuli was significantly larger during the reading with query condition compared to the no-task condition. Variations in task demands might cause momentary condition-specific changes in either selective attention or nonselective arousal (Picton, Campbell, Baribeau-Braun, & Proulx, 1978). In intermodal attention tasks, the P2 elicited by the auditory standard has been reported to be larger when attention is directed to the auditory channel than when it is directed toward the visual channel (the Pd effect; see Hackley, 1993). Again, it is unlikely that subjects would have been *most* attentive to the auditory stream during the reading with query condition. P2 is also susceptible to modulations of the subject's state of cortical arousal, although the effect is not always consistent. In some studies, it has nevertheless been apparent that the P2 amplitude decreased following the administration of CNS depressants, such as nitrous oxide gas (Pang & Fowler, 1999) or alcohol (Jääskeläinen et al., 1995). Interestingly, in these studies, the decrease in P2 amplitude was paralleled by a decrease in the MMN.

It is difficult to reconcile the complex pattern of ERP results obtained in this study with the presumed attentional demands of the different tasks. The psychological and physiological state of the subject may have considerably differed across the diversion tasks, and contributed to the present task effects. In the second experiment, the effects of task demands on the MMN elicited by a small intensity change will be examined. The intensity MMN has been suggested to be more susceptible to the effects of attention (Näätänen et al., 1993b).

3. Experiment 2: Effects of task demands on the intensity MMN

3.1. Methods

The experimental procedures were very similar to those used in Exp. 1. Only the methodological differences between these experiments will be highlighted.

3.1.1. Subjects

Twelve university students (9 women and 3 men) volunteered to participate in this study. Subjects were between the ages of 19 and 24 years (M = 20.6, SD = 1.7). None of these subjects participated in Exp. 1.

3.1.2. Stimuli and Procedure

As was the case in Exp. 1, the standard stimulus was a 1000 Hz, 80 dB SPL tone pip. In Exp. 2, the deviant, however, differed from the standard in intensity rather than frequency. A 1000 Hz, 70 dB SPL deviant stimulus was presented on 15% of trials. Subjects were again instructed to engage in three different reading tasks (self-selected reading; experimenter-selected reading; reading with query). The passive condition in which the subject's attentional focus was most difficult to control was not included among the task conditions in this experiment. The EEG activity was recorded from Fz, Cz, Pz, F3, F4, M1 and M2. Other recording and analysis procedures were identical to those used previously.

3.2. Results

3.2.1. Standard and deviant ERPs

Figure 3 depicts the grand-average ERPs elicited by the standard and the intensity deviant for each task condition. In the standard waveforms, N1, P2 and N2 peaked at 86, 138 and 230 ms, respectively, following stimulus onset. One-way repeated measure ANOVAs were performed on the peak amplitude and latency of these deflections. The nature of the task did not significantly affect the latency or amplitude of either N1, P2 or N2, Fs < 1.

The ERP to the deviant stimulus was characterized by an enhanced negativity in the latency range of 150 to 250 ms when compared to the standard ERP. This additional negativity was most pronounced at frontal electrode sites and inverted in polarity at the mastoid sites.

----------Insert Figure 2.3 about here---------

3.2.2. Difference (deviant - standard) waveforms

Figure 4 illustrates the difference waveforms obtained during each of the three experimental conditions. A prominent MMN, peaking at approximately 190 ms was elicited by the small intensity decrement in all conditions. Peak measurements of this deflection at Fz were subjected to one-way repeated measures ANOVAs. The nature of the task did not significantly affect the latency or the amplitude of the MMN, Fs < 1.

----------Insert Figure 2.4 about here---------

The peak amplitude and latency of the MMN was also analysed at F3 and F4 by means of two-way repeated measure (task, electrode site) ANOVAs. The peak amplitude of the MMN did significantly differ between left (F3) and right (F4) hemispheres, $F(1,11) = 9.5, p < .01$. The MMN was larger at F4 (M = -1.29 μV, SD = 1.27 μV) than at F3 (M = -1.02 μV, SD = 1.13 μV). In accordance with the results at Fz, no significant main effect of task was found at these frontal sites, Fs < 1. ANOVAs with two within-subject variables were also carried out on the peak measurements of the MMN at left (M1) and right (M2) mastoid sites. No hemispheric or task effects were found based on these data, all Fs < 1.

In the interval analysis, the mean amplitudes of each interval at Fz and M1 were subjected to one-way repeated ANOVAs. Consistent with the results from the peak analyses, the interval analyses at Fz and M1 yielded non-significant task differences, F < 1 for all intervals.

3.3. Discussion

As was the case in Exp.1, the ERP elicited by the deviant stimulus was negatively displaced relative to the standard ERP, in each of the experimental conditions. The DRN, with peak latency of about 190 ms, displayed all characteristics specific to the MMN. It was maximal at fronto-central sites, inverted in polarity below the Sylvian fissure and showed a right-hemisphere preponderant distribution. The MMN elicited by the small intensity change was delayed and attenuated when compared to the frequency MMN in Exp.1. This MMN difference is probably related to the ease of discriminability of the deviants from the standard. Näätänen et al (1993) presented the same standard and deviant stimuli as those used in this study and noted that subjects were indeed better able to behaviourally discriminate the frequency than the intensity deviant. As the deviant becomes more difficult to discriminate from the standard, MMN amplitude typically decreases while its peak latency increases (Sams et al., 1985). There is evidence, nevertheless, that the morphology of the MMN is affected by the specific physical characteristics of the deviant, independent of its discriminability. Deouell and Bentin (1998) equated the subjective discriminability of different types of deviants. The frequency deviant continued to elicit a larger MMN at frontal sites than the intensity deviant. No differences were found at the mastoids.

In contrast to the findings of Exp.1, task demands did not modulate the intensity MMN. In fact, there were no significant differences between conditions either for the standard ERP or for the difference waveform. The divergence between the results of the two experiments is most likely due to the difference in the feature that characterized the deviant[20]. Giard et al. (1995) showed that the intensity and the frequency MMN varied in scalp distribution, and proposed that these MMNs may derive from different neural populations within the supratemporal auditory cortex. Task demands may thus have differently affected the neuronal mechanisms specific to intensity and frequency change. Alternatively, as noted above, the frequency deviant employed in this study has been found to be better detected from the otherwise homogenous auditory stimulation than the intensity deviant. As a result, the task-irrelevant auditory stimulation that included the frequency change may have been more obtrusive under certain task conditions.

4. Conclusion

The MMN elicited by the small intensity change was not significantly modulated by the demands of the reading task. This finding would appear to support Näätänen's proposal that the processing leading up to the MMN elicitation is task-independent. According to this view, the quality and quantity of the sensory information arriving at the MMN generator is unchanged by the requirements of the task. Caution should be exercised, however, in reaching such a conclusion. The present study was intended to address a methodological issue. It was not designed to test Näätänen's strong-automaticity theory. As pointed out by Woldorff and Hillyard (1990), such a test would involve the presentation of the to-be-ignored auditory

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[20] Because different subject samples were employed in the two experiments, it is possible that random individual differences within the two groups could also be involved.

stimuli under conditions that optimize selective attention. These experimental conditions include a large separation between the to-be-attended and to-be-ignored channels, a diversion task that necessitates highly-focused attention, and a very fast rate of stimulus presentation. These requirements may not have been met in the present study. The reading tasks, even when followed by query, might not have been demanding enough to force inhibition of task-irrelevant auditory processing. Furthermore, the rate of stimulus presentation may not have allowed subjects to disregard the auditory stimulation.

The present study also failed to establish a systematic relationship between the presumed attentional demands of the diversion tasks and the amplitude of the MMN to a small change in frequency. Nevertheless, the frequency MMN did significantly vary depending on the requirements of the reading task. It is possible that this modulation is related to the level of task-induced cortical excitability. However, in the absence of the critical physiological and behavioural evidence, the interpretation of these task effects must remain speculative. Still, the present findings lead to the recommendation that the diversion task performed during MMN recording be identical for all subjects. Moreover, MMN studies should at the very least describe the nature of the diversion task and also include evidence that it was indeed carried out. In order to achieve this, better control should be exercised over the subject's activities when employing the classical reading task.

Table 1. Mean amplitude (µV) and standard deviation (parenthesis) of the difference waveforms at Fz and M1 for each 50 ms interval of the total 600 ms sweep. The difference waves were computed by subtracting the ERP elicited by the standard stimulus from that elicited by the frequency deviant.

	Time (ms)											
	0-50	50-100	100-150	150-200	200-250	250-300	300-350	350-400	400-450	450-500	500-550	550-600
Experimenter-Selected Reading with Query:												
Fz	0.07	-0.14	-1.20	-2.05	-1.14	-0.05	-0.02	-0.68	-0.87	-1.02	-0.90	-0.62
	(0.75)	(0.83)	(0.90)	(1.13)	(0.80)	(1.11)	(1.23)	(1.11)	(0.89)	(1.18)	(1.54)	(1.38)
M1	-0.21	0.00	0.13	0.56	0.37	-0.02	0.15	0.26	0.53	0.60	0.51	0.44
	(0.48)	(0.50)	(0.57)	(0.96)	(0.86)	(0.70)	(0.68)	(0.72)	(0.89)	(0.86)	(0.89)	(0.75)
Experimenter-Selected Reading:												
Fz	-0.18	0.17	-0.70	-1.52	-0.87	0.15	-0.02	-0.54	-0.81	-0.88	-0.84	-0.68
	(0.38)	(0.58)	(0.85)	(1.08)	(0.53)	(0.55)	(0.96)	(1.41)	(1.25)	(1.28)	(1.35)	(1.32)
M1	0.10	0.38	0.72	1.04	0.62	0.35	0.43	0.67	0.62	0.77	0.75	0.74
	(0.46)	(0.66)	(0.61)	(0.78)	(1.02)	(0.76)	(0.64)	(0.77)	(0.73)	(0.80)	(0.98)	(1.11)
Self-Selected Reading:												
Fz	0.17	0.27	-0.38	-0.90	-0.53	0.19	-0.03	-0.14	-0.06	-0.07	-0.02	0.12
	(0.68)	(0.60)	(0.84)	(1.16)	(0.91)	(1.01)	(0.74)	(0.64)	(0.84)	(0.82)	(0.82)	(0.62)
M1	0.06	0.28	0.36	0.78	0.13	-0.25	0.05	0.40	0.53	0.84	0.81	0.63
	(0.54)	(0.52)	(0.75)	(0.79)	(0.67)	(0.52)	(0.85)	(1.09)	(0.88)	(0.92)	(0.85)	(0.79)
Passive (No Reading):												
Fz	0.05	0.11	-0.58	-1.41	-1.30	-0.31	-0.20	-0.77	-1.21	-1.39	-1.43	-1.35
	(0.89)	(0.84)	(1.05)	(1.20)	(1.09)	(1.24)	(1.19)	(1.29)	(1.08)	(1.06)	(1.07)	(1.15)
M1	0.04	0.23	0.65	1.12	0.54	0.24	0.46	0.85	0.77	0.80	0.70	0.59
	(0.58)	(0.66)	(0.75)	(0.94)	(0.87)	(1.14)	(0.90)	(0.99)	(0.86)	(1.07)	(0.90)	(1.03)

Figure Captions

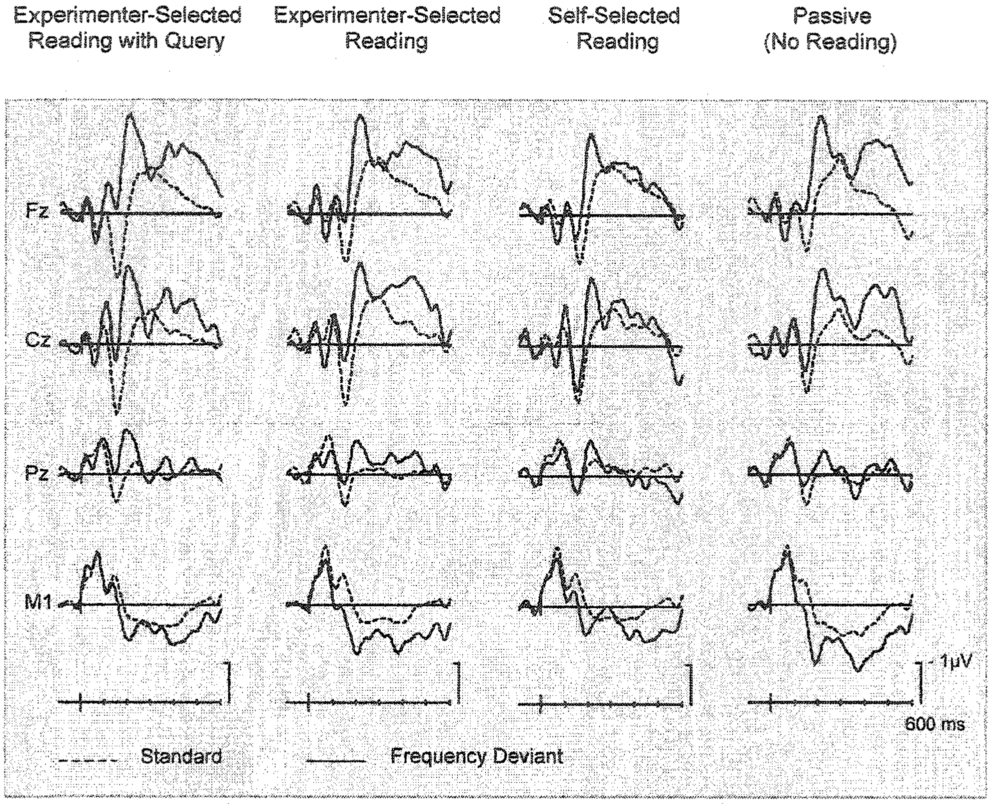
Figure 1. Experiment 1: Grand average ERP waveforms elicited by standard (1000 Hz; dashed line) and deviant (1050 Hz; solid line) stimuli under different task demands. In this and subsequent figures, negativity is traced as an upward deflection.

Figure 2. Experiment 1: Grand average difference waveforms computed by subtracting the ERP elicited by the standard from the ERP elicited by the frequency deviant in the same task condition. Difference waveforms for the Experimenter-Selected Reading with Query (thick solid line), Experimenter-Selected Reading (thick dashed line), Self-Selected Reading (thin solid line) and Passive (thin dashed line) conditions are superimposed. A large MMN, peaking at about 180 ms, is apparent in all conditions. It was significantly larger in the Experimenter-Selected Reading with Query condition when compared to the Self-Selected Reading condition. Note that a late negativity (400- 600 ms) is also apparent, except in the Self-Selected Reading condition.

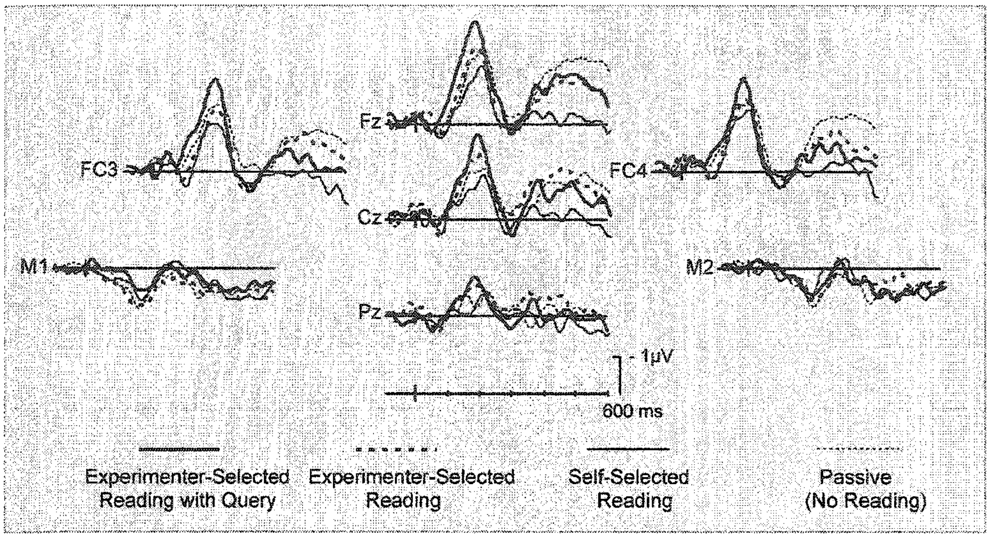
Figure 3. Experiment 2: Grand average ERP waveforms elicited by standard (80 dB; dashed line) and deviant (70 dB; solid line) stimuli under different task demands.

Figure 4. Experiment 2: Grand average difference waveforms computed by subtracting the ERP elicited by the standard from the ERP elicited by the intensity deviant in the same task condition. Difference waveforms for the Experimenter-Selected Reading with Query (thick solid line), Experimenter-Selected Reading (thick dashed line) and Self-Selected Reading (thin solid line) conditions are superimposed. The MMN, peaking at approximately 190 ms, did not significantly vary with task conditions.

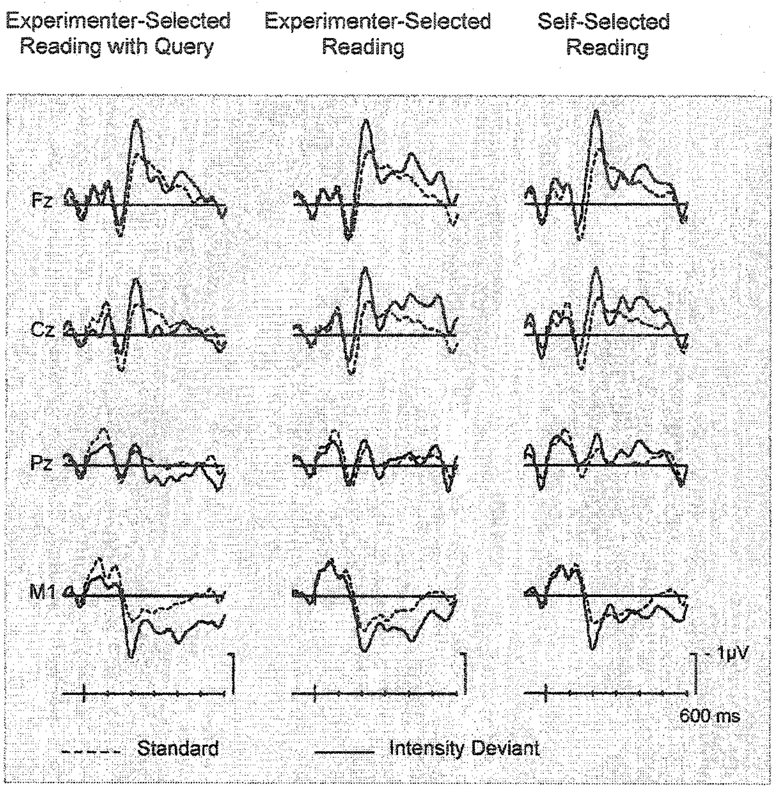
Standard and Frequency Deviant ERPs



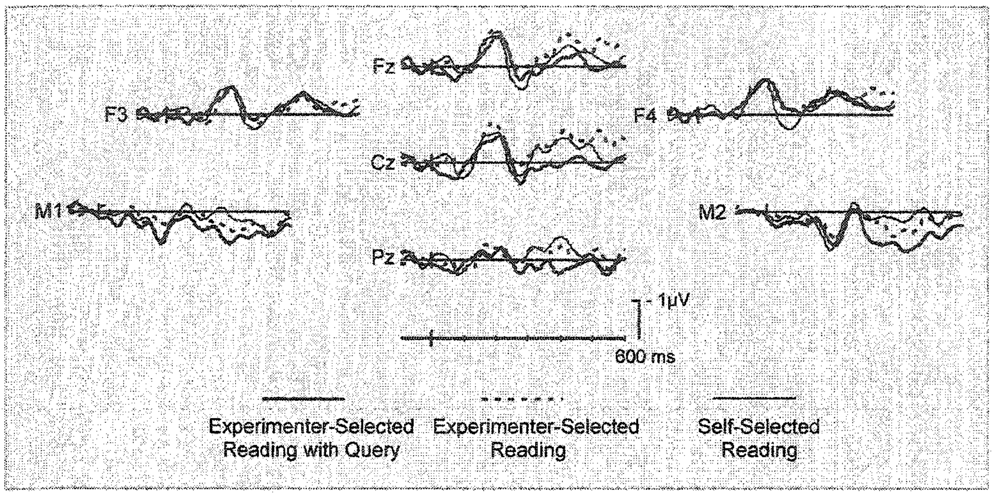
Frequency Difference Waveforms



Standard and Intensity Deviant ERPs



Intensity Difference Waveforms



CHAPTER 3

THE EFFECT OF VISUAL TASK DIFFICULTY ON THE MMN DURING FOCUSED (VISUAL) AND DIVIDED (AUDITORY-VISUAL) ATTENTION

1. Introduction

The Mismatch Negativity (MMN), a component of the auditory event-related potential (ERP), has proven to be a sensitive index of the detection of change (Näätänen, 1992). The MMN is elicited by a rare change in an otherwise homogeneous stream of auditory stimuli. This component can best be observed in a difference waveform, computed by subtracting the ERP response to the standard stimuli from the response to the deviant stimuli. The MMN reaches maximal amplitude at fronto-central scalp sites and often inverts at sites below the Sylvian fissure when the nose is used as a reference (Alho et al., 1986a). The peak latency of the MMN usually occurs from 100 to 250 ms from stimulus onset. It has been elicited by changes in a variety of static and temporal stimulus features (Näätänen & Winkler, 1999). The magnitude of physical difference between standard and deviant generally affects the amplitude and latency of the MMN. As the deviant becomes more difficult to discriminate from the standard, MMN amplitude typically decreases while its peak latency increases (Sams et al., 1985).

In Näätänen's model of auditory processing (Näätänen, 1990; Näätänen, 1992; Näätänen & Winkler, 1999), the generator mechanism of the MMN is associated with the functions of a brief-lasting auditory sensory memory. According to this model, a feature detector system forwards information about the physical properties of the incoming stimulus to a sensory memory store where feature and temporal integration takes place. The resulting stimulus representation is strengthened with repeated presentations of the same auditory stimulus (i.e., standard). However, if a subsequent incoming stimulus is detected as different (i.e., deviant) from the well-formed stimulus trace, the MMN generator mechanism is activated. It is proposed that this automatic change-detector sends an interrupt signal to higher executive mechanisms in order to re-direct attention to potentially significant changes in the environment. A later ERP component, the P3a, is thought to reflect the occurrence of such an involuntary attention-switch (Escera et al., 1998).

Central to Näätänen's model is the claim that the physical features of auditory stimuli are fully analyzed and encoded whether the channel in which the stimuli occur is attended or not. That is, the quality and quantity of sensory information entering the MMN generator mechanism is not modulated by attention. Näätänen proposes that the function of attention is to increase the likelihood that a stimulus will gain access to a limited-capacity system where it will be further evaluated. The additional processing afforded to the attended stimuli is performed by a different system operating in parallel with the obligatory sensory analysis. Näätänen's assertions concerning the role of attention in auditory processing have been challenged. Proponents of gain theories have argued that the processing of unattended stimuli can be attenuated or gated relative to that of attended stimuli at an early sensory level (Hackley, 1993; Woldorff et al., 1991). According to this view, the unattended stimulus is associated with a degraded sensory memory representation.

Very early studies of the MMN indeed indicated that it could be elicited by small changes in auditory stimulation when the subject's attention was directed to another cognitive activity in either auditory or visual modalities (Näätänen et al., 1978; Sams et al., 1984). Further support for the attentional insensitivity of the MMN came from experiments reporting comparable MMNs elicited by attended and unattended stimuli (Näätänen et al., 1980; Näätänen et al., 1978). These studies were criticized, however, for employing conditions that did not require a strong selective focusing of attention. As such, subjects may have been able to divert resources to the processing of the auditory stimuli even when they were presented in the to-be-ignored channel. In order to maximize and facilitate early selective attention, stimuli must be presented at very rapid rates, the task must be difficult, and the attended and ignored channels must be easily distinguished (Woldorff & Hillyard, 1990).

More recent studies, in particular those employing intramodal auditory selective attention tasks requiring a strong attentional focus, indicated that attention can affect the MMN (Alain & Woods, 1997; Arnott & Alain, 2002; Näätänen et al., 1993b; Szymanski et al., 1999; Trejo et al., 1995; Woldorff et al., 1998; Woldorff et al., 1991). These studies reported that the MMN elicited by a deviant delivered in the unattended channel was smaller than that elicited by the same deviant when it was part of the attended sequence. The ERP elicited by a deviant stimulus presented in the attended channel, however, is characterized by additional components, most notably the N2b. The N2b may overlap both spatially and temporally with the MMN, resulting in a composite negative deflection. A contribution of the N2b component to the attentional effect on the MMN cannot therefore be excluded in these studies.

The problem of the N2b overlap is generally overcome in most MMN studies by instructing the subject to engage in a visual diversion task. The extent to which attentional focus is required by the visual diversion task is often considered incidental. The primary aim of the present study was to determine if the attentional requirements imposed by visual tasks do modulate the passively-elicited MMN. Surprisingly, this issue has not yet been extensively investigated. The few studies that have considered this question have generally concluded that the demands of the visual task have little effect on the MMN (Alho et al., 1992; Dittmann-Balcar et al., 1999; Harmony et al., 2000; Kathmann et al., 1999; Otten et al., 2000 see however Kramer et al., 1995). In these studies, two visual diversion tasks were typically employed. One task is made to be more difficult than the other and thus presumed to demand a greater focusing of attention. The underlying assumption in these studies is that the strong demands of the difficult visual task do not allow the subject to either rapidly switch or allocate resources to the processing of the task-irrelevant auditory stimuli. In contrast, it is assumed that during the easy task, subjects have available resources for the processing of the auditory stimuli. On this basis, it has generally been expected that, if the MMN were modulated by attention, a much-reduced MMN would be elicited during the difficult relative to easy visual task condition.

The elicitation of prominent and equivalent MMNs during easy and difficult visual conditions led Alho (1992) to conclude: "*This finding supports the proposal that the MMN is automatically elicited by unattended-stimulus changes and is not caused by covert attention to the to-be-ignored auditory stimuli because less attentional resources would have been allocated for auditory processing during a difficult visual task than during an easy one*" (Alho, 1992, p. 257). This conclusion may not be warranted because: (1) the experimental conditions needed to find an effect of task demands on the MMN were not optimized in these studies and (2) the assumption that fewer attentional resources are available for auditory processing during a difficult than easy visual task has been inferred, but not, in fact, verified. In the present study, the effect of visual attention on the MMN is more rigorously tested, by maximizing the likelihood of finding an effect of task demands. The extent to which visual task difficulty affects subjects' ability to concomitantly process auditory stimuli is subsequently assessed.

The effects of attention are often only apparent under highly specific conditions. In many MMN studies, the failure to find effects of task demands may be explained by these methodological issues. Several of these studies employed a slow auditory (Dittmann-Balcar et al., 1999) or visual (Dittmann-Balcar et al., 1999; Harmony et al., 2000; Kathmann et al., 1999; Otten et al., 2000) stimulus presentation rate. When stimuli are presented slowly, there is sufficient time between presentations to switch between the attended and ignored channels and therefore less need for early selectivity (Schwent, Hillyard, & Galambos, 1976). Furthermore, when the unattended auditory stimuli are presented at slow rates, these stimuli are likely to cause involuntary attention shifts toward the to-be-ignored channel (Hansen & Hillyard, 1984).

Slow rates of stimulus presentation are hence not conducive to the selective focusing of attention. In addition, manipulation of task demands in previous studies has not resulted in a wide range of task performance. For example, in the Kathmann et al. and Otten et al. studies, both "easy" and "difficult" tasks were easily completed, hit rates ranging from 0.83 to 0.95 in the difficult condition. In contrast, in the Alho et al. study, "easy" and "difficult" tasks were difficult to complete, both tasks having hit rates below 0.80. A wider range of task difficulty may be required in order to elicit statistically measurable differences in the MMN. Finally, previous studies have almost exclusively employed small (Alho et al., 1992; Harmony et al., 2000; Kathmann et al., 1999) or large (Alho et al., 1992; Otten et al., 2000) frequency deviants. MMNs elicited by large deviants have generally not been affected by attentional manipulations (Woods et al., 1992). Moreover, the MMN to an intensity deviant has been reported to be particularly susceptible to the effects of attention (Näätänen et al., 1993b). An intensity deviant was not employed in these studies.

In the present study, subjects were instructed to perform a visual discrimination task while ignoring the auditory stimuli. In one condition this task was very easy, with hit rates close to 1.0. In another condition, the discriminability of the visual target was adjusted for each subject in order to obtain hit rates that were close to 0.50. Therefore, in contrast to previous studies, this experiment was designed to assure a large separation in terms of performance between the "easy" and "difficult" tasks. Furthermore, auditory and visual stimuli were presented at rapid and unpredictable rates. The auditory stimulus sequence included both small frequency and intensity deviants.

As previously mentioned, the manipulation of the demands of the visual task has been assumed to vary the extent to which attention can also be directed to the auditory channel. More specifically, it is believed that as the demands of the task increase, the available resources for covert processing of the task-irrelevant auditory stimuli decrease. This assumption is tested in the present study. Divided attention paradigms are often used to determine the extent to which processing of different tasks actually compete for the same resources (Pashler, 1994). In the second part of this study, subjects were again asked to perform, in separate conditions, an easy or difficult visual discrimination task. In addition, they were instructed to concurrently discriminate the rare intensity and frequency stimulus changes presented in the auditory channel. It was expected that if processing resources were to a large extent shared by the auditory and visual tasks, then auditory performance measures and auditory ERPs would be sensitive to the manipulation of visual task difficulty.

The main purpose of the present study was to examine the effects of visual task demands on the passively-elicited MMN. A second and related question also addressed in this study concerned the effects of the direction of attention on the MMN. This issue has previously been investigated by studies employing intermodal auditory-visual selective attention tasks. These studies have shown that, under some circumstances, the MMN appeared to be larger when subjects attended to the eliciting auditory stimuli compared to when they were engaged in a visual task such as reading (Alain & Woods, 1997; Schröger, 1995) a visual discrimination task (Alho et al., 1992; Woods et al., 1992) or a video game (Gomes et al., 2000; Kramer et al., 1995; Woods et al., 1992). This attentional effect emerged primarily when the MMN-eliciting deviants closely resembled the standard stimuli, such as those employed in the present study (Alho et al., 1992; Woods et al., 1992). Again however, the larger MMN reported in the attended condition may in part be explained by an overlapping attention-dependent N2b component. Subtle differences between the characteristics of the MMN and N2b may be useful in disentangling their respective contribution to the composite negativity. The MMN often has maximal amplitude at fronto-central scalp sites, inverts in polarity below the Sylvian fissure, and occurs prior to 200 ms following stimulus onset. The N2b is typically largest at central sites, remains negative-going at sites below the Sylvian fissure, and reaches peak amplitude after 250 ms (Alho et al., 1986a). In the present study, attention was directed exclusively to the visual task during the focused visual condition, whereas subjects attended to both the visual and auditory channels during the divided attention condition. The effects of the direction of attention were evaluated by comparing the MMNs obtained when the auditory stimuli were ignored (focused condition) with that obtained when the auditory stimuli were attended (divided condition).

2. Methods

2.1. Subjects

Twelve university students (6 women and 6 men) with self-reported normal hearing and no history of neurological or psychiatric problems volunteered to participate in this study. Subjects were right-handed and between the ages of 17 and 27 years (M = 20.9, SD = 2.9). Written informed consent was obtained prior to the study and an honorarium was offered as compensation. This study was conducted following the guidelines of the Canadian Tri-Council (Medical, Natural and Social Sciences) on ethical conduct for research involving humans.

2.2. Stimuli

The standard auditory stimulus was an 80 dB SPL 1000 Hz tone pip having a total duration of 55 ms (5 ms rise/fall time). It was presented binaurally via insert earphones (EAR 3A) with a 0.85 probability of occurrence. A frequency deviant (80 dB SPL 1050 Hz) and an intensity deviant (70 dB SPL 1000 Hz) were presented at random in the same auditory condition, each with a probability of 0.075. The auditory standard and deviants were identical to those employed in the Näätänen et al. (1993b) study. A Bruel and Kjaer 2209 sound level meter equipped with a 2 cm^3 coupler was used to calibrate the stimulus intensity.

Visual stimuli were presented for a duration of 50 ms on a computer monitor situated approximately 80 cm from the subject. The standard visual stimulus was a 21.0 cm horizontal x 12.5 cm vertical black-and-white (contrast = 0.99) checkerboard display having 5 rows and 7 columns. Each check thus measured 3.0 cm in width and 2.5 cm in height. The standard stimulus occurred with a probability of 0.925. On the remaining 7.5 % of trials, a visual target was randomly presented. In different conditions, the target was either easy or a difficult to discriminate from the standard. The easy visual target was constructed by superimposing a large green ellipse measuring 15.0 cm in width and 12.5 cm in height over the standard checkerboard. The difficult visual target was constructed by changing the color of the central white check to a light shade of blue. The saturation of this central check was adjusted for each subject depending on their performance in a practice session (as explained in the Procedure section). Figure 1 illustrates the standard, easy-to-detect and difficult-to-detect visual stimuli.

Mixed sequences of equiprobable auditory and visual stimuli were presented with a random ISI (onset-to-onset) ranging between 250 and 350 ms. The order of presentation of both visual and auditory stimuli was pseudo-randomized. Auditory deviants were separated by at least three auditory standards. Visual targets were separated by at least two visual standards. Eight percent of the auditory frequency deviants and 8% of the intensity deviants were immediately followed by presentation of a visual target. At no time did a visual target immediately precede an auditory deviant.

---------------- Figure 3.1 about here ----------------

2.3. Procedure

During the EEG recording session, subjects were seated in a dimly lit, sound attenuated room. They were asked to focus on a fixation point (a + in the central check) presented on the computer monitor.

2.3.1. Focused Attention

In the first part of the experiment, subjects were instructed to attend exclusively to the visual stimuli (i.e. ignore the auditory stimulation) and to detect the rare visual targets. In separate conditions, the visual targets were either easy or difficult to discriminate from the standard. Detection of the target was indicated by pressing the space bar on the computer keyboard with the right index finger. Both speed and accuracy of responding were stressed.

Before the start of the experiment, subjects received training in the difficult visual target detection task. If the subject's hit rate was over 0.65, the saturation of the light blue central check was decreased. When a hit rate of 0.35 was not achieved after extensive training, the saturation was increased. All subjects subsequently received two practice blocks (one for each level of difficulty) of the visual target detection task without hearing tones. Each practice block included 400 visual stimuli, consisting of 370 standards and 30 targets.

A total of 2000 trials were presented in each experimental block. Three blocks of stimuli were presented in both the easy and difficult conditions (i.e., a total of 6000 trials per condition consisting of 2775 visual standards, 225 visual targets, 2550 auditory standards, 225 frequency deviants and 225 intensity deviants). The presentation of the conditions alternated between easy and difficult visual tasks and was counterbalanced across subjects. Short breaks were given between each block. During the break, subjects were asked to rate the difficulty of the previous task on a 1 (easy) to 10 (difficult) scale.

2.3.2. Divided Attention

In the second part of the experiment, subjects were again asked to perform, in separate conditions, the easy and difficult visual discrimination tasks. In addition, they were instructed to concurrently discriminate the auditory (frequency and intensity) deviants. This thus required that they divide their attention between the visual and auditory channels. Subjects were asked to press the space bar on the computed keyboard as quickly and accurately as possible when a visual or auditory target was detected. Prior to the presentation of the experimental blocks, subjects received training in discriminating the frequency and intensity deviants.

Again, a total of 2000 trials were presented per block. One block of stimuli was presented for each level of visual task difficulty (i.e., a total of 925 visual standards, 75 visual targets, 850 auditory standards, 75 frequency targets and 75 intensity targets per condition). The order of conditions was counterbalanced across participants.

2.4. EEG/ERP Recording

EEG activity was recorded from 6 scalp channels (Fz, Cz, Pz, Oz, F3, F4) using tin electrodes attached to an electrode cap (Electro-Cap International Inc., Eaton, OH). Two additional channels were recorded from individual tin cup electrodes placed on the left and right mastoids (M1, M2). The nose served as a reference. A vertical EOG was recorded from electrodes placed at the infra- and supra-orbital ridges of the right eye. A horizontal EOG was recorded from electrodes placed at the outer canthus of each eye. The ground electrode was attached to the forehead. Inter-electrode impedances were below 5 kOhms.

The physiological signals were digitized continuously at a 256 Hz sampling rate using a 12-bit analogue-to-digital (A/D) converter and stored on hard disk for later off-line analysis. The analogue high frequency filter was set at 30 Hz and the time constant at 2 s. Eye movement and blink artifact were corrected using an algorithm operating in the time and frequency domain (Woestenburg et al., 1983). The continuous data were subsequently reconstructed into discrete trials or “sweeps”. The sweep time was 1000 ms, which included a 100 ms pre-stimulus baseline period. Trials containing values greater than ± 100 μV relative to the baseline on the EEG channels were excluded from further analyses. The single-subject ERPs were averaged separately for each stimulus type (visual standard, visual deviant, auditory standard, frequency deviant, intensity deviant), each level of visual task difficulty (easy, difficult) and the direction of attention (focused, divided), yielding 20 different average waveforms per subject. The ERP averages to targets (visual or auditory) only included trials in which a correct response occurred 200-1100 ms following stimulus onset. Responses outside of this range were considered to be outliers, occurring on fewer than 2% of trials. The non-target averages only included trials in which a response was withheld. Subsequently, ERPs were digitally low-pass filtered using an inverse FFT algorithm with a 20 Hz high frequency cutoff.

2.5. Performance and Physiological Data Analyses

Performance data were collected for the visual targets during the focused attention conditions, and for the visual and auditory targets during the divided attention conditions. A response occurring between 200 and 1100 ms of target presentation was classified as a "hit". A response that occurred outside of this time interval (i.e., prior to 200 ms or after 1100 ms) was presumed to reflect a response to a standard stimulus and was thus classified as a "false alarm". In addition to the hit and false alarm rates, the mean reaction time (RT) to correctly detected targets was also collected during each of these conditions.

Analyses were performed on various visual and auditory ERP waveforms elicited by both the frequently occurring standard stimuli and the infrequently occurring deviant/target stimuli. The purpose of the analyses on the non-MMN waveforms was to verify that the experimental manipulations (attention, task difficulty) were indeed effective. Some of the ERP waveforms appeared as a distinctive peak while others appeared as a slow wave. Two methods were therefore used to quantify these data (Hoormann, Falkenstein, Schwarzenau, & Hohnbein, 1998). Maximum peak amplitude detection methods were used when discrete peaks were apparent. On the other hand, when the waveform consisted of a long-lasting slow potential, the latency range of interest was divided into consecutive 50 ms intervals. All data points within each 50 ms interval were then averaged yielding a mean amplitude for each interval. For both the peak and interval analyses, the average of all data points in the 100 ms pre-stimulus interval was used as a baseline.

2.5.1. Standard ERPs

In all experimental conditions, the ERPs to the visual and auditory standards were quantified by computing a mean amplitude for each 50 ms interval. Intervals were analyzed at

Oz, for the visual standards and at Cz, for the auditory standards, sites at which selective attention has been shown to have large effects within the respective modality (Alho et al., 1992).

2.5.2. Target ERPs

Target ERPs included the ERPs elicited by the visual targets in the focused attention conditions, and those elicited by the visual and auditory targets in the divided attention conditions. The peak amplitude and latency of N2 and P3b were scored on the target ERPs at Cz and Pz, respectively. The latency windows for these peaks were selected based on grand average waveforms.

2.5.3. Deviant – Standard Difference Waveforms

The MMN is generally scored in the difference waveform. Frequency and intensity difference waves were obtained by subtracting point-by-point the auditory standard ERP from the respective auditory deviant ERP, at each electrode site. Difference waves were computed for focused attention conditions, as well as for divided attention conditions. In all conditions, the peak amplitude and latency of the MMN were scored at Fz, F3, F4, M1 and M2 during a time window determined based on grand average waveforms[21]. The MMN may sometimes appear as a negative slow wave. For this reason, an analysis of mean amplitude values, computed by averaging all data points within a 50 ms interval was also performed on the difference waveform at Fz and M1. The interval analysis included possible waveforms occurring after the MMN.

2.6. Statistical Analyses

2.6.1. Focused Attention

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[21] The most negative peak in this time window was labeled the "MMN", although it may have received a contribution from other deviance-related negativities, such as the N2b. This issue will further be addressed in the discussion.

Most of the performance and physiological data collected in the focused attention conditions were subjected to one-way ANOVAs with repeated measures on task difficulty (Easy, Difficult). Hemispheric MMN differences at frontal (F3, F4) and mastoid (M1, M2) sites were analyzed with two-way (task difficulty, hemispheric site) repeated measure ANOVAs. When other types of analyses were performed, they are specified in the Result section.

2.6.2. Divided Attention

The data obtained during the divided attention conditions were primarily subjected to analyses that also included the data obtained during the focused attention conditions. These analyses thus consisted of two-way ANOVAs with repeated measures on task difficulty (Easy, Difficult) and on the direction of attention (Focused, Divided). Three-way repeated measures (Task difficulty, Direction of attention, Hemispheric site) ANOVAs were performed on the peak MMN data at F3 and F4, as well as at M1 and M2. Again, any deviation from this analysis procedure is specified in the Result section.

3. Results

3.1. Focused Attention

3.1.1. Performance Data

The means for hit rate, RT and false alarm rate obtained in the easy and the difficult visual tasks during focused attention are presented in the left portion of Table 1. Visual task difficulty had a significant effect on performance[22]. The hit rate for the easy visual target was significantly higher than for the difficult target, $F(1,11) = 66.4$, $p < 10^{-5}$. In addition, RT to the detected easy visual targets was significantly faster than to the detected difficult targets, $F(1,11) = 146.0$, $p < 10^{-7}$. The high hit rate for easy-to-detect targets was not accomplished by

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[22] A 2 X 3 repeated measure (task difficulty, presentation block) ANOVAs indicated that the performance measures did not significantly vary across blocks. These data were therefore collapsed across blocks.

adopting a liberal response strategy. The false alarm rate in the easy condition was significantly lower than in the difficult condition, $F(1,11) = 19.8, p < 10^{-3}$. Subjective ratings of task difficulty were in accordance with the performance measures. The easy visual task was rated as being significantly less demanding ($M = 2.0$; $SD = 0.7$) than the difficult visual task ($M = 8.1$; $SD = 1.9$), $F(1,11) = 87.8, p < 10^{-6}$.

----------------- Insert Table 3.1 about here -----------------

The effect of auditory distraction on visual performance was examined by comparing visual target trials that were preceded by an auditory standard to those that were preceded by an auditory deviant (Alho et al., 1992; Woods et al., 1992). Eight percent of frequency and intensity deviants were immediately followed by presentation of a visual target. For purposes of comparison, an equal number of trials in which an auditory standard preceded the visual target were also randomly selected. A two-way ANOVA with repeated measures on visual task difficulty and type of preceding auditory stimulus (standard, frequency deviant, intensity deviant) was performed on the performance data. The type of preceding auditory stimulus did not have a significant effect on either the visual target hit rate or RT.

3.1.2. Visual ERPs

The left panel of Figure 2 illustrates the grand average ERPs following the visual standard and target stimulus during the focused attention conditions. As may be observed, the visual standard stimulus elicited a polyphasic sequence of deflections at Oz, including a large P120, N160 and P200. The standard ERP in the difficult condition was associated with a small positive enhancement (positive visual difference wave – Pd_v) from 90-130 ms followed by a longer-lasting negative enhancement (negative visual difference wave – Nd_v) from 130-300 ms relative to the standard ERP in the easy condition. The effect of task difficulty on the visual standard ERP was significant in the intervals ranging from 200-300 ms, $F(1,11) = 5.8$ and 26.8, $p < .04$ for both intervals.

The visual target stimuli elicited additional ERP components, most notably, the N2-P3b complex. As is evident in the left panel of Figure 2, the N2-P3b components were significantly affected by visual task difficulty. The P3b peaked at 405 ms (SD = 33 ms) and 554 ms (SD = 50 ms) in the easy and difficult conditions, respectively, $F(1,11) = 89.2$, $p < 10^{-6}$. Its amplitude was significantly smaller in the difficult relative to the easy condition, $F(1,11) = 43.3$, $p < 10^{-4}$. N2 also peaked earlier in the easy condition (M = 247 ms, SD = 20 ms) than in the difficult condition (M = 357 ms, SD = 35 ms), $F(1,11) = 75.6$, $p < 10^{-5}$. The amplitude of N2 at Cz, however, did not significantly vary between the two task conditions.

----------------- Insert Figure 3.2 about here -----------------

3.1.3. Auditory ERPs

The ERPs elicited by the auditory standard and deviant stimuli during the focused attention conditions are presented in the left panel of Figure 3. The ERPs to the auditory standards mainly consisted of N1 (100 ms), P2 (170 ms) and N2 (230 ms) deflections. The intervals that included these deflections were not significantly affected by visual task difficulty. The ERPs elicited by the frequency and intensity deviants were characterized by an additional negativity, the MMN, peaking between 150-200 ms. The MMN was analyzed in the difference waves, computed by subtracting the ERP to the standard from the ERP to the frequency and intensity deviants.

----------------- Insert Figure 3.3 about here -----------------

3.1.4. Frequency Difference Waveforms

The frequency difference waves are illustrated in Figure 4. A large MMN (approximately –2.0 µV at Fz) was elicited by the frequency change under both the easy and difficult task conditions. The MMN was maximal over fronto-central areas of the scalp and inverted in polarity at the mastoids. The MMN was slightly but significantly larger at right than left frontal sites, $F(1,11) = 6.2$, $p < .03$. At Fz, it peaked at 169 ms (SD = 17 ms) in the easy condition and at 173 ms (SD = 23 ms) in the difficult condition, F < 1. Importantly, the peak amplitude of the MMN at frontal (Fz, F3, F4) and mastoid (M1, M2) sites was not significantly modulated by the difficulty of the visual task, all Fs < 1. The interval analyses confirmed these results. When the data at Fz were averaged in consecutive 50 ms time intervals, no significant differences were found in the 100-250 ms intervals, which included the MMN. Similarly, at M1, none of the intervals between 100 and 250 ms revealed significant differences as a result of visual task difficulty. A small central positivity (P3a) was apparent following the MMN but the interval that included this positivity (250-300 ms) did not significantly vary between task conditions. A later 400-500 ms negativity was also evident over frontal sites, but again the difference between visual task conditions was not significant.

---------------- Insert Figure 3.4 about here ----------------

3.1.5. Intensity Difference Waveforms

The MMN to the small intensity change is visible in the difference waves presented in Figure 5. The MMN in both task conditions was again relatively large (approximately –1.4 μV), with a fronto-central scalp distribution and polarity inversion at the mastoids. The intensity MMN was larger over the right than the left frontal site, F(1,11) = 7.4, p < .02. It peaked at 175 ms (SD = 22 ms) in the easy condition and at 178 ms (SD = 19 ms) in the difficult condition, F < 1. The peak amplitude of the MMN at frontal (Fz, F3, F4) and mastoid (M1, M2) sites did not significantly differ between the two visual task conditions, all Fs < 1. The interval analysis at Fz and M1 similarly indicated that visual task difficulty did not have an effect on the intervals between 100-250 ms. In contrast to the frequency difference waveform, the intensity difference waveform did not reveal a central positivity following the MMN or a late negativity.

---------------- Insert Figure 3.5 about here ----------------

3.2. Divided Attention

3.2.1. Performance Data

Mean hit rate, RT and false alarm rate for the easy and difficult visual discrimination task during divided attention can be found in the right portion of Table 1. The main effect of visual task difficulty was again significant for both hit rate and RT, $F(1,11) = 48.4$ and 92.1 respectively, $p < 10^{-4}$ in both cases. The direction of attention also significantly affected the hit rate and RT to the visual targets, $F(1,11) = 13.5$ and 22.4 respectively, $p < .01$ in both cases. When attention was focused exclusively on the visual channel, the hit rate was higher and the RT was faster compared to when attention was divided between the visual and auditory channels. Importantly, the Task difficulty x Direction of attention interaction was not significant for either hit rate or RT, $Fs < 1$.

In the divided attention conditions, subjects were asked to detect the auditory deviants in addition to the visual deviants. The auditory performance data were examined using two-way ANOVAs with repeated measures on visual task difficulty and type of auditory deviant (frequency, intensity). Table 2 contains the mean hit rate, RT and false alarm rate for the frequency and intensity targets during the easy and difficult visual task conditions. The main effect of visual task difficulty was not significant for either the auditory target hit rate or RT, $F(1,11) = 3.1$ and 3.3 respectively, $ps > .05$. Hit rate and RT were significantly modulated, however, by the type of auditory target, $F(1,11) = 40.2$ and 23.2 respectively, $ps < 10^{-3}$. Subjects obtained higher hit rates and faster RTs for the frequency target detection than for the intensity target detection.

----------------- Insert Table 3.2 about here -----------------

The hit rates obtained for the visual and auditory target detections during divided attention were not achieved by a lax response bias. The visual and auditory false alarm rates remained low (< .04) for both the easy and difficult divided attention conditions (see Table 1 and 2). As was the case in the focused attention condition, the false alarm rates obtained during visual and auditory task were significantly affected by visual task difficulty, F(1,11) = 51.9 and 10.1, respectively, ps < .01. They were higher during the difficult than the easy visual discrimination task.

3.2.2. Visual ERPs

The right panel of Figure 2 illustrates the ERPs following the visual standard and target stimuli when subjects divided their attention between the visual and auditory channels. The visual standard ERP was again characterized by a P120-N160-P200 complex at Oz. When attention was divided between visual and auditory channels, the intervals that included these deflections were not significantly affected by visual task difficulty. The direction of attention also had minimal effects on the visual standard ERP. When the visual task was easy, there was no difference between the standard ERPs elicited during divided and focused attention. When the visual task was difficult, the N160-P200 deflections showed a small negative enhancement (Nd_v) in the focused relative to the divided condition. This interaction reached significance during the 150-200 ms interval, F(1,11) = 5.6, p < .04. The interaction was due to an effect of task difficulty in the focused (rather than the divided) attention condition.

During the divided attention condition, the visual target stimuli again elicited an N2 followed by a P3b deflection. The effects of visual task difficulty on the target ERPs during divided attention replicated those previously reported for the focused attention condition. N2 was significantly delayed when targets were difficult to detect (M = 370 ms; SD = 33 ms) compared to when they were easy to detect (M = 254 ms; SD = 22 ms), F(1,11) = 248.4, $p < 10^{-7}$, independently of the direction of attention. A significant interaction was found for the latency of P3b, F(1,11) = 8.8, p < .01. Simple effects testing showed that in both focused and divided attention conditions, the P3b to the easy target peaked significantly earlier (M = 427 ms; SD = 41 ms) than that to the difficult target (M = 565 ms; SD = 55 ms). The amplitude of the P3b was also significantly larger when the task was easy compared to difficult regardless of the direction of attention, $F(1,11) = 19.5$, $p < 10^{-3}$. Important P3b differences were noted due to the direction of attention. Simple effect testing on the P3b latency data further indicated that P3b occurred earlier in the focused (M = 405 ms; SD = 33 ms) than divided (M = 451 ms; SD = 54 ms) condition but this was only significant when the target was easy to detect. A main effect of the direction of attention was also found for the amplitude of P3b, $F(1,11) = 14.5$, $p < .01$. It was larger when attention was exclusively focused on the visual channel.

3.2.3. Auditory ERPs

The right panel of Figure 3 illustrates the auditory standard and target ERPs obtained during the divided attention conditions. The ERP elicited by the auditory standard during the divided condition showed an early negative enhancement (Negative auditory difference wave – Nd_a) followed by a positive enhancement (Positive auditory difference wave – Pd_a) relative to that elicited during the focused visual conditions. These attention-related waves can best be observed in the difference waveforms computed by subtracting the standard ERP obtained during the focused condition from the standard ERP obtained during the divided condition (see Figure 6). In the intervals between 50-150 ms, a significant interaction between the task difficulty and the direction of attention was found, $F(1,11) = 5.0$ and 9.8 respectively, $p < .05$ for both intervals. Simple effects testing revealed that the Nd_a was significant during these intervals only when the visual task was difficult (as compared to easy). Between 150 and 200 ms, regardless of the difficulty of the visual task, the auditory standard ERP remained more negative-going when attention was divided between the auditory and visual channels, although the main effect of the direction of attention just failed to reach significance, $F(1,11) = 4.3$, $p < .07$. Finally, from 200-300 ms, the trend reversed such that the ERP in the divided condition was more positive-going than that in the focused condition for both levels of task difficulty. A significant interaction during these intervals indicated, however, that this attention effect was only significant for the easy task condition, $F(1,11) = 5.1$ and 5.0, $p < .05$ in both intervals.

----------------- Insert Figure 3.6 about here -----------------

When subjects were asked to divide their attention, the detection of the auditory deviants resulted in ERP components that were not apparent when subjects focused only on the visual channel. These additional ERP components, including a central negativity (N2b) and a large parietal positivity (P3b), are illustrated in the right panel of Figure 3. The peak amplitude and latency of these deflections were examined using two-way ANOVAs with repeated measures on visual task difficulty and type of auditory deviant (frequency, intensity). P3b peaked at approximately 550 ms following stimulus onset. No significant main effects or interaction were found for either the latency or amplitude of this component. The analysis of the N2b latency data yielded a significant main effect of the type of auditory target, $F(1,11) = 17.1$, $p < .01$. N2b occurred significantly later following presentation of the intensity ($M = 310$ ms; $SD = 43$ ms) compared to the frequency ($M = 265$ ms; $SD = 32$ ms) target. The amplitude of N2b was not significantly affected by the type of auditory target or the difficulty of the task.

3.2.4. Frequency Difference Waveforms

The frequency difference waves obtained during the focused and divided attention conditions are presented in the left panel of Figure 7. As indicated in the previous section, attention to the auditory channel (i.e., divided attention condition) resulted in the elicitation of several additional deviance-related components other than the MMN. In the divided condition, the difference wave revealed a late positivity preceded by a long-lasting negativity. This long-lasting negativity consisted of a composite of an earlier MMN and a later attention-dependent N2b. The peak amplitude and latency of the frequency MMN were scored in the time window of 130 to 210 ms in the divided attention conditions. The MMN peaked at approximately 170 ms. It inverted in polarity at the mastoid at this peak latency. N2b peaked at 265 ms (as noted above) and it did not invert in amplitude at the mastoids. The peak latency of the MMN did not significantly vary as a function of the direction of attention or task difficulty, all $Fs < 1$.

Independently of the direction of attention or the task difficulty, the MMN was significantly larger at F4 than at F3, F(1,11) = 6.6, p < .03. Its peak amplitude at frontal (Fz, F3, F4) sites was not significantly affected by the direction of attention, Fs < 1, or the visual task difficulty, Fs < 1. The main effect of the direction of attention, nevertheless, did approach significance at the mastoid sites, F(1,11) = 4.4, p < .06. The MMN at the mastoids was larger when subjects divided their attention than when they focused on the visual channel.

The interval analysis of the frequency difference waveforms at Fz and M1 also failed to reveal either significant main effects or an interaction in the intervals ranging from 0 to 200 ms, which included the MMN. Between 200 and 300 ms, the main effect of the direction of attention was significant at Fz, F(1,11) = 8.8 and 16.6, respectively, p < .01 for both intervals. The frequency difference wave was significantly more negative-going (mainly because of N2b) when subjects divided their attention between the auditory and visual channels than when they focused only on the visual channel. From 350 to 500 ms, a main effect of the direction of attention was again found at Fz, F(1,11) = 5.1 to 8.4, p < .05 for all intervals. The frequency difference wave was significantly more positive-going (because of P3b) during the divided than focused attention conditions.

----------------- Insert Figure 3.7 about here -----------------

3.2.5. Intensity Difference Waveforms

The intensity difference waves for the divided and focused conditions are presented in the right panel of Figure 7. The MMN was scored in a 150 to 230 ms time window of in the divided attention conditions. It peaked at approximately 190 ms. At this latency, the MMN was maximal over frontal regions and inverted in amplitude at the mastoids. In contrast, the later N2b (310 ms) was maximal at Cz and did not invert in amplitude at the mastoids. The MMN was again significantly larger at the right than left frontal site, F(1,11) = 11.1, p < .01. There were no significant main effects or interaction involving the latency of the MMN, F(1,11) = 1.4

to 1.9, $p > .05$ in all cases. Visual task difficulty did not significantly modulate the amplitude of the MMN at either frontal (Fz, F3, F4) or mastoid (M1, M2) sites, Fs < 1. In contrast, the direction of attention did have a significant effect on the amplitude of the MMN at Fz, $F(1,11) = 5.9$, $p < .04$, as well as at F3 and F4, $F(1,11) = 6.3$, $p < .03$. The intensity MMN was larger when subjects divided their attention between channels than when they focused only on the visual channel. The direction of attention did not significantly affect the MMN at left and right mastoid sites, $F(1,11) = 2.1$, $p > .05$.

The interval analysis revealed similar effects. At Fz, a significant main effect of the direction of attention was found for the 200-250 ms interval, corresponding to the latency range of the MMN, $F(1,11) = 5.4$, $p < .04$. During this time interval, the difference wave was more negative in the divided than focused attention condition. No significant effect of the direction of attention, however, was found in this time interval at M1. The main effect of the direction of attention at Fz continued in the 250-350 ms intervals, $F(1,11) = 5.3$ and 6.3 respectively, ps < .04. The difference wave in the divided condition remained more negative during these intervals (because of the N2b). Finally, from 500-550 ms, the difference wave in the divided attention condition was significantly more positive (because of the P3b) relative to that of the focused attention condition, $F(1,11) = 5.2$, $p < .04$.

4. Discussion

The present study examined the effect of visual attentional engagement on the passively-elicited MMN. Subjects were instructed to perform an easy and difficult visual discrimination task while ignoring the auditory stimuli. In order to assure a strong focusing of attention, stimuli were presented at rapid rates. The extent to which the visual task required attentional resources was manipulated by varying the ease of discrimination of a rarely occurring visual target. Behavioural and ERP findings suggest that this manipulation was successful. The hit rate was considerably higher and the reaction time was considerably faster for the easy compared to the difficult task. Subjective difficulty ratings were in accordance with the performance measures.

The ERPs elicited by the detected visual targets included late N2 and P3b deflections. When the visual target was difficult to detect, the latency of the N2-P3b complex was delayed and the amplitude of P3b was attenuated. Many studies have reported similar effects with increasing difficulty of visual target discrimination (Brecher, Porjesz, & Begleiter, 1987; Magliero, Bashore, Coles, & Donchin, 1984). The latency effects are believed to reflect the additional time required for stimulus evaluation when the target is difficult to discriminate from the standard (Donchin, 1979). The latency of these components is largely unaffected by the response production and execution processes that might have accounted for variation in the behavioural reaction time (Donchin & Coles, 1988). P3b amplitude is affected by equivocation of decision-making, the certainty that the rare target stimulus was indeed presented (Johnson, 1993). Finally, task difficulty also modulated general visual processing, as indexed by the standard visual ERPs. Attention to visual stimuli has been associated with an early positive enhancement followed by a broad negative wave (Pd_v – Nd_v effect, see Alho et al., 1992; Woods et al., 1992). In the present study, the standard ERP in the difficult condition showed a small, but non-significant positive enhancement followed by a significant negative enhancement relative to the standard ERP of the easy condition. Together, these results strongly suggest that the attentional load of the difficult task was greater than that of the easy task.

The small frequency and intensity changes elicited a large MMN that peaked between 170 and 180 ms. The frequency and intensity MMNs were maximal at fronto-central scalp sites, inverted in amplitude below the Sylvian fissure and displayed a right-hemisphere preponderant distribution. These characteristics have often been associated with the MMN (Paavilainen et al., 1991). Importantly, the amplitude of the frequency and intensity MMNs was essentially identical in both easy and difficult visual discrimination tasks, in spite of the wide variation in performance measures. The failure to find an effect of visual task demands on the MMN was observed in several other studies (Alho et al., 1992; Dittmann-Balcar et al., 1999; Harmony et al., 2000; Kathmann et al., 1999; Otten et al., 2000), although they did not report differences in visual task performance as large as those observed here. Furthermore, the insensitivity of the MMN to variations in task difficulty now extends to that elicited by a small intensity change.

These results provide convincing evidence that the amplitude of the MMN occurs independently of the allocation of attentional resources to the visual domain. Similar findings have previously been interpreted as evidence that the MMN process does not require and is not modulated by attention. This interpretation is based on the assumption that the focus required by the difficult visual task does not allow subjects to process the irrelevant auditory input, whereas during the easy visual task additional resources are available for this purpose. This assumption was tested in the present study by assessing the extent to which visual engagement affects active auditory processing. In order to achieve this, a divided-attention paradigm was employed.

In the divided attention condition, subjects were instructed to attend to both the visual and auditory channels and behaviourally respond to the deviants in both modalities. The auditory target detection was easily performed, with hit rates comparable to those previously obtained when subjects focused exclusively on an identical auditory target discrimination task (Näätänen et al., 1993b). Critically, auditory performance was not significantly affected by visual task difficulty, whether the auditory target was a small intensity or frequency change. Therefore, the demands of the visual task did not differentially interfere with subject's ability to overtly detect the auditory targets. The introduction of the auditory task did cause, however, a small deterioration in the visual task performance. This performance decrement was, nevertheless, independent of visual task difficulty.

The performance effects were reflected in the visual and auditory target ERPs. The amplitude of the visual P3b was significantly attenuated by the introduction of the auditory task, regardless of visual task difficulty. This replicates many other studies indicating that P3b amplitude is dependent on workload demands (Wickens, Kramer, Vanasse, & Donchin, 1983). Detection of the auditory targets also resulted in the elicitation of an N2b-P3b complex. Importantly, visual task difficulty did not affect these auditory components. When intensity and frequency deviants were targets, the respective difference waveforms were characterized by a double-peaked negative deflection. The first peak presumably reflected the MMN, whereas the second peak was identified as the N2b. The earlier deviance-related negativity occurred between 170-190 ms, showed a fronto-central scalp distribution, an inversion at the mastoid and a right-hemispheric preponderance. These characteristics suggest that this early negativity did indeed reflect a genuine MMN component. The MMN, like the N2b and P3b components, was not affected by the difficulty of the visual task when the auditory stimuli were attended.

Together these results argue against the assumption that during a difficult visual task, subjects are minimally able to process the auditory channel whereas more resources could be allocated to the processing of this irrelevant auditory channel during the easy visual task. Overt processing of the auditory channel can be carried out rather easily and with minimal cost to detection of the visual targets, even when the visual discrimination task is exceedingly difficult. When resources are shared between two tasks, the secondary task is usually affected by the level of difficulty of the primary task (Wickens, 1980). The present study also failed to find a modulation of secondary (auditory) task performance with variations in the difficulty level of the primary (visual) task. These results suggest that the auditory discrimination task was largely carried out independently of the visual discrimination task. As such, in intermodal discrimination tasks, it is may be possible for subjects to monitor the irrelevant auditory channel and still maintain a high level of performance even when the visual detection task makes strong attentional demands. Lavie (1997) has noted that if perceptual systems are not overloaded, then all stimuli, whether attended or not, can be processed. This would then overcome the need to discard apparently irrelevant information that might later prove to be useful.

Finally, the effects of attention on the MMN were also examined by comparing conditions of active and passive acoustic change detection. During the focused visual condition, the auditory channel was to-be-ignored, whereas during the divided condition, it was to-be-attended. There was evidence in the standard auditory ERPs that subjects did indeed direct more attention to the auditory channel during the divided than focused condition. Auditory attention was associated with an early negative enhancement (Nd_a) followed by a small positive deflection (Pd_a). Several auditory-visual intermodal selective attention studies have reported a similar attention-related biphasic (Nd_a-Pd_a) modulation of the auditory ERPs (Alho et al., 1992; Woods et al., 1992). This intermodal attention effect is in contrast with the long-lasting negativity (early and late Nd_a) elicited with attention in auditory intramodal selective attention studies (Alho, 1992).

The direction of attention had little effect on the MMN elicited by the frequency deviant. On the other hand, it had a significant effect on the MMN elicited by the intensity deviant. Regardless of task difficulty, the intensity MMN at frontal sites was larger when attention was directed to the auditory channel. This attention-related effect is unlikely to be due to the overlapping and summating effects of the later N2b. The larger early negativity elicited by the intensity deviant under divided attention displayed the temporal and spatial characteristics typical of the MMN. In addition, the attentional effect started early, before the peak of the MMN. The contribution of the N2b to such an attention effect would be expected to be greatest when the N2b and the MMN occur in close temporal proximity. The MMN and

N2b processes occurred in closer temporal proximity following presentation of the frequency deviant. Yet, attention did not affect the frequency MMN.

Different interpretations of the attentional modulation of the MMN have been offered. It is possible that the ignored auditory sensory input may have been inhibited or degraded relative to the attended input prior to entry into the MMN generating system (Woldorff et al., 1991). As Näätänen (1991) has argued however, it is difficult to understand how sensory gating could explain an attention-related MMN effect for only one deviant feature (i.e. intensity) in a two-deviant sequence (i.e. intensity and frequency). Presumably, sensory gating should affect all unattended sensory input. Instead, Näätänen suggested such an effect could be due to the specific attentional modulation of the intensity-MMN generator process. This explanation would require separate generators for the frequency and intensity MMNs. Findings that the underlying sources for the frequency and intensity MMNs may differ supports this proposal (Giard et al., 1995).

The pattern of attention effects noted in the present study may alternatively be explained by the difference in perceptual discriminability of the intensity and frequency deviants. Both Woods et al. (1992) and Alho et al. (1992) found that attention resulted in a larger MMN to a frequency deviant when it was close in pitch to the standard; attention had little effect on the MMN when the frequency deviant was more distant from the standard. Several results in the present study suggest that the frequency changes were more perceptible than the intensity changes. The frequency deviants were detected more accurately and more rapidly than the intensity deviants. The N2b elicited by the intensity deviant was also delayed relative to that elicited by the frequency. This is consistent with findings that N2b occurs later with increasing difficulty of the auditory target discrimination (Fitzgerald & Picton, 1983). Furthermore, the MMN in the focused condition was larger following the frequency than the intensity deviant[23]. The amplitude of the MMN typically varies as a function of the ease of discrimination of the deviant (Sams et al., 1985). An explanation that is more consistent with the present findings is that attention enhances the discriminability of the deviant relative to the standard. According to Cowan (1995), attention may result in a more accurate and longer-lasting stimulus representation. In this way, attention could increase the quality and strength of the memory trace for the standard, effectively increasing the discriminability of the deviant (Alain & Woods, 1997; Szymanski et al., 1999). In the present study, the same standard neuronal representation served for comparison to the frequency and intensity deviants. The improved signal-to-noise ratio of the representation of this standard would greatly enhance the discriminability of the difficult-to-detect intensity deviant but would do little to enhance the discriminability of the already easy-to-detect frequency deviant. Large changes in the auditory environment may be readily detected even when occurring outside the focus of attention, whereas attention may increase the sensitivity to smaller acoustic changes.

5. Conclusion

The passively-elicited MMN was not modulated by visual task difficulty, even though the difficult visual condition required strong focusing of attention. This finding suggests that MMN is not sensitive to the difficulty of the visual task. The present study cautions, however, against interpreting this effect as evidence for the attentional independence of the MMN. This is because subjects, when asked to do so, were able to successfully discriminate the small auditory targets while concurrently performing the visual task. Subjects might thus be equally able to monitor the auditory channel in both very easy and difficult visual discrimination tasks.

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[23] In contrast to the smaller intensity MMN, the larger frequency MMN was followed by a modest P3a. The P3a is believed to indicate the actual switching of attention following the detection of the deviant (Escera et al., 1998). There was however no behavioral evidence of such switching when the occurrence of the frequency deviant was immediately followed by a visual target. In fact, performance measures for the subsequent visual target were not affected by the type of preceding auditory stimulus (standard, frequency deviant or intensity deviant)

The MMN to a small intensity deviant was modulated, however, by the direction of attention. It was larger when subjects also actively attended to the auditory channel compared to when attention was focused exclusively on the visual channel, independently of task difficulty. The frequency MMN was not affected by the direction of attention. The attentional modulation of the intensity MMN but not the frequency MMN may be due to the specific deviant feature or the perceptual discriminability of the deviant from the standard.

Table 1. Mean (standard deviation) values for hit rate, RT and false alarm rate for easy and difficult visual task performance during focused and divided attention conditions.

	Focused Attention		Divided Attention	
	Easy Task	Difficult Task	Easy Task	Difficult Task
Hit Rate	.95 (.01)	.58 (.15)	.82 (.10)	.46 (.15)
Reaction Time (ms)	417 (34)	582 (51)	459 (40)	611 (68)
False Alarm Rate	.005 (.002)	.04 (.03)	.008 (.003)	.04 (.01)

Table 2. Mean (standard deviation) values for hit rate, RT and false alarm rate for the frequency and intensity auditory targets during the easy and difficult visual tasks. The values reported here were obtained during divided attention.

	Frequency Target		Intensity Target	
	Easy Task	Difficult Task	Easy Task	Difficult Task
Hit Rate	.86 (.13)	.82 (.11)	.64 (.15)	.56 (.12)
Reaction Time (ms)	535 (68)	590 (75)	630 (85)	667 (61)
False Alarm Rate[*]	.010 (.002)	.03 (.02)	.010 (.002)	.03 (.02)

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[*] The false alarm rate reflects the incorrect responses to the auditory standard stimuli. Because frequency and intensity targets were presented in the same auditory sequence, the false alarm rates are identical for both targets.

Figure Captions

Figure 1. The visual discrimination task included a standard and a target stimulus. The target was, in separate conditions, either easy or difficult to discriminate from the standard. The easy visual target was constructed by superimposing a large green ellipse over the standard checkerboard. The difficult visual target was constructed by changing the color of the central white check to a light shade of blue. The saturation of this central check was adjusted for each subject.

Figure 2. Grand average ERPs elicited by the visual standard (solid line) and target (dashed line) stimuli. The left panel presents the ERPs obtained while subjects focused attention on either the easy or the difficult visual discrimination tasks and ignored the auditory channel. The right panel presents the ERPs obtained while subjects divided their attention between the auditory and visual channels in order to detect the auditory and visual targets. The RT histogram depicts the correct responses occurring within 30 ms bin intervals. In this and subsequent figures, negativity is traced as an upward deflection.

Figure 3. Grand average ERPs elicited by the auditory standard (thin solid line), the frequency deviant/target (dashed line) and the intensity deviant/target (thick solid line) stimuli. The left panel represents the ERP responses to the unattended auditory stimuli while subjects perform the easy or difficult visual discrimination tasks. The right panel presents the ERPs elicited while subjects performed the auditory discrimination task concurrently with the easy and difficult visual discrimination tasks. The RT histogram depicts the correct responses occurring within 30 ms bin intervals. Note that the time and voltage scales are different for the focused and divided attention conditions.

Figure 4. Grand average difference waveforms computed by subtracting the ERP to the auditory standard from the ERP to the auditory frequency deviant. These ERPs were elicited while subjects ignored the auditory stimulation and performed an easy (solid line) or difficult

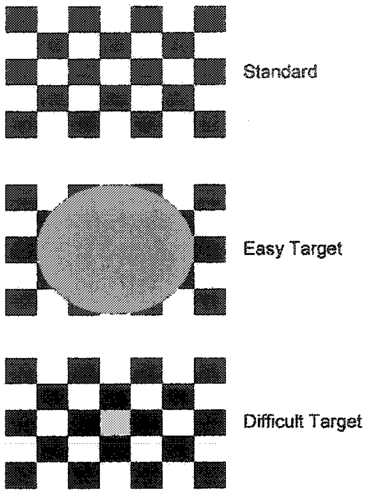
(dashed line) visual discrimination task. Visual task difficulty did not have a significant effect on the peak amplitude and latency of the frequency MMN.

Figure 5. Grand average difference waveforms computed by subtracting the ERP to the auditory standard from the ERP to the auditory intensity deviant. These ERPs were elicited while subjects ignored the auditory stimulation and performed an easy (solid line) or difficult (dashed line) visual discrimination task. Visual task difficulty did not have a significant effect on the peak amplitude and latency of the intensity MMN.

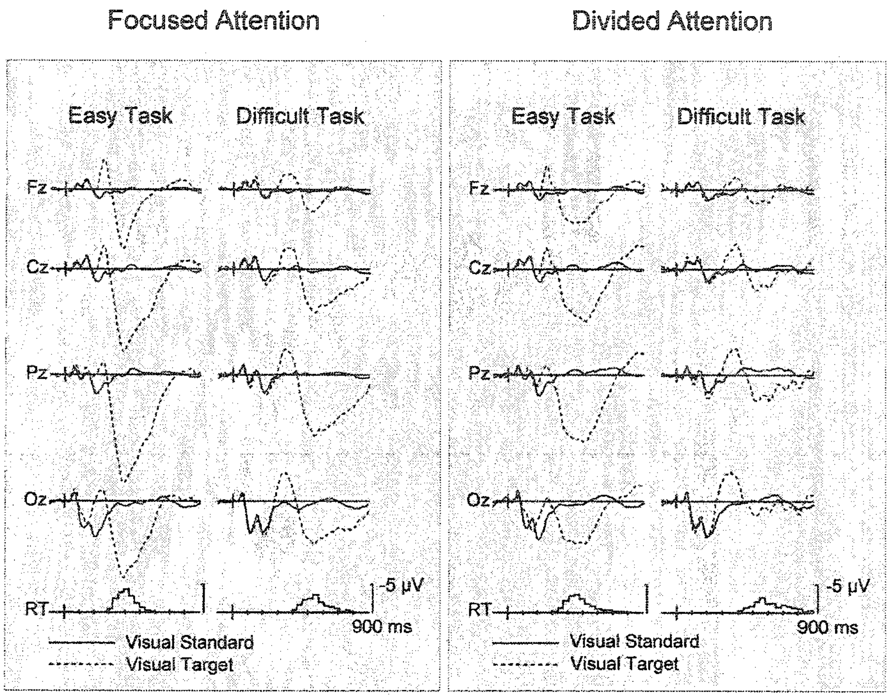
Figure 6. Grand average ERPs elicited by the standard auditory stimuli during focused (dashed line) and divided (thin solid line) attention conditions. This figure also illustrates the attention difference waveform (thick solid line) computed by subtracting the standard ERP elicited in the focused condition from the standard ERP elicited in the divided condition. This consisted of a negative-going wave (Nd_a) followed by a positive-going wave (Pd_a).

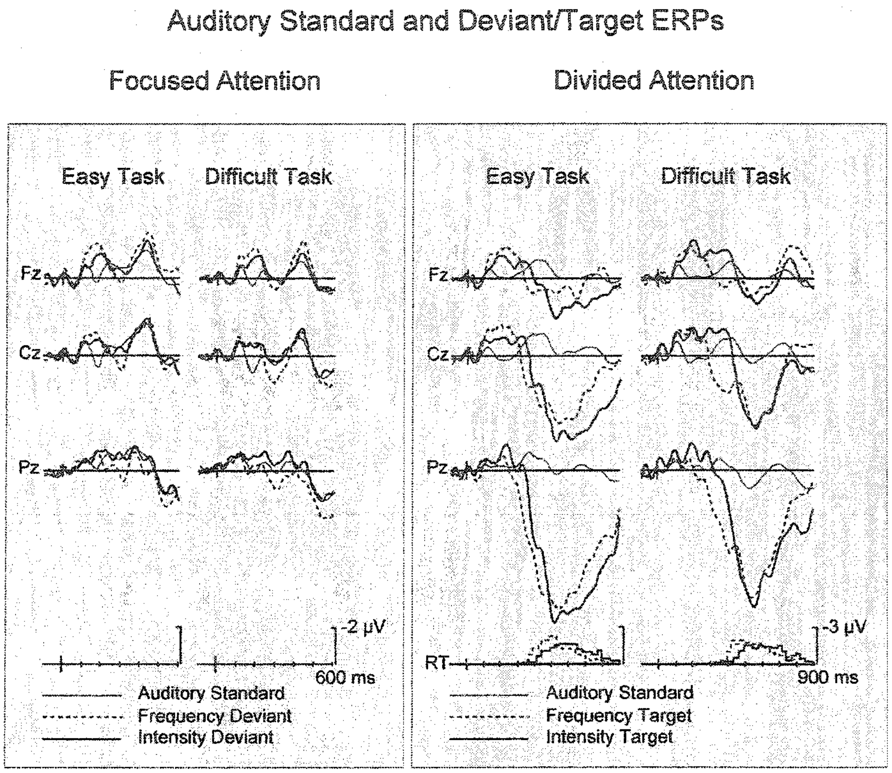
Figure 7. Grand average auditory difference waveforms during focused (dashed line) and divided (solid line) attention conditions. These waveforms were computed by subtracting the standard auditory ERP from the respective deviant auditory ERP while subjects ignored the auditory channel or actively detected the auditory deviants. The left panel of the figure illustrates the frequency difference waveforms. The frequency MMN was not significantly affected by task difficulty or by the direction of attention. In contrast, the intensity MMN (right panel) was significantly affected by the direction of attention, independently of visual task difficulty. It was larger when subjects performed the auditory discrimination task compared to when they exclusively focused on the visual channel. Both the frequency and intensity MMNs inverted in amplitude at the mastoids. A later N2b was significantly larger in the divided than in the focus conditions. The N2b did not invert in amplitude at the mastoids.

Visual Stimuli

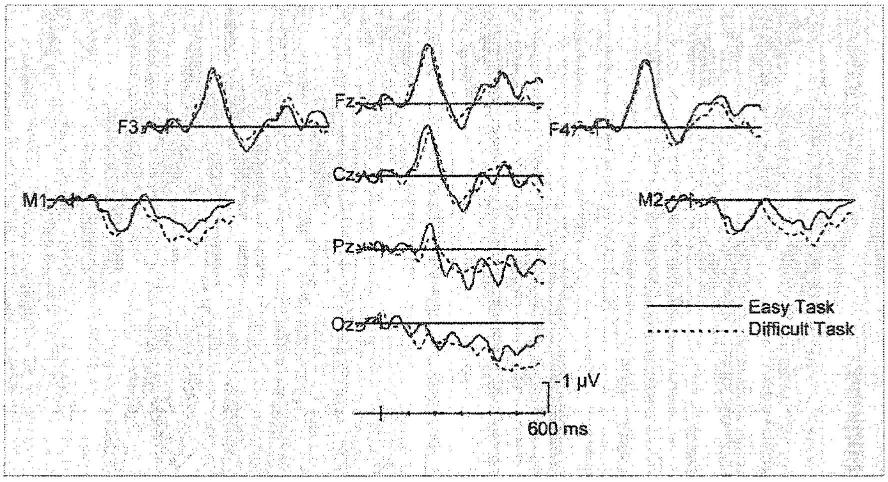


Visual Standard and Target ERPs

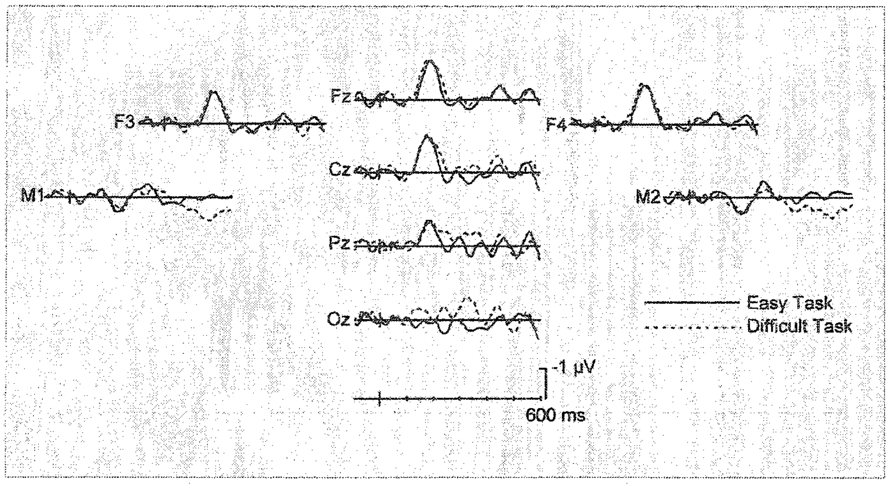



Auditory Standard and Deviant/Target ERPs
Focused Attention
Divided Attention
Easy Task
Difficult Task
Easy Task
Difficult Task
Fz
Cz
Pz
Fz
Cz
Pz
RT
-2 µV
600 ms
-3 µV
900 ms
Auditory Standard
Frequency Deviant
Intensity Deviant
Auditory Standard
Frequency Target
Intensity Target

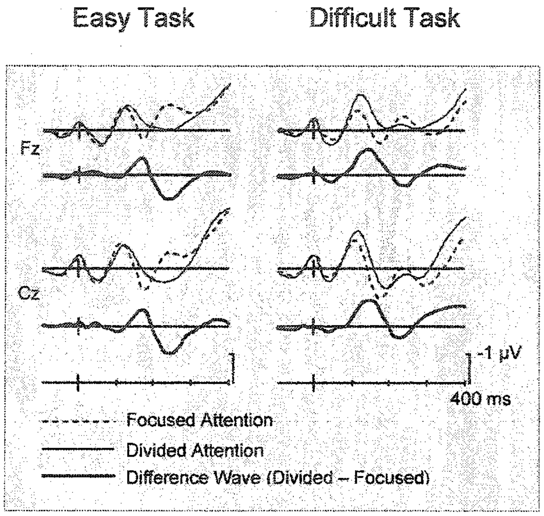
The Effect of Visual Task Difficulty:
Frequency Difference Waveforms



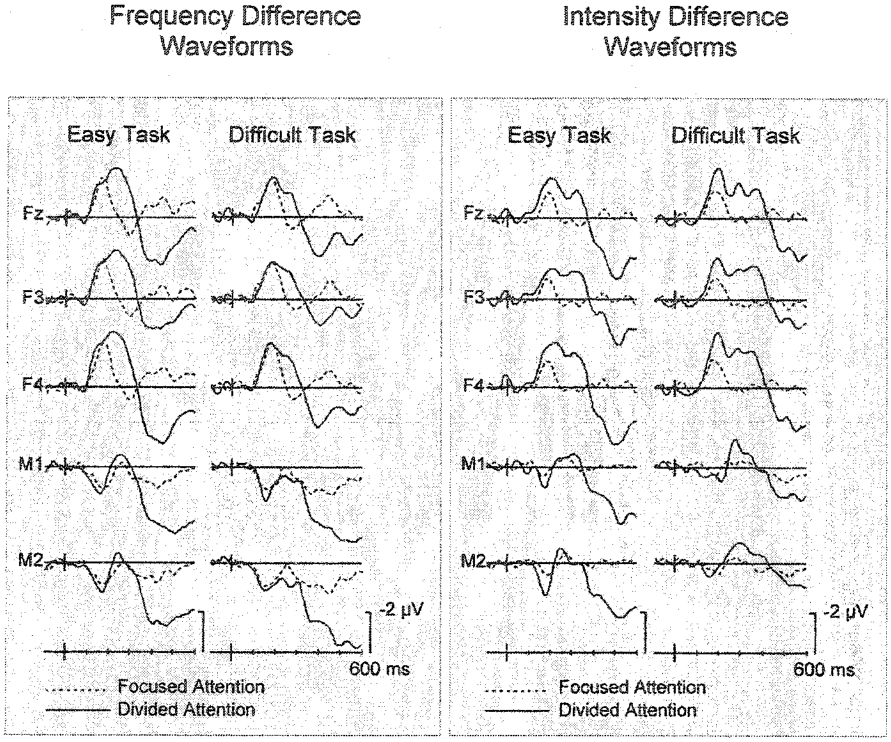
The Effect of Visual Task Difficulty:
Intensity Difference Waveforms



The Effect of the Direction of Attention:
Auditory Standard ERPs



The Effect of the Direction of Attention:
Auditory Difference Waveforms



CHAPTER 4

DOES THE DEVIANT FEATURE OR THE DEVIANT DISCRIMINABILITY ACCOUNT FOR THE ATTENTIONAL MODULATION OF THE MMN?

1. Introduction

The previous study indicated that visual task difficulty did not significantly modulate the MMN elicited by either a small change in the frequency or intensity of an auditory standard stimulus. The direction of attention, however, did affect the intensity MMN. It was larger when the MMN-eliciting stimuli were attended compared to when they were ignored. No such effect was found for the frequency MMN.

A purpose of the present study was to clarify the nature of the effect of the direction of attention on the MMN. As was noted in the previous study, the attentional effect on the intensity MMN could be explained by the type of deviant feature or the perceptibility of the deviant. The intensity deviant was less perceptible than the frequency deviant and its detection may have therefore benefited more from attention. Such an interpretation is supported by the finding that the MMN to small but not large deviants is affected by the direction of attention (Alho et al., 1992; Gomes et al., 2000; Woods et al., 1992). Alternatively, attention may affect the intensity MMN generator in a unique manner. This possibility was originally proposed by Näätänen et al. (1993b). In this study, Näätänen et al. found that attention affected the MMN to a small intensity but not a small frequency change, although these deviants were not equated in perceptibility. The effect of deviant perceptibility and deviant feature are deconfounded in the present study. Again, subjects initially engaged in easy and difficult visual tasks while ignoring the auditory stimuli. The visual stimuli were identical to those employed in the previous study. The discriminability between auditory standard and deviant stimuli, however, was increased for the intensity deviant and decreased for the frequency deviant. Subsequently, subjects divided their attention between visual and auditory channels in order to detect both visual and auditory targets. If directing attention to the MMN-eliciting channel benefits the detection of small changes in the environment, then attention would be expected to have a greater effect on the MMN to the very small frequency change.

Because the present study employs an experimental design identical to that used in our previous study, a further test of the effects of visual task demands on the passively-elicited MMN is afforded. Several studies had indicated that the MMN occurs independently of the demands of the visual diversion task (Alho et al., 1992; Dittmann-Balcar et al., 1999; Harmony et al., 2000; Kathmann et al., 1999; Otten et al., 2000). A criticism of these studies is that the experimental conditions were not optimized to find such an effect. For this reason, in the previous study, visual task demands were extensively varied and stimuli were presented at rapid and unpredictable rates. The results nevertheless indicated that the prominent MMNs elicited by unattended auditory stimuli during easy and difficult visual task conditions were not significantly different. The present study will thus determine the replicability of this critical finding.

2. Methods

The present study employed a paradigm and procedures that were essentially identical to those described in the previous study, except for changes in the perceptual discriminability for the intensity and frequency deviants. Only the methodological differences between these studies will be highlighted.

2.1. Subjects

Ten university students (9 females, 1 male) volunteered to participate in this experiment. Age ranged from 19 to 34 years (M = 21.5; SD = 4.5). All reported normal hearing and no history of neurological or psychiatric problems. None of the subjects had participated in the previous study.

2.2. Stimuli and Procedure

The auditory sequence included a standard stimulus (80 dB SPL 1000 Hz), a frequency deviant (80 dB SPL 1016 Hz) and an intensity deviant (60 dB SPL 1000 Hz). These values were selected based on a behavioural pilot study; differences in detection rates between the more and the less perceptible deviants were equated with those of the previous experiment. The visual stimuli were identical to those of the previous study. In the Focused attention condition, subjects were asked to attend to the visual channel and detect a rare visual target presented among the more frequently occurring standards. In different conditions, the target was easy or difficult to detect. The effects of visual task difficulty on performance and ERP data were again examined. Later, subjects were also asked to divide their attention between the visual and auditory channels and detect any rare target in either modality. The physiological and performance data obtained during divided attention were compared to those obtained when subjects focused only on the visual channel.

2.3. EEG/ERP Recording and Data Analyses

EEG/ERP recording and data analyses were performed in the same manner as those described in the previous study.

3. Results

3.1. Focused Attention

The analyses in the focused attention condition primarily consisted of one-way ANOVAs with repeated measures on task difficulty (Easy, Difficult).

3.1.1. Performance Data

The mean values for the performance measures obtained during the easy and difficult task conditions are presented in the left portion of Table 1. Performance measures[24] were significantly affected by visual task difficulty. Hit rates were significantly higher and RT was significantly faster in the easy than in the difficult visual condition, $F(1,9) = 239.9$ and 88.1, respectively, $ps < 10^{-5}$. The higher hit rate during the easy visual task was not achieved by adopting a more liberal response strategy. Indeed, the false alarm rate was significantly lower during the easy than the difficult task, $F(1,9) = 10.4$, $p < .01$. Subjects rated the easy visual task ($M = 2.7$; $SD = 1.3$) as significantly less demanding than the difficult visual task ($M = 8.1$; $SD = 0.9$), $F(1,9) = 104.5$, $p < 10^{-5}$.

----------------- Insert Table 4.1 about here -----------------

An analysis was performed to determine if the type of auditory stimulus (standard, frequency deviant or intensity deviant) presented immediately prior to the visual target had an effect on visual task performance (Alho et al., 1992; Woods et al., 1992). Eight percent of auditory deviant trials immediately preceded the visual target presentation. An equal number of visual target trials that were preceded by a standard auditory trial were randomly selected for purpose of comparison. The visual performance data was subjected to two-way ANOVAs with repeated measures on visual task difficulty and type of preceding stimulus. Neither hit rate nor RT was significantly affected by the type of preceding stimulus.

3.1.2. Visual ERPs

The ERP elicited by the visual standard and target stimuli are presented in the left panel of Figure 1. The ERP to the visual standard stimulus was characterized by a series of deflections at Oz, including a P130, N170 and P210. Starting at approximately 150 ms, the standard ERP in the difficult visual condition was negatively displaced compared to that

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[24] The performance data were collapsed across the three presentation blocks in the absence of a significant main effect of block or a significant Block x Task difficulty interaction.

elicited in the easy condition (Negative visual difference wave – Nd_v). This difference reached significance in the intervals ranging from 150-250 ms, $F(1,9) = 8.0$ and 5.9 respectively, $p < .04$ for both intervals.

In contrast to the standard ERPs, the target ERPs included an N2 and a P3b deflection (see left panel of Figure 1). Visual task difficulty significantly affected the amplitude and latency of the P3b. It occurred earlier during the easy ($M = 404$ ms; $SD = 32$ ms) relative to the difficult visual condition ($M = 527$ ms; $SD = 24$ ms), $F(1,9) = 74.5$, $p < 10^{-5}$. P3b was also significantly larger in the easy condition, $F(1,9) = 24.8$, $p < 10^{-3}$. The P3b was preceded by an N2, which peaked at 245 ms ($SD = 15$ ms) in the easy condition and significantly later, at 373 ms ($SD = 44$ ms) in the difficult condition, $F(1,9) = 63.6$, $p < 10^{-4}$. Task difficulty did not significantly affect the amplitude of N2 at Cz.

----------------- Insert Figure 4.1 about here -----------------

3.1.3. Auditory ERPs

The left panel of Figure 2 illustrates the ERPs to the auditory standard and deviant stimuli when subjects focused only on the visual channel. The standard stimulus elicited small amplitude N1 (100 ms), P2 (165 ms) and N2 (280 ms) deflections. There were no significant effects of visual task difficulty in the intervals ranging from 50-250 ms. In the interval from 250-300 ms, the auditory standard ERP was negatively displaced, however, in the easy relative to the difficult visual task condition, $F(1,9) = 10.4$, $p < .01$. The frequency and intensity deviant stimuli elicited a negative waveform that overlapped the N1-P2-N2 complex. This negativity, the MMN, was analyzed in the difference wave, computed by subtracting the standard auditory ERP from the respective deviant ERP.

----------------- Insert Figure 4.2 about here -----------------

3.1.4. Frequency Difference Waveforms

As is visible in Figure 3, a relatively small fronto-central MMN (approximately –0.7 µV at Fz) was elicited by the frequency deviant in both the easy and difficult visual conditions. The MMN peaked at 187 ms (SD = 19 ms) in the easy condition and at 197 ms (SD = 30 ms) in the difficult condition, F (1,9) = 1.3, $p > .05$. At this latency, a small positive deflection was visible at the mastoids. The peak amplitude of the MMN at Fz appeared larger when the visual task was easy compared to when it was difficult, but the difference did not attain significance, F(1,9) = 2.1, $p > .05$. MMN differences at frontal (F3, F4) and mastoid (M1, M2) sites were analyzed with two-way (task difficulty, hemispheric site) repeated measure ANOVAs. No significant main effects or interaction were found in these analyses.

The results of the interval analyses were consistent with those of the peak analyses. Between 150 and 200 ms, the effect of visual task difficulty again failed to attain significance at Fz, F(1,9) = 3.6, $p < .09$. Between 200 and 500 ms, none of the averaged interval data at Fz revealed significant differences between the easy and difficult tasks. Similarly, visual task difficulty did not significantly affect any of the intervals at M1.

---------------- Insert Figure 4.3 about here ----------------

3.1.5. Intensity Difference Waveforms

A large MMN (approximately –2.2 µV at Fz) was elicited by the intensity deviant (see Figure 4). The MMN peaked at 162 ms (SD = 13 ms) in the easy condition and at 174 ms (SD = 14 ms) in the difficult condition, F(1,9) = 2.4, $p > .05$. The peak amplitude of the MMN at Fz was not significantly affected by visual task difficulty, $F < 1$. The analyses performed on the MMN at frontal (F3, F4) and mastoid (M1, M2) sites similarly failed to reveal significant main or interactive effects.

In accordance with the peak analysis, the mean amplitude of the intervals corresponding to the MMN (100-150 and 150-200 ms) did not significantly differ as a function of the difficulty of the visual discrimination task at either Fz or at M1, $Fs < 1$. A large fronto-central positive wave, the P3a, was observed between 250 and 300 ms. At Fz, the mean amplitude in this interval was significantly larger when the visual task was easy compared to when it was difficult, F(1,9) = 5.6, $p < .04$.

---------------- Insert Figure 4.4 about here ----------------

3.2. Divided Attention

Most of the analyses performed on the data obtained during the divided attention conditions also included the data obtained during the focused attention conditions. These consisted of two-way ANOVAs with repeated measures on task difficulty (Easy, Difficult) and on the direction of attention (Focused, Divided).

3.2.1. Performance Data

The right portion of Table 1 presents the performance data obtained for the easy and difficult visual tasks during divided attention. Again, the hit rate and the RT were significantly modulated by visual task difficulty, F (1,9) = 182.1 and 80.5, respectively, ps $< 10^{-5}$. The main effect of the direction of attention was also significant for both the hit rate and RT, F (1,9) = 92.9 and 17.1, respectively, ps < .01. The hit rate was higher and the RT was faster during focused compared to divided attention conditions. The Task difficulty x Direction of attention interaction was not significant for hit rate or RT, F(1,9) = 1.8 and 0.9, respectively, $p > .05$ in both cases.

Performance measures for the auditory discrimination task during divided attention are presented in Table 2. These data were subjected to two-way ANOVAs with repeated measures on task difficulty and type of auditory deviant (Frequency, Intensity). The difficulty of the visual detection task significantly affected the hit rate for the auditory targets, F(1,9) = 8.0, $p < .02$, but not the RT, $F < 1$. The hit rate was higher for the auditory targets during the easy compared to the difficult visual task. The main effect of the type of auditory target was significant for both the hit rate and RT, F(1,9) = 8.2 and 25.7, respectively, ps < .02. The intensity targets were associated with higher hit rates and faster RTs compared to the frequency targets.

----------------- Insert Table 4.2 about here -----------------

The effects of visual task difficulty on the visual and auditory hit rates were not a result of a lax response bias during the easy visual task. The false alarm rate for the visual and auditory discrimination tasks was significantly lower during the easy relative to the difficult visual task, F(1,9) = 14.0 and 10.1, respectively, $p < .02$ (see Table 1 and 2).

3.2.2. Visual ERPs

The ERPs elicited by the visual standard and target stimuli during divided attention are presented in the right panel of Figure 1. At Oz, the P130-N170-P210 complex was again readily visible in the visual standard ERP during easy and difficult task conditions. The intervals that included this series of deflections were not significantly affected by visual task difficulty during divided attention. The main effect of the direction of attention, however, did approach significance for the mean amplitude between 100 and 150 ms, F(1,9) = 4.1, $p < .08$. During this interval, the visual ERP was more positive-going (Positive visual difference wave – Pd_v) when attention was focused on the visual channel compared to when it was divided between the visual and auditory channels.

During divided attention, the visual target stimuli elicited an N2-P3b complex that was again affected by visual task difficulty (see right panel of Figure 1). The latency of N2 and P3b was significantly delayed when the visual target was difficult to detect, F (1,9) = 34.7 and 22.9, respectively, ps $< 10^{-3}$. N2 and P3b peaked at 249 ms (SD = 22 ms) and 432 ms (SD = 35 ms), respectively, during the easy condition, and at 368 ms (SD = 41 ms) and 560 ms (SD = 46 ms), respectively, during the difficult condition. The P3b was also significantly smaller in the easy compared to difficult visual condition, F (1,9) = 40.5, $p < 10^{-4}$. The main effect of the direction of attention was significant for the amplitude and latency of the P3b, F (1,9) = 31.1 and 20.0, respectively, ps < 10^{-3}. The P3b was delayed and reduced when attention was divided between channels compared to when it was focused only on the visual channel.

3.2.3. Auditory ERPs

The auditory standard and target ERPs elicited in the divided attention conditions are illustrated in the right panel of Figure 2. During divided attention, visual task difficulty did not significantly affect the ERPs to the auditory standard. The auditory standard ERPs were modulated, however, by the direction of attention. This effect can best be observed in the attention difference waveforms presented in Figure 5. These difference waveforms were computed by subtracting the standard ERP obtained in the focused condition from the standard ERP obtained in the divided condition. In the 100-150 ms and 150-200 ms intervals, a significant main effect of the direction of attention was found, $F(1,9) = 4.9$ and 6.1 respectively, $p < .05$. The auditory standard ERP was more negative-going (Negative auditory difference wave – Nd_a effect) when attention was divided between the auditory and visual channels compared to when it was focused only on the visual channel. A significant interaction between task difficulty and the direction of attention was revealed in the 250-300 interval, $F(1,9) = 12.8$, $p < .01$. Simple effects testing revealed that the ERP was significantly more negative in the divided compared to focused attention condition but only for the difficult task. This interaction was due to an effect of visual task difficulty during the focused (rather than divided) attention condition.

---------------- Insert Figure 4.5 about here ----------------

As is evident in Figure 2, the active detection of the auditory targets during the divided attention condition (right panel of figure) resulted in additional ERPs that were not apparent when subjects ignored these auditory stimuli (left panel of figure). The peak amplitude and latency of the N2b and P3b deflections were analyzed using two-way ANOVAs with repeated measures on visual task difficulty and type of auditory target (Frequency, Intensity). These deflections were not significantly affected by visual task difficulty. A main effect of the type of auditory target, however, was found for both N2b and P3b. The N2b peaked earlier following presentation of the intensity (M = 244 ms; SD = 40 ms) compared to the frequency (M = 377 ms; SD = 43 ms) target, $F(1,9) = 66.3$, $p < 10^{-5}$. Similarly, the P3b elicited by the intensity target (M= 505 ms; SD = 44 ms) occurred prior to that elicited by the frequency target (M = 560 ms; SD = 47 ms), $F(1,9) = 34.6$, $p < 10^{-3}$. The P3b was also significantly larger following the presentation of the intensity target, $F(1,9) = 20.8$, $p < 10^{-3}$.

3.2.4. Frequency Difference Waveforms

The left panel of Figure 6 illustrates the frequency difference waveforms obtained during focused and divided attention conditions. As is apparent in this figure, a larger and longer-lasting negativity was elicited during the divided attention condition. This negative slow wave was a composite of an earlier MMN and a later attention-dependent N2b. Although the frequency MMN did not appear as a distinctive peak, its maximum amplitude was measured in the time window of 140-220 ms. During the divided attention condition, the MMN was maximum at approximately 180 ms. Visual task difficulty did not affect the peak amplitude and latency of the MMN at Fz, Fs < 1. The peak latency of the MMN did not significantly vary as a function of the direction of attention, F < 1. The main effect of the direction of attention just failed to reach significance for the amplitude of the MMN at Fz, $F(1,9) = 3.9$, $p < .08$. It was larger during divided compared to focused attention. This main effect, however, was found to be significant in the analysis performed on the data at F3 and F4, $F(1,9) = 5.1$, $p < .05$. Again, the amplitude of the MMN at left and right frontal sites was larger when subjects divided their attention between visual and auditory channels. No clear MMN inversion was visible at the mastoid sites. Therefore, MMN peak analysis at M1 and M2 was not performed.

The interval analysis at Fz revealed differences as a result of the direction of attention. Between 150-200 ms, the negativity in the frequency difference wave was larger during the divided compared to the focused attention condition, although this difference just failed to reach significance, F(1,9) = 3.6, p < .09. This effect became significant in the 200-250 ms interval, F(1,9) = 5.0, p < .05. In the frequency target waveform, the N2b peaked at approximately 375 ms following stimulus onset. It however was difficult to observe a distinct N2b in the frequency difference waveforms. From 300-350 ms, the interaction between task difficulty and the direction of attention approached significance at Fz, F(1,9) = 4.2, p < .07. During this interval, the negativity was larger in the divided condition relative to the focused condition but only when subjects performed the easy visual task. No significant main or interactive effects were found in the interval ranging from 350-400 ms, F(1,9) = 1.4 to 2.5, ps > .05. There were no significant differences in any of the intervals at M1.

---------------- Insert Figure 4.6 about here ----------------

3.2.5. Intensity Difference Waveforms

The intensity difference waves during focused and divided attention are presented in the right panel of Figure 6. As is evident from these difference waves, attention to the auditory channel (i.e. divided attention condition) resulted in an early MMN that inverted at the mastoid, a later N2b that appeared as a negative wave at the mastoid, and a large P3b. In the divided attention conditions, the MMN, peaking at approximately 160 ms, was scored in the time interval ranging from 120-200 ms. Visual task difficulty did not have a significant effect on either the latency or the amplitude of the MMN at Fz, Fs < 1. The direction of attention also failed to significantly affect the peak amplitude, F(1,9) = 2.6, p > .05, and latency, F(1,9) = 2.3, p > .05, of the MMN at Fz. No significant main or interactive effects were noted at left and right frontal (F3, F4) or mastoid (M1, M2) sites.

The results of the interval analyses were in accordance with the MMN peak analysis. The 100-150 and 150-200 ms intervals (including the MMN) did not reveal any significant main or interactive effects at Fz, Fs < 1. After 200 ms, significant differences due to the direction of attention were apparent. In the interval ranging from 200-250 ms, the difference waveform was significantly more negative (mainly due to N2b) when attention was directed toward both the auditory and visual channels compared to when attention was focused only on the visual channel, $F(1,9) = 13.8$, $p < .01$. The difference waveform at M1 was also significantly more negative in the divided condition during this time interval, $F(1,9) = 7.2$, $p < .03$. From 350 ms until the end of the sweep, a significantly greater extended positivity (P3b) was found at Fz during the divided compared to the focused attention condition, $F(1,9)$ ranging from 13.1 to 20.5, $ps < .01$.

4. Discussion

ERP and performance data again suggested that visual task difficulty was successfully manipulated, with the difficult visual task requiring more attentional resources than the easy visual task. Nevertheless, the present study replicated the important results from the previous study indicating that the passively-elicited MMN is not affected by visual task demands. The MMN, whether elicited by the frequency or intensity deviant, was essentially identical during the easy and difficult visual task conditions. This result clearly supports the idea that during passive MMN recording the difficulty of the visual diversion task is incidental and does not introduce a source of MMN variance. Still, it is possible that subjects could have covertly monitored the auditory channel during the passive recording of the MMN in both easy *and* difficult visual task conditions. This is suggested by the finding that subjects were again able to overtly detect both visual and auditory targets concomitantly, even during the very difficult visual condition. Effects on visual and auditory target detection, as indicated by performance and ERP indices, were very similar to those found in our previous study. The introduction of the auditory task (during the divided attention condition) resulted in only a very small deterioration in visual target detection, independently of visual task difficulty. Similarly, only a slight decrement in auditory target detection was observed during the difficult as compared to the easy visual condition. Conclusions about the attentional independence of the MMN can therefore not be drawn based on these findings, as it was not established that more resources were available for auditory processing during the easy than difficult visual task.

The present study also examined the effect of the direction of attention on the MMN. In our previous study, the MMN to the intensity change was larger when the MMN-eliciting stimuli were attended compared to when they were ignored. This was not the case for the MMN elicited by the frequency change. Because the intensity deviant was less perceptible than the frequency deviant, it was unclear if the specific deviant feature or its perceptibility was the determinant of the attentional effect. In order to address this issue, the present study attempted to reverse the perceptibility of the intensity and frequency deviants. Performance and ERP findings suggest that the frequency deviant was indeed made to be less perceptible than the intensity deviant. When subjects were asked to overtly detect the auditory deviants, hit rates were lower and reaction times were delayed for the frequency deviant. Consistent with this, when attention was divided between the visual and auditory channels, frequency targets elicited N2b and P3b deflections that peaked later than those elicited by intensity targets. The amplitude of P3b was also smaller following the frequency deviant. The modulation of N2b and P3b with changes in the perceptual discriminability of the auditory target from the auditory standard has been reported in numerous studies (Lang et al., 1990; Sams et al., 1985).

In the focused attention condition, both deviants elicited MMNs that peaked between 160-200 ms and inverted in polarity below the Sylvian fissure. The MMN to the frequency deviant, however, was much smaller and occurred later than that to the intensity deviant. This is not surprising in light of the well-established finding that MMN varies in amplitude and latency with the perceptibility of the deviant (Muller-Gass et al., 2001).

In the divided attention condition, the standard auditory ERP showed the usual attention-related negativity (Nd_a; Woods et al., 1992). Furthermore, when subjects actively engaged in the auditory discrimination task, the deviance-related negativity (DRN) elicited by both types of deviants was much larger and longer-lasting compared to when they focused only on the visual discrimination task. In the present study, the intensity DRN during the divided attention condition may reflect the composite activity of both MMN and N2b sources; this is unlikely to be the case for the frequency DRN. The frequency DRN elicited during auditory attention was initiated prior to the peak latency of the passively-elicited frequency MMN. Furthermore, the N2b for the frequency target occurred much later, at about 375 ms. The early attentional effect observed in the frequency difference wave cannot therefore be easily explained by the overlapping and summating effects of the N2b. A clear enhancement of the MMN with attention, however, could not be discerned following the intensity deviant. The N2b occurred in close temporal proximity to the intensity MMN, the latter peaking at about 170 ms in the focused attention condition. At this latency, the amplitude of the intensity DRN was not altered when attention was directed to the auditory channel during the divided attention condition. The results of the present study concerning the frequency MMN quite clearly suggest that the attentional enhancement of the MMN does not exclusively occur for auditory changes involving stimulus intensity. As such, the attentional modulation of the MMN may be limited to the processing of small stimulus changes, whereas larger auditory changes are handled automatically and do not further benefit from attention. Attention may be viewed as a means to sharpen the memory trace of the attended stimuli and consequently enhance the processing of small auditory changes. This interpretation of the attentional effect on the MMN would also be consistent with our findings concerning the insensivity of the MMN to visual task difficulty.

The evaluation of an attentional effect on the intensity MMN was complicated by the morphology of the passively-elicited MMN to the intensity deviant. When subjects were instructed to ignore the auditory sequence, the intensity MMN was largest at the central scalp site. This is more consistent with the scalp distribution of the N2b. This negativity was followed by a large P3a. The N2b-P3a complex can be elicited when a deviant stimulus is particularly obtrusive even when the auditory stimuli are ignored (Näätänen, 1992)[25]. Therefore, the reported intensity MMN during the focused attention condition may in fact be a composite of the MMN and the N2b.

The MMN process has been implicated in the initiation of an involuntary attention switch from task-relevant stimuli (the visual stimuli in this study) to task-irrelevant auditory stimuli (Näätänen, 1990). This process permits the conscious detection of acoustic change even when it occurs outside of the focus of attention. The P3a, rather than the MMN, is thought to reflect the actual involuntary orienting of attention to the deviant (Escera, Alho, Schröger, & Winkler, 2000). In Näätänen's model, the success of an auditory change in causing an involuntary attention switch is not only determined by the extent of auditory deviance but also by the direction and strength of the attentional focus. In accordance with this, the P3a occurred only to the more perceptible intensity deviant. Furthermore, the P3a elicited by the intensity deviant was smaller when subjects focused on the difficult rather than the easy visual task. A similar effect of task difficulty on the P3a has previously been reported by Harmony et al. (2000). In spite of the difference in the amplitude of the intensity P3a between easy and difficult conditions, there was no evidence of behavioural distraction. Behavioural detection of the visual target occurring immediately after the intensity deviant was unaffected by task difficulty. Indeed, detection of the visual target appeared to be independent of the P3a process. Visual performance did not vary whether the visual target was preceded by an auditory stimulus that did elicit a P3a (i.e., an intensity deviant) or one that did not elicit it (i.e., a

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[25] The behavioral results for the intensity target detection (hit rates < .70) do not indicate that the deviant was particularly obtrusive. However, the intensity deviant (intensity decrement of 20 dB) was not very audible. Subjects might have been less inclined to behaviorally report the occurrence (or what may have appeared as a non-occurrence) of such a stimulus.

frequency deviant or an auditory standard). A performance decrement for targets following deviants that elicited a P3a has been reported in numerous studies (Escera et al., 1998; Grillon et al., 1990; Woods, 1992). However, as Schröger (1996) cogently notes, the extent of distraction varies as a function of the obtrusiveness of the auditory deviant stimulus and the channel separation between the target (task-relevant) and distracter (task-irrelevant) stimuli. In studies employing similar auditory stimuli and paradigms (attend visual, ignore auditory), no RT effect was reported for the visual target following the deviant auditory stimuli (Alho et al., 1992; Woods et al., 1992).

5. Conclusion

As was reported in the previous study, the passively-elicited MMN was not affected by visual task difficulty. However, the MMN did vary as a function of the direction of attention, that is, whether or not the auditory sequence was within the focus of attention. The previous study showed such an attentional effect for the MMN elicited by a small intensity deviant. In the present study, a similar effect was found for the MMN to a small frequency deviant. The most parsimonious explanation of these results is that attention enhances the processing of small auditory changes. Larger auditory changes would be fully processed even when occurring outside the focus of attention.

Table 1. Mean (standard deviation) values for hit rate, RT and false alarm rate for easy and difficult visual task performance during focused and divided attention conditions.

	Focused Attention		Divided Attention	
	Easy Task	Difficult Task	Easy Task	Difficult Task
Hit Rate	.94 (.03)	.51 (.09)	.78 (.06)	.35 (.12)
Reaction Time (ms)	410 (44)	645 (52)	463 (41)	711 (82)
False Alarm Rate	.007 (.006)	.06 (.05)	.015 (.006)	.05 (.03)

Table 2. Mean (standard deviation) values for hit rate, RT and false alarm rate for the frequency and intensity auditory targets during the easy and difficult visual tasks. The values reported here were obtained during divided attention.

	Frequency Target		Intensity Target	
	Easy Task	Difficult Task	Easy Task	Difficult Task
Hit Rate	.48 (.17)	.44 (.18)	.70 (.12)	.65 (.15)
Reaction Time (ms)	771 (60)	741 (110)	576 (70)	616 (77)
False Alarm Rate*	.023 (.007)	.04 (.02)	.023 (.007)	.04 (.02)

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* The false alarm rate reflects the incorrect responses to the auditory standard stimuli. Because frequency and intensity targets were presented in the same auditory sequence, the false alarm rates are identical for both targets.

Figure Captions

Figure 1. Grand average ERPs elicited by the visual standard (solid line) and target (dashed line) stimuli. The left panel presents the ERPs obtained while subjects focused attention on either the easy or the difficult visual discrimination tasks and ignored the auditory channel. The right panel presents the ERPs obtained while subjects divided their attention between the auditory and visual channels in order to detect the auditory and visual targets. The RT histogram depicts the correct responses occurring within 30 ms bin intervals. In this and subsequent figures, negativity is traced as an upward deflection.

Figure 2. Grand average ERPs elicited by the auditory standard (thin solid line), the frequency deviant/target (dashed line) and the intensity deviant/target (thick solid line) stimuli. The left panel represents the ERP responses to the unattended auditory stimuli while subjects perform the easy or difficult visual discrimination tasks. The right panel presents the ERPs elicited while subjects performed the auditory discrimination task concurrently with the easy and difficult visual discrimination tasks. The RT histogram depicts the correct responses occurring within 30 ms bin intervals. Note that the time and voltage scales are different for the focused and divided attention conditions.

Figure 3. Grand average difference waveforms computed by subtracting the ERP to the auditory standard from the ERP to the auditory frequency deviant. These ERPs were elicited while subjects ignored the auditory stimulation and performed an easy (solid line) or difficult (dashed line) visual discrimination task. The MMN differences between easy and difficult visual task conditions were not significant.

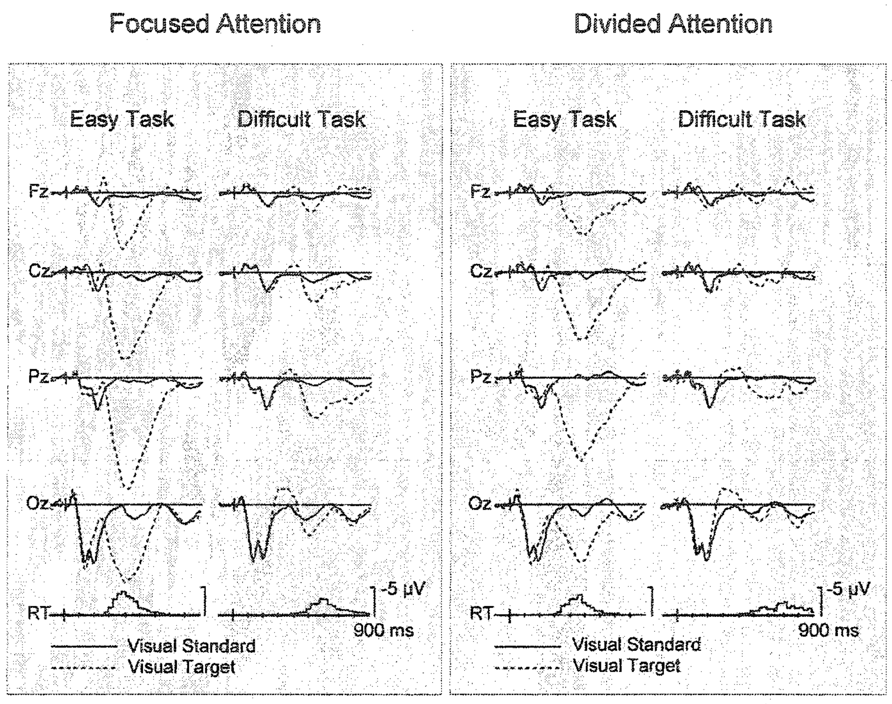
Figure 4. Grand average difference waveforms computed by subtracting the ERP to the auditory standard from the ERP to the auditory intensity deviant. These ERPs were elicited while subjects ignored the auditory stimulation and performed an easy (solid line) or difficult

(dashed line) visual discrimination task. Visual task difficulty did not have a significant effect on the intensity MMN.

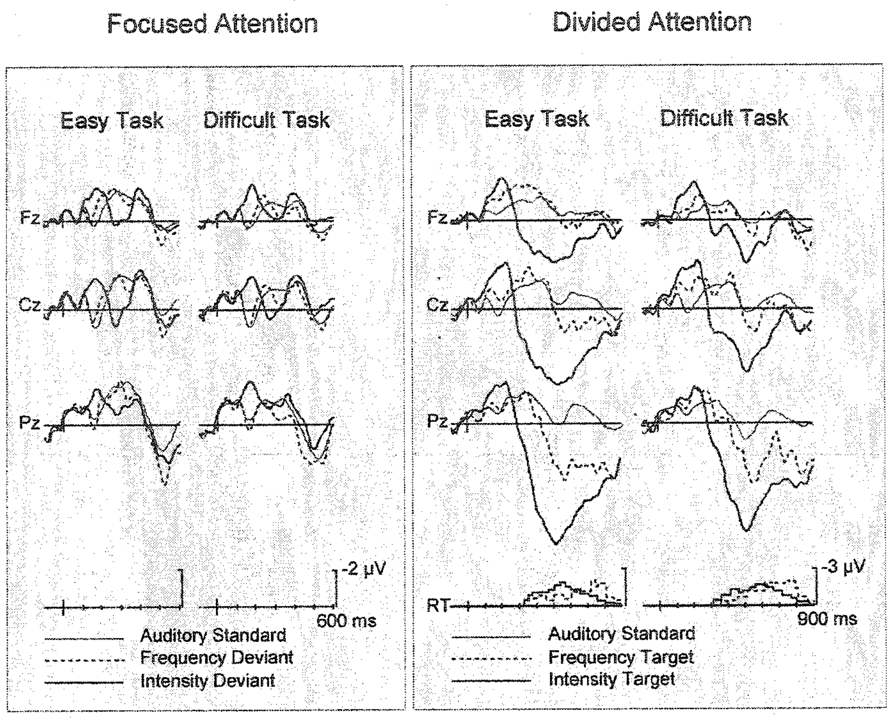
Figure 5. Grand average ERPs elicited by the standard auditory stimuli during focused (dashed line) and divided (thin solid line) attention conditions. This figure also illustrates the attention difference waveform (thick solid line) computed by subtracting the standard ERP elicited in the focused condition from the standard ERP elicited in the divided condition. This consisted of a negative-going wave (Nd_a) lasting from approximately 100-200 ms.

Figure 6. Grand average auditory difference waveforms during focused (dashed line) and divided (solid line) attention conditions. These waveforms were computed by subtracting the standard auditory ERP from the respective deviant auditory ERP while subjects ignored the auditory channel or actively detected the auditory deviants. The left panel of the figure illustrates the frequency difference waveforms. The frequency MMN was larger during divided relative to focused attention, reaching significance at the F3 and F4 scalp sites. In contrast, the intensity MMN (right panel) was not significantly affected by the direction of attention.

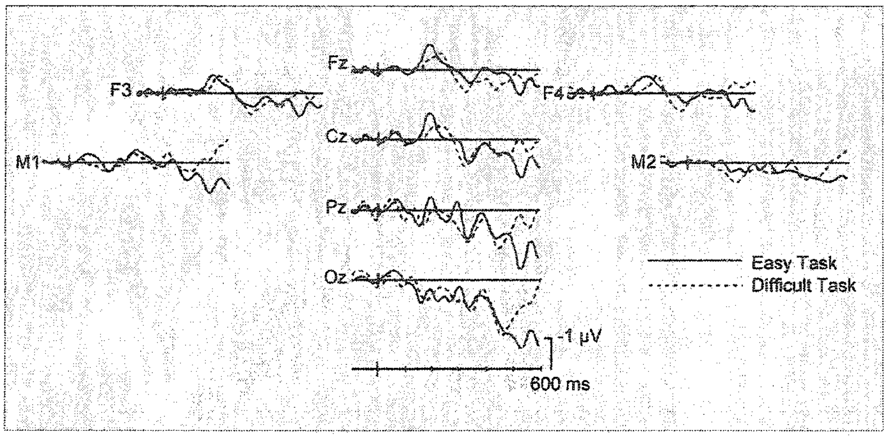
Visual Standard and Target ERPs



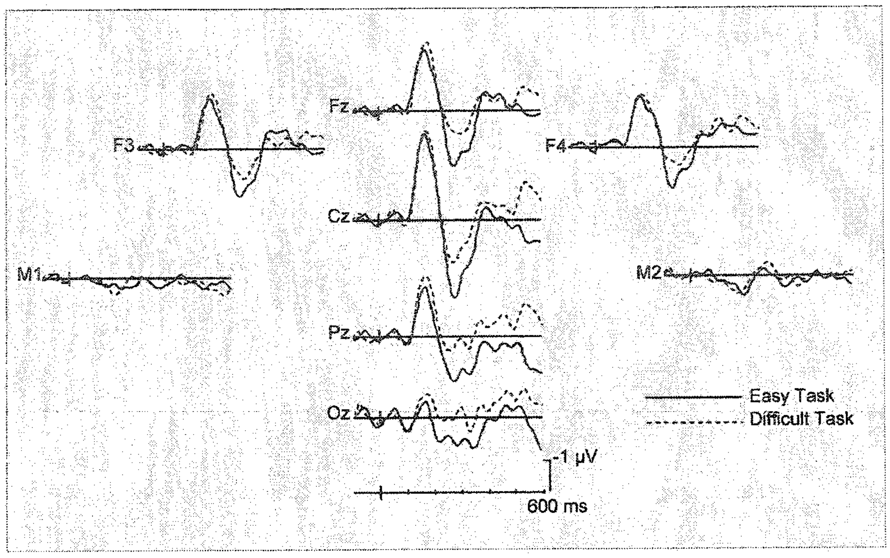
Auditory Standard and Deviant/Target ERPs



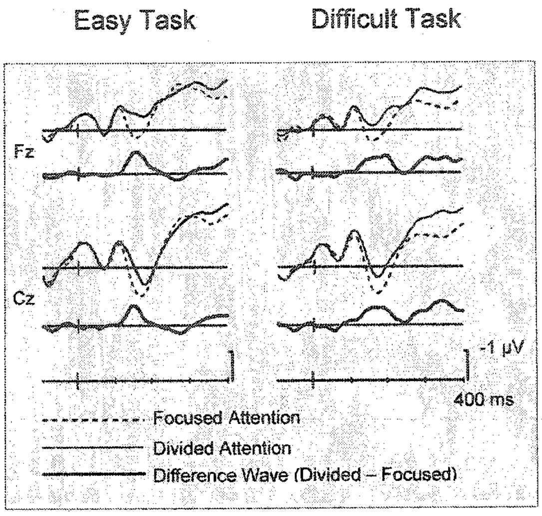
The Effect of Visual Task Difficulty:
Frequency Difference Waveforms



The Effect of Visual Task Difficulty:
Intensity Difference Waveforms



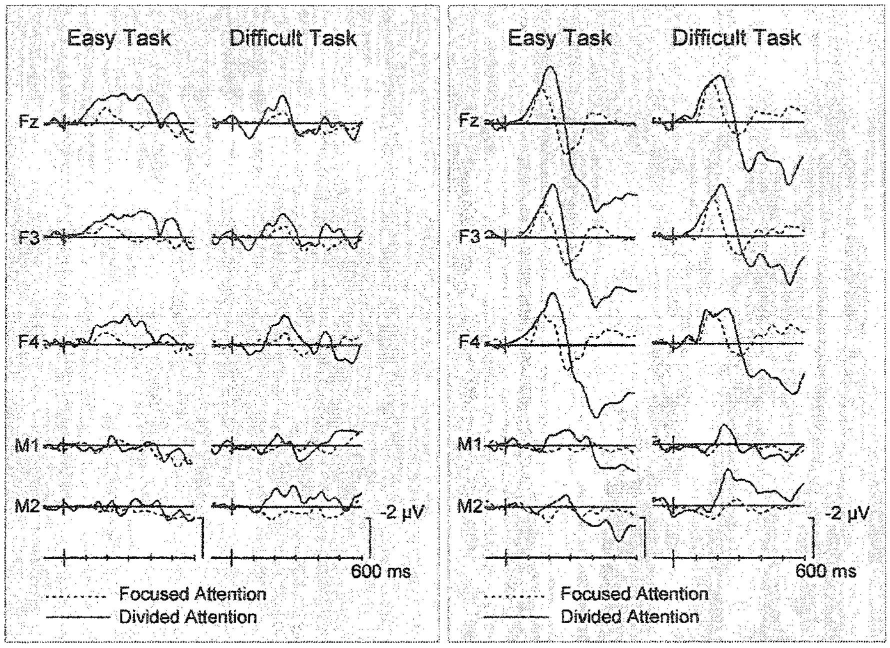
The Effect of the Direction of Attention:
Auditory Standard ERPs



The Effect of the Direction of Attention:
Auditory Difference Waveforms

Frequency Difference Waveforms

Intensity Difference Waveforms



CHAPTER 5

SUMMARY AND CONCLUSIONS

1. Statement of Problem

In Näätänen's model of auditory processing, the basic auditory processes (i.e. the extraction and storage of stimulus features, the formation and storage of the stimulus representation in sensory memory) and the change detection process (based on the stimulus representations in sensory memory) are unaffected by the mechanisms of selective attention. In this view, the MMN, an ERP index of the outcome of the change detection process, neither requires attention for its elicitation (i.e. partial automaticity) nor is altered in amplitude by attention (i.e. strong automaticity). Although several studies have indeed indicated that the MMN is independent of attention, findings from several other studies have challenged this view.

Evidence challenging the strongly automatic nature of the MMN has mainly come from studies on the effects of the direction of attention on the MMN. These studies showed that the MMN to the eliciting deviant is larger when this stimulus is part of the attended stimulus sequence compared to when this stimulus is to be ignored. The limitation of such studies is that when the MMN-eliciting stimulus is part of the attended stimulus sequence, an attention-dependent ERP, the N2b, overlaps with the MMN, making the latter difficult to discern. Näätänen has thus generally dismissed these findings as an effect on the N2b rather than a true attentional effect on the MMN.

Studies on the effect of the intensity of attention on the MMN have cleverly circumvented the problem of the N2b overlap; in these studies, the MMN-eliciting stimulus is never part of the attended stimulus sequence. Subjects are instructed to ignore the auditory channel in which the MMN-eliciting stimuli occur, and engage in a diversion task presented in a different auditory channel or in a visual channel. The nature or difficulty of the diversion task is varied in order to make it easy or difficult to perform. The assumption underlying these studies is that of a limited and centralized (modality-unspecific) pool of attentional resources (Kahneman, 1973). During the difficult diversion task, more attentional resources are drawn for task performance than during the easy diversion task. From this, it follows that fewer attentional resources are available for, and deflected toward task-irrelevant processing (such as processing of the stimuli in the to-be-ignored auditory channel) during the difficult compared to the easy diversion task. Hence, if the MMN is affected by attention, then the MMN should be larger during the easy than the difficult diversion task. Most studies have reported that the MMN is unaltered by the demands of a variety of diversion tasks (see however Alain & Woods, 1997; Kramer et al., 1995; Näätänen et al., 1993b). While these results provide strong support for the Näätänen view that the MMN is independent of attention, the experimental conditions in these studies were unfortunately not optimal for demonstrating attentional effects.

2. Rationale for the Present Studies

The aim of the four experiments presented in the present thesis was to examine the effect of attention on the MMN.

2.1. Manipulation of the Visual Task Demands

In a first instance, this issue was studied by varying the demands of the visual diversion task during passive MMN recording. The attentional resources required for the visual task were manipulated by varying the nature of a reading task (Experiments 1 and 2) and the difficulty of a visual discrimination task (Experiments 3 and 4). It was assumed that when more resources were required for the visual diversion task, fewer resources would be available for the processing of the task-irrelevant auditory stimuli. If the demands of the visual diversion task affected the MMN, then at least some of the processes underlying the MMN could not be characterized as being strongly automatic.

2.2. Manipulation of the Direction of Attention

A second means of investigating the issue of the attentional modulation of the MMN was to manipulate the attentional resources engaged in auditory processing by directing attention toward or away from the auditory stimulation (Experiments 3 and 4). If the direction of attention affected the MMN, then at least some of the processes underlying the MMN could not be characterized as being strongly automatic.

3. Main Findings and Conclusions

3.1. Manipulation of the Visual Task Demands (Experiments 1- 4)

- The MMN elicited by frequency and intensity deviants was not affected by the manipulation of the attentional resources achieved by varying the demands of the visual diversion task (although the results of Experiment 1 indicate that the nature of the visual diversion task may introduce a source of MMN variance)
- The findings endorse Näätänen's view that the MMN process and its underlying processes are strongly automatic.
- The absence of visual task difficulty effects on auditory task performance (during the divided attention condition of Experiments 3 and 4) does raise questions about the commonly-held assumption of a central pool of attentional resources. The introduction of the auditory detection task resulted in only a slight deterioration in visual target detection, independently of visual task difficulty. Thus, it was not established that more attentional resources were deflected toward auditory processing during the easy than difficult visual task. The attentional resources required for the processing of the visual stimuli are perhaps different from (and not shared with) those required for the

processing of the auditory stimuli (Duncan, Martens & Ward, 1997). A possible reason for the failure of many studies to find an attentional effect on the MMN is that the manipulation of attentional demands in the visual domain has little bearing on the availability of attentional resources for auditory processing.

3.2. Manipulation of the Direction of Attention (Experiments 3 and 4)

- The direction of attention did affect the amplitude of the MMN when the discriminability of the auditory deviant from the auditory standard was poor (hit rates < .65). The amplitude of the MMN to very small frequency and intensity deviants was larger when these stimuli were part of the attended stimulus sequence. In contrast, when the difference between standard and deviant was more accurately detected (hit rates > .65), no clear effect of attention was noted on the amplitude of the MMN to frequency and intensity deviants.
- The findings suggest that the processing of very small auditory changes is only partially automatic, whereas the processing of larger changes may proceed in a strongly automatic fashion.
- These results are thus not fully consistent with Näätänen's model of auditory processing, as attentional mechanisms may selectively affect the MMN process or its underlying processes.
- It is possible that attention leads to a clearer representation of the stimuli within the attended auditory channel, and consequently leads to the generation of a larger difference signal (MMN). The difference signal of an unattended auditory sequence containing large deviants may already be at its maximum, and therefore may not be increased by attention.

4. Future Directions

The present thesis addressed the issue of automaticity and the MMN. The results showed that task-directed attention may enhance the MMN to small auditory changes, whether the changing feature involved frequency or intensity. This supports the view that the MMN (or the processes leading up to the MMN) may only be partially automatic. However, the present thesis was unsuccessful in demonstrating that the elicitation of the MMN is attention-dependent. This is because even when attention was strongly focused away from the auditory channel (during the difficult visual task), an MMN to the auditory deviants was elicited. As such, it appears that the elicitation of the MMN occurs even in the absence of attention. Behavioural results from the divided (visual-auditory) attention condition however cast doubt on the latter conclusion, as visual processing did not significantly interfere with auditory processing. It is possible that attentional resources are modality-dependent, and in that case, a manipulation in visual task demands would not be expected to have an effect on the MMN (and most such studies have not found an effect on the MMN). A better way to address the attentional dependence/independence of the MMN may thus be through the use of an auditory diversion task.

Interestingly, studies that have employed an auditory diversion task reported that the MMN, recorded from a different auditory channel, was attenuated when compared to that elicited while subjects engaged in a visual diversion; this MMN was however not completely abolished (Alain & Woods, 1997; Näätänen et al., 1993b). Furthermore, a recent study by Sussman, Winkler and Wang (2003) reported that the passively-elicited MMN to a frequency change was abolished when attention was focused on an auditory diversion task involving a frequency target. In contrast, the passively-elicited MMN to an intensity change presented in the same unattended auditory sequence was not abolished. To account for these results, they suggested an auditory competition hypothesis which purports that when the same feature deviates in both (attended and ignored) auditory channels, a competition for the same MMN resource occurs. In their view, attention however does not affect the MMN process per se but rather the sensory information that reaches the MMN generator.

In conclusion, it seems that the most promising method to determine the role of attention in early auditory processing is through competing auditory channels. In future work, it would be worthwhile to include a means to verify the subject's ability to concurrently complete the tasks in both (to-be-attended and to-be-ignored) channels (i.e. divided attention paradigm). This verification would at least lend support in deeming the designated to-be-ignored channel as "unattended".

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