INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ATTENTIVE AND PRE-ATTENTIVE MECHANISMS OF AUDITORY STREAM SEGREGATION: AN INVESTIGATION USING EVENT-RELATED BRAIN POTENTIALS

by

ELYSE SUSSMAN

A dissertation submitted to the Graduate Faculty in Psychology in
partial fulfillment of the requirements for the degree of Doctor
of Philosophy, The City University of New York

1998

UMI Number: 9820582

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

This manuscript has been read and accepted for the Graduate Faculty in Psychology in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

12-19-97
Date

Walter Ritter
Chair of Examining Committee

01/05/98
Date

Executive Officer

Dr. Walter Ritter

Dr. Diana Deacon

Dr. David Friedman

Dr. Kevin Sailor

Dr. Daniel Javitt

Supervisory Committee

The City University of New York

Abstract

ATTENTIVE AND PRE-ATTENTIVE MECHANISMS OF AUDITORY STREAM SEGREGATION: AN INVESTIGATION USING EVENT-RELATED BRAIN POTENTIALS

by

Elyse Sussman

Adviser: Professor Walter Ritter

There is uncertainty concerning the extent to which the auditory streaming effect is a function of attentive or pre-attentive mechanisms of the auditory system. The streaming effect is an auditory phenomenon that occurs when alternating tones in high and low frequency ranges result in the experience of two segregated streams of sound, one made up of high tones and one made up of low tones. The mismatch negativity (MMN), a component of event-related brain potentials, which indexes pre-attentive acoustic processing, was used as a probe to determine whether the segregation associated with the streaming effect occurs pre-attentively.

In Experiment 1, a sequence of six different high (H) and low (L) tones were presented at fast and slow paces, while subjects ignored the stimuli. At the slow pace, the tones were heard as alternating high and low pitches, and no MMN was elicited. When the tones were alternated at a fast pace inducing a streaming effect, a pattern of standards emerged separately in each stream (e.g., H1-H2-H3), with a deviant pattern occurring infrequently within each stream (e.g., H3-H2-H1). An MMN was observed for the low frequency stream at the rapid stimulus presentation, indicating a pre-attentive locus for the streaming effect. The high frequency deviant, which immediately followed the low frequency deviant, did not elicit an MMN.

In Experiment 2 a streaming condition was run with a wider interval between the across-stream deviants than used in Experiment 1. MMNs were obtained to both the high and low deviants when the interval between the across-stream deviance was widened to more than 250 msec, indicating that the MMN system is susceptible to processing constraints.

For Experiment 3, subjects were presented with sequences of alternating high and low tones occurring at a constant rate, to investigate the affect of attention on stream segregation. When subjects ignored the stimuli, no MMNs were obtained. When subjects selectively attended the high-pitched tones, MMNs were obtained to the deviants within both the attended and unattended streams. The results indicate that attention can produce segregation altering the organization of sensory input in the early stages of acoustic processing.

Acknowledgments

There are, of course, many people who contributed to the completion of this dissertation that I would like to thank.

I express my deepest gratitude to Dr. Walter Ritter, whose wisdom and love for science keep challenging me to reach further in my own work. It was under his mentorship that this dissertation was created. Prof. Ritter has taught me much more than I have room to express. He continues to shape, guide and direct my learning with his unique blend of mentoring, compassion, and respect for the learning process, allowing me the room to grow and find my own way. The results of his untiring efforts are reflected on every page of this dissertation.

Thanks to my committee members, Dr. David Friedman and Dr. Diana Deacon, for their support and encouragement; and especially for Prof. Deacon's sense of humor, that brought a bit of relief so many times throughout the process.

Thanks to my outside readers, Dr. Kevin Sailor and Dr. Daniel Javitt, for their thoughtful and insightful comments on the work.

Thanks to Dr. Herb Vaughan, for his enthusiastic willingness to discuss the data and share his knowledge and expertise with me. Many thanks to my colleagues at the lab, among whom Valerie Shafer, Judy Kreuzer, Diane Kurtzberg, and Molly Schroeder, offered advice, friendship, and moral support.

Lastly, I would like to express thanks to my husband, Mark, for his patience and understanding of the long hours of work spent throughout the many stages of this dissertation project.

Table of Contents

List of Tables

List of Figures

Introduction

This dissertation study, composed of three experiments, uses a component of event-related brain potentials (ERPs) called the mismatch negativity (MMN) to investigate attentive and pre-attentive mechanisms involved in the process of auditory stream segregation. Auditory stream segregation, an aspect of Auditory Scene Analysis (Bregman, 1990), describes a process by which the brain disentangles the mixture of sounds that reach the ear, to their distinct sources. Determining whether some mechanisms responsible for stream segregation are attention-independent and others attention-dependent is the subject of investigation for this study.

The process reflected by the MMN, associated with auditory sensory memory, is thought to be an automatic response to deviations occurring within repetitive auditory stimulation. The MMN system operates on repetition in the acoustic environment. Since an MMN has not, as yet, been obtained to a deviant that follows a single presentation of a standard tone it may be inferred that the MMN system is involved in the determination of invariance of the acoustic environment. In order to determine what has changed or deviated from a set of stimuli, it first needs to be established what was constant. The MMN is believed to be an indicator that the brain has detected a change that has occurred within the recent acoustic past. Therefore, the MMN can be used to determine how a set of stimuli is organized since the detection of a change in an ongoing, repetitive tonal environment also indicates the brain detected what is repeating (i.e., what is constant) within that environment. Experiments 1 and 3 exploit this notion. In Experiment 1, the MMN was used to determine whether the organization of streaming occurred automatically (i.e., without attention) and in Experiment 3 the MMN was used to determine whether attention could alter the organization of the incoming sound pre-attentively.

Most commonly, the MMN has been used in investigations of auditory processing in which one or more features of the repeating stimuli (or standards) change on roughly 10% of the trials (i.e., "oddball" paradigms). The stimulus features can change in frequency, intensity, duration, or spatial location from the standards, in the simpler paradigms, and elicit a negative waveform peaking about 100-200 msec post-stimulus onset, denoting the MMN. The MMN, thought to originate in primary auditory cortex (Javitt, Schroeder, Arezzo, & Vaughan, 1991), is usually maximal in the fronto-central regions of the scalp and reverses in polarity at the scalp regions below the sylvian fissure (Alho, Paavilainen, Reinikainen, Sams, & Näätänen, 1986). There is some evidence for feature-specific generators of the MMN (Giard, Perrin, Pernier, & Bouchet, 1990; Paavilainen, Alho, Reinikainen, Sams, & Näätänen, 1991) though this has not yet been established conclusively. The inversion in polarity obtained in the Paavilainen, et al. (1991) study showed slightly different scalp topographies for the different stimulus features with duration deviants exhibiting the largest inversion, indicating the possibility of different feature-specific loci.

The sum of the initial investigations indicate that the amplitude of the MMN is affected by a number of factors, including stimulus probability (Näätänen, Paavilainen, Alho, Reinikainen, & Sams, 1987), magnitude of the difference between the standard and the deviant (Novak, Ritter, & Vaughan, 1990), and attention (Woldorff, Hackley, & Hillyard, 1991).

Recently the MMN has been elicited by stimuli that evoke complex processing of the acoustic environment. For example, changes in the periodicity of a stimulus sequence has evoked MMNs (Winkler & Schröger, 1995; Schröger, Paavilainen, & Näatänen, 1994; Schröger, Tervaniemi, Wolff, & Näätänen, 1996). In the study by Winkler & Schröger (1995), an MMN was elicited by the exchange in position of two tonal elements within a four-element standard pattern without breaks between the repetition of the pattern. The two exchanged tonal elements had different durations but the same frequency values. Therefore, the MMN was elicited by the change occurring in the duration of the exchanged tones since the frequency values of them remained the same.

These recent experiments lend support to the notion that the brain automatically sorts, stores, and codes the incoming stimuli based on the stimulus characteristics of the input over time. These more recent MMN studies using complex stimulus arrangements indicate that at very early stages of auditory analysis the brain monitors the relationship between the tones, in addition to the features of the tones. For example in Experiment 1, an MMN was elicited to the reversal of a three-tone pattern. In order to elicit the MMN in this paradigm, the brain detected the changes occurring in specific positions within the series of the tones. The temporal relationship between the tones was coded prior to the MMN detection system, along with the frequency values of the tones themselves.

Subjects can ignore a stimulus presentation (e.g., by reading a book) and the MMN component will be elicited by deviant physical and/or temporal characteristics of the stimuli. Although attention is not required to elicit the MMN response, attention to the stimuli can also be associated with MMNs. In dichotic listening paradigms, for example, MMNs can be obtained to deviations that occur in both the attended and unattended channels (e.g., Alho, Sams, Paavilainen, Reinikainen, & Näätanen, 1989; Näätänen, Gaillard, & Mäntysalo, 1978). That is, attention is neither required to elicit the MMN, nor does it preclude its occurrence.

Given that the MMN can be elicited when subjects ignore the stimuli or when subjects pay attention to the stimuli, the MMN component was used as a tool to investigate attentive and pre-attentive processing of auditory stream segregation.

Specific aims of the study

The purpose of Experiment 1 was to determine whether the streaming effect is governed by pre-attentive mechanisms of the auditory system. Experiment 1 was designed such that an MMN would be elicited by the deviants occurring in both the high and low tones sequences if the high and low tones segregated automatically.

Experiment 2 was designed to test whether the MMN system is sensitive to processing constraints because an MMN was obtained only in the low stream of Experiment 1. If the global properties of tones influence the MMN process such that an MMN can only be elicited by the first of two deviant events that occur in a row across two streams of sound, then widening the time between across-stream deviance may make an MMN appear to the second deviant as well.

The purpose of Experiment 3 was to determine whether attention can function to segregate tonal sequences which were pre-attentively processed as alternating high and low tones (i.e., without stream segregation) when subjects ignored the tones. The presence of an MMN in this study would indicate that attention could alter the organization of auditory input.

Experiment 1. Pre-attentive Mechanisms of Auditory Streaming

Introduction

Multiple sources of acoustic energy can impinge on the ear constantly in our everyday experience. It is not uncommon for the sounds of voices, office equipment, or the ringing of telephones to occur simultaneously. The task of the brain is to tease apart the cacophony of these sounds, forming meaningful representations of the incoming acoustic information. This requires, among other processes, a mechanism for segregating the inputs into their original sources. A now classic example, the cocktail party phenomenon, illustrates the ease with which the brain is able to perform this task. Amid the steady din of party sounds (e.g., tinkling of glasses, multiple conversations, music), the brain keeps the sources distinct. Auditory cues such as the location of the sound or the pitch of a speaker's voice help this process of segregating the total stream of sound, which has been called Auditory Stream Segregation (Bregman, 1990).

When tones of a sufficient frequency separation are alternated continuously at a fast enough rate, for a period of time, a streaming effect occurs (Bregman, 1978, 1990; Bregman & Campbell, 1971). The streaming effect, an aspect of stream segregation, is a perceptual phenomenon governed by both the rate of stimulation and the frequency relationship of a tonal sequence. The perception is that the sets of high and low tones split into separate streams of sound, one formed of the high tones and one of the low tones. It sounds somewhat like counterpoint in music, as though the two streams are occurring independently and simultaneously. The purpose of this perceptual segregation is presumably to sort the tones in terms of sound sources, thereby improving the ability to perceive patterns within them. Natural differences of acoustic properties emanating from different sound sources are often reflected in pitch (e.g., the voice of a man versus the voice of a woman). Therefore, within a mixture of sounds striking the ear, it is likely that those in a high frequency range will belong to a separate source than those in a low frequency range. If streaming occurs for a sequence of high (H) and low (L) tones (e.g., H1, L1, H2, L2, H3, L3, etc.), the ability to identify the order of the tones within a stream is enhanced (such as H1, H2, H3 and L1, L2, L3), whereas the ability to identify the order of the original sequence of tones is largely impossible (viz., H1, L1, H2, L2, H3, L3; Bregman, 1978, 1990; Bregman & Campbell, 1971). That is, the sequence of tones occurring across streams is less easily perceived than the sequence occurring within the streams. The tones appear to belong to either one or the other stream sequences, but not to both. There is a transformation from the original information about all the sounds (the raw input) to information about what is happening with the sounds of given sources.

The main purpose of this study was to investigate where in the stages of auditory processing streaming occurs. There is uncertainty about the mechanisms responsible for the streaming phenomenon. Two explanations have been offered: one based upon selective attention theories and the other based upon automatic processing theories. Jones and her colleagues (Jones, 1976; Jones, Maser, & Kidd, 1978) use Broadbent's (1958) theory of selective attention to explain streaming as a function of attentional mechanisms. Bregman and his colleagues (Bregman, 1990; Bregman & Campbell, 1971) use Neisser's (1967) theory of pre-attentive acoustic processing mechanisms as governing the formation of streams. That is, there is disagreement about whether attentive or pre-attentive processes are responsible for the segregation of the tones to streams.

In Broadbent's (1958) research, a series of digits was presented dichotically at slow and fast paces. When the digits were presented slowly the subjects had no difficulty reporting the order of the digits in which they were presented. When presented at a fast pace, however, the subjects could no longer report the order of the digits as they were presented and instead reported by ear: first the digits were reported as they were heard in one ear, then the other. Broadbent reasoned that report by ear was a breakdown of attention. The subject was unable to switch back and forth between the ears fast enough, so first one ear was attended, and then the other. Along similar lines, Jones and her colleagues (Jones, Maser, & Kidd, 1978; Jones, Kidd, & Wetzel, 1981), interpret the streaming effect in terms of a perceptual overload, the inability to shift attention quickly enough along a multidimensional acoustic space. Thereby, the frequency ranges of the stimuli serve the same function as the ear of input described by Broadbent. The inability to switch attention across the large frequency jumps, occurring in quick succession, results in the segregation of the stimuli to streams (cf. Dowling, 1973; Norman, 1967).

Bregman and Campbell (1971) presented subjects with sequences of high and low tones (at a fast rate), rather than digits, and asked subjects to report their order. Subjects mostly reported the order of tones by pitch similarity: first reporting the order of the high tones, then the low tones (or the reverse). Overall, subjects could not report the order of the tones across streams. Conversely, when the same tones were presented at a slower pace, subjects easily reported the order of the tones as they were presented. Bregman & Campbell (1971) interpret their findings in terms of pre-attentive auditory mechanisms governing the separation of the tones, suggesting that the segregation occurs automatically, early in auditory processing. Specifically, the authors suggested that the organization of tones to streams occurred prior to any conscious selection criteria. One could then attribute the strategy used by Bregman & Campbell's subjects (organization of tones to high and low streams) as a function of the tones having already been sorted into different sources when they were perceived. Since what is perceived is information about sources and not the original sequence, the reports depict information about sources.

It is important to realize that the difference in interpretation of these experiments may suitably describe the differences in the methods and data to which they were applied. That is, in the Broadbent experiment, speech stimuli were presented simultaneously to the left and right ears. A strategy of switching back and forth between the ears would break down when the stimuli were coming at a fast rate (two digits per s). In contrast, the stimuli in the Bregman experiment were alternated (binaurally) at a much faster pace, which induced streaming (ten tones per s). Considering these differences in stimulus presentation, using Broadbent's interpretation to explain stream segregation, while appealing, may not be fitting.

The mismatch negativity (MMN), a component of event-related potentials associated with auditory sensory memory, has been used to investigate automatic processing of acoustic input (for reviews see Näätänen, 1992; Ritter, Deacon, Gomes, Javitt, & Vaughan, 1995). A common way to elicit an MMN is to present an infrequent stimulus (called the deviant) amid a homogeneous series of tones (called the standard). The MMN is generally thought of as the outcome of a change-detection mechanism. That is, the component is the result of the detection of a change from the immediately preceding acoustic inputs. This mechanism was originally explored using simple acoustic feature changes. Recently, the MMN has been used to investigate more complex aspects of sound processing. For example, MMNs have been reliably elicited to changes in the position of tones within a multiple-tone sequence (Schröger, Näätänen, & Paavilainen, 1992; Näätänen, Schröger, Karakas, Tervaniemi, & Paavilainen, 1993), and to the repetition of a tone within an alternating pattern of two tones (Nordby, Roth, & Pfefferbaum, 1988; Alain & Woods, in press). MMNs have also been obtained to changes in the abstract qualities of tone pairs (e.g., rising/falling; Saarinen, Paavilainen, Schröger, Tervaniemi, & Näätänen, 1992; Paavilainen, Saarinen, Tervaniemi, & Näätänen, 1995). The direction of tonal frequency (e.g., rising in pitch) from the first of the tone pair to the second was held constant (the standard) while the absolute tonal frequency of the tones varied trial to trial. A change in the direction of the first to the second tone of the pair (e.g., falling in pitch) produced an MMN.

The detection of the deviant is associated with an MMN, which is maximal over the fronto-central regions of the scalp and usually peaks around 140 - 220 ms poststimulus onset. The amplitude of the MMN response is related to the magnitude of the stimulus deviance in a direct relationship (the larger the difference between the standard and the deviant, the larger the amplitude of the response).

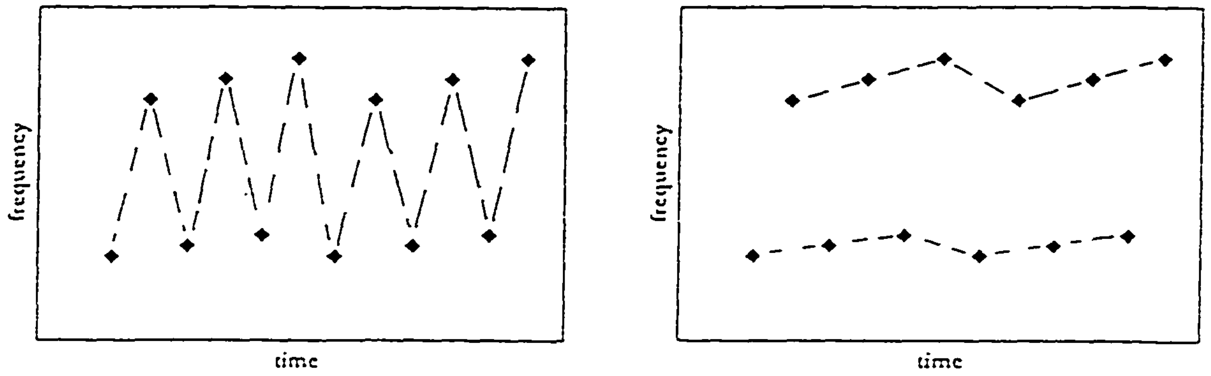
The MMN indexes early, automatic processing of auditory input, independent of subject attention (i.e., attention is not required to elicit the response; Näätänen, 1992). The MMN component is believed to be an automatic response to deviations occurring within a repetitive acoustic environment because it has been elicited when subjects' attention is highly focused on other tasks such as reading a book or doing a demanding visual task (see Näätänen, 1992 for a review). Further, the amplitude of the MMN has been found to be similar when subjects attend to stimuli as when they ignore (e.g., Alain & Woods, 1997; Näätänen, Paavilainen, Tiitinen, Jiang, & Alho, 1993; Novak, Ritter, Vaughan, & Wiznitzer, 1990). While attention can modulate the amplitude of the MMN component under certain circumstances (e.g., Alho, Woods, Algazi, & Näätänen, 1993; Woldorff, et al., 1991; Näätänen, et al., 1993), attention is not required to elicit the response. The MMN can be used to determine whether auditory stream segregation is a pre-attentive process, since the MMN can be elicited by acoustic changes that are independent of the subject's task.

In the current study, a sequence of six different high and low tones was presented at both slow and fast paces. The slow-paced sequence (750 ms stimulus onset asynchrony [SOA]) was heard as alternating high and low pitches. The fast-paced sequence (100 ms SOA) created a streaming effect in which a standard sequence of three tones emerged separately in each stream (e.g., L1, L2, L3), with a deviant sequence of three tones occurring infrequently within each stream (e.g., L3, L2, L1). There is a distinct difference between the order of the tones that enter the system (the alternating sequence of high and low tones; Figure 1a) and the perception of the tones as segregated into separate sequences of high and low tones (see Figure 1b). This difference was exploited in order to assess where in the system the segregation of the tones occurs.

It was hypothesized that the tones presented at a fast rate would segregate to low- and high-tone sequences pre-attentively and that the memory underlying the MMN system would maintain the two sequences independently and separately. We therefore expected that two MMNs would be obtained, one generated by the low tone sequence and one by the high tone sequence. Further, we expected that no MMN would occur when the sequence was presented

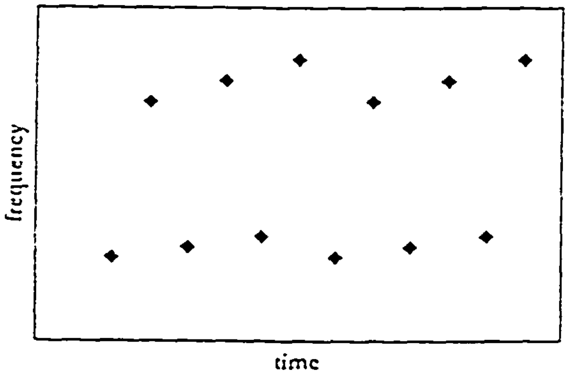
Figure 1

The difference between the order of the tones that enter the system (a) and the segregation of the tones to high and low streams (b); a repeating standard cycle of six tones (c) and deviant stimulus sequences, one cycle of six tones for each (d-e).

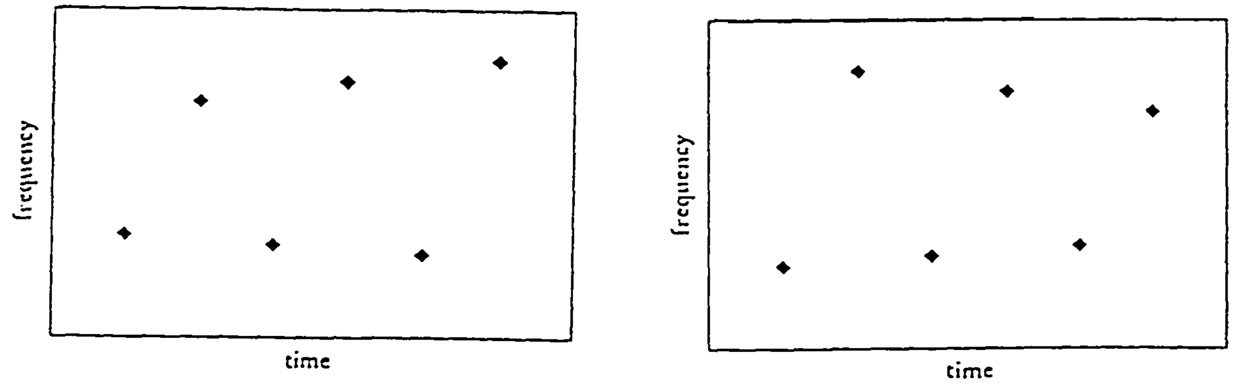


a. alternating sequence of high and low tones

b. segregated sequences of high and low tones



c. repeating standard cycle of six tones



d. low deviant

e. high deviant

at a slow pace, because the alternation of the high and low tones would interfere with the detection of the standard sequence of tones within the high- and low-pitched sequences. This prediction was based on results of behavioral studies that have reported that slow-paced alternating high and low tones are perceived as a single stream of sound that jumps up and down in pitch (Bregman, 1990).

Two control conditions were run: one for the slow- and one for the fast-paced sequence. One set of the tones (the series of low tones) was presented alone in each. The purpose of the fast-paced control was to determine whether isochronous three-tone standard and deviant sequences could elicit an MMN. Since this particular experimental paradigm has not been used before, the absence of an MMN in the fast-paced alternating condition would have been uninterpretable. Therefore, it was necessary to establish that an isochronous three-tone standard and deviant sequence could elicit an MMN (i.e., the low tone stream presented alone). The purpose of the slow-paced control was to determine whether the 1.5 s pace of the low tones, as they occurred in the slow-paced alternating condition, could elicit an MMN. Otherwise, we could not explain the absence of an MMN for the slow-paced alternating condition. The duration of the memory that underlies the MMN system has been estimated to last about 10 seconds (Sams, Hari, Rif, & Knuutila, 1993; Cowan, Winkler, Teder, & Näätänen, 1993). In MMN experiments using frequency deviants it has been determined that at least two standards in a row are necessary in order to elicit an MMN (Winkler, Cowan, Teder, & Näätänen, 1996).

It is not known, however, how many standards in a row are needed when the standard consists of several tones. If three sequences are needed, for example, the time to deliver them in this paradigm would exceed the estimated duration of the underlying memory. Therefore, it was necessary to establish that an MMN could be elicited with the slow-paced sequence.

Methods

Subjects

Ten subjects (nine females) between the ages of 23 and 42 years, with reportedly normal hearing, were paid for their participation in the experiment. The Control/1.5 s condition was run separately, in a later session. Nine subjects (four females), between 24-47 years of age, participated in the Control/1.5 s condition (five of whom participated in the other conditions).

Experimental Procedure

Subjects were seated in a comfortable chair and instructed to ignore the stimuli by reading a book of their choice, during the presentation of all conditions. The stimuli were six pure tones (400 Hz, 450 Hz, 500 Hz, 1150 Hz, 1250 Hz, and 1350 Hz) presented binaurally with insert earphones. Each tone was 50 ms in duration (rise and fall time 7.50 ms) and had an intensity of 75 dB SPL.

Two experimental conditions (Alternating/100 ms and Alternating/750 ms condition) and two control conditions

(Control/200 ms and Control/1.5 s) were used. 200 deviants were collected for each stimulus type, in eight runs of stimuli presented for each condition. The order of the runs was counterbalanced across subjects, except for the Control/1.5 s condition (because it was run at a different time). Subjects took short breaks at approximately one-third and two-thirds of the way through the recording session.

In the Alternating/100 ms condition high (1150 Hz and above) and low (500 Hz and below) frequency tones were alternated at a constant SOA of 100 ms. The standard consisted of a cycle of six tones that, in addition to alternating, rose in frequency from first to the third tone within each frequency set (e.g., L1, H1, L2, H2, L3, H3; where L1 equals 400 Hz and H1 equals 1150 Hz). Alternating high and low frequency tones at the rate of ten stimuli per second creates a streaming effect (see Bregman, 1990). The stimulus sequence was organized so that when the streams segregated a three-tone sequence of standards (occurring non-randomly on 84% of the trials) emerged separately in each stream (e.g., H1, H2, H3; L1, L2, L3). Likewise, a three-tone deviant sequence (occurring non-randomly on 16% of the trials) occurred non-randomly in each stream (e.g., L3, L2, L1; H3, H2, H1). Half of the deviants occurred in the low stream and half in the high stream. The occurrence of the deviant sequences in the high or low streams was offset by one cycle so that the low- and high-tone deviants did not occur within the same cycle of six tones. The low tones deviant always preceded the high tones deviant. The standard and deviant sequences are presented in Figure 1 (c-e).

In the Alternating/750 ms condition, the same sequence of alternating high and low tones as described above was presented at a slower rate of stimulation (750 ms SOA). When tones are presented at this slower pace, they are heard as alternating high and low pitches.

In the Alternating/100 ms Condition, the stimulus parameters were selected to produce the strongest streaming effect as have been reported from numerous behavioral studies (Bregman, 1990). In the Alternating/750 ms Condition, the repetition rate of the tones was slowed from the streaming pace to a pace that would be heard as a single stream of sound that alternates in pitch.

For both control conditions the low tones only (500 Hz and below) were used. The order of the tones was kept the same as the low frequency tones in the experimental conditions (see Figure 1, bottom). In the Alternating/100 ms condition, a low frequency tone occurred every 200 ms. Therefore, a 200 ms SOA was used in the Control/200 ms condition to replicate the stimulus rate of the low frequency tones of the Alternating/100 ms condition. In the Alternating/750 ms condition, a low frequency tone occurred every 1.5 s. Therefore, a 1.5 s SOA was used in the Control/1.5 s condition to replicate the stimulus rate of the low frequency tones of the Alternating/750 ms condition. The standard sequence was L1-L2-L3. The deviant sequence was L3-L2-L1. The probability that a deviant pattern would occur was 16%.

Recording

The electrical brain activity was recorded using DC-coupled amplifiers, with a low-pass filter setting of 40 Hz. The digitization rate was 400 Hz. An epoch duration of 600 ms was used, which included a 100 ms prestimulus baseline. Electrode recordings were obtained at the following sites: Fpz, Fz, Cz, Pz, Oz, Fp1, Fp2, F3, F4, F7, F8, FC1, FC2, P3, P4, LM, and RM (left and right mastoids, respectively). All recordings were referenced to the nose. Vertical ocular potentials were monitored with a bipolar electrode configuration using Fp1 and an external electrode placed below the left eye. Horizontal eye movements were monitored using electrodes F7 and F8. Trials on which electrical activity exceeded ±100 μV were automatically rejected. The remaining averaged ERPs were examined for residual artifact.

Data Analysis

ERPs elicited by the first tone of each standard sequence were averaged together across the eight runs for each subject, separately for the high and low tones, in each condition. Likewise, the ERPs elicited by the first tone of the deviant sequence were averaged together across the eight runs, separately for each subject, and each set of tones, in each condition.

The grand mean ERPs were used for the purposes of display. Grand mean difference waveforms were calculated by subtracting the ERPs from the standard from those of the deviant, separately for each set of high and low tones and each condition. The peak latency of the MMN was selected in the grand mean difference waveforms. A latency window from 25 ms before to 25 ms after the peak latency of the MMN in the grand means was used to measure the mean amplitude of the ERPs elicited by the standards and deviants for each subject and each condition. Peak latency was selected as 174 ms in the Alternating/100 ms condition, 188 ms in the Control/200 ms condition, and 260 ms in the Control/1.5 s condition. There was no evidence of an MMN in the Alternating/750 ms condition to either the high or low frequency tones nor in the Alternating/100 ms condition to the high frequency tones.

Where there was evidence of an MMN, the data were statistically analyzed using a two-way analysis of variance (ANOVA) for repeated measures with factors of stimulus type (standard and deviant) and electrode. The MMN component was measured relative to the 100 ms pre-stimulus activity. The mean voltages, in the 50 ms window taken around the peak of the MMN were used to determine whether the ERPs to the standard and deviant differed significantly at Fz, FC1, FC2, LM, and RM. Since there was no evidence of an MMN in the high tones of the Alternating/100 ms Condition, the mean voltages in the 50 ms latency window around the peak of the MMN as obtained in the grand mean for the low tones was used to measure the difference between the standard and deviant ERPs. Tukey HSD (honestly significant difference) post-hoc comparisons were then used to determine statistical significance at individual electrode sites.

To compare scalp distributions between the control and experimental conditions the data were scaled (McCarthy & Wood, 1985) and then evaluated using the factors of condition and electrode in a two-way repeated measures ANOVA.

Greenhouse-Geisser procedures were used as appropriate. An alpha level of .05 was used.

Results

Subject report

At the end of the recording session subjects were asked their subjective experience of the tones occurring in the alternating conditions. All subjects reported hearing two different paces of tones, one fast and one slow. The slow-paced tones were reported as alternating high and low pitches. The fast-paced sequence was reported as two parallel melodies. Some of the subjects experienced the sequences as dichotic. That is, the streaming effect was so strong it sounded as if the low tone melody was presented to one ear and the high tone melody to the other.

Control/200 ms condition

The low frequency tones were presented at a rate of one tone per 200 ms. Figure 2 (upper left) presents the across-subjects averages of the ERPs to the standard and deviant stimuli at seven recording sites. The N1-P2 components can be seen, though are not distinctive because the interval between the tones was short (Javitt, Doneshka, Zylberman, Ritter, & Vaughan, 1993). The N1-

P2 components elicited by subsequent stimuli can also be seen since the epoch extends 500 ms poststimulus onset. A broad negative deflection, separating the deviant from the standard beginning about 140 ms, represents the MMN. Figure 3 (upper left) presents the difference waveforms, obtained by subtracting the ERPs to the standard from the ERPs to the deviant. The first negative peak, seen at Fz, Cz, FC1, and FC2, delineates the MMN component. The presence of the MMN was established by an overall significant difference between the standard and deviant waveforms revealed in a two-way repeated measures ANOVA, F (1,9) = 14.9, p = .004. Tukey HSD post hoc comparisons confirmed the difference of stimulus type at the frontal electrodes and the right mastoid at the .01 level but not at the left mastoid site. Table 1 presents the grand mean amplitudes of the standard and deviant ERPs measured in the latency range of the MMN. The mean amplitudes of the MMN component obtained in the same latency window are also provided. These data show that an MMN can be obtained using an isochronous three-tone standard.

Alternating/100 ms condition

In this condition, the high and low tones were alternated at a rate of one every 100 ms, inducing a streaming effect. The ERPs elicited by the high and low tones were analyzed separately and are presented in Figure 4 (left column). As described above, the N1-P2 components from subsequent stimuli can also be seen in this epoch period. In the low stream, a negative deflection, separating the deviant from the standard waveforms, can be seen beginning about 140 ms and represents the MMN. No MMN was

Figure 2

Standard (thin line) and deviant (thick line) ERPs at Fz, Cz, Pz, FC1, FC2, P3, P4, LM, and RM in three conditions when low tones were presented alone (Control/200 ms, Control/1.5 s, and Control/1 s).

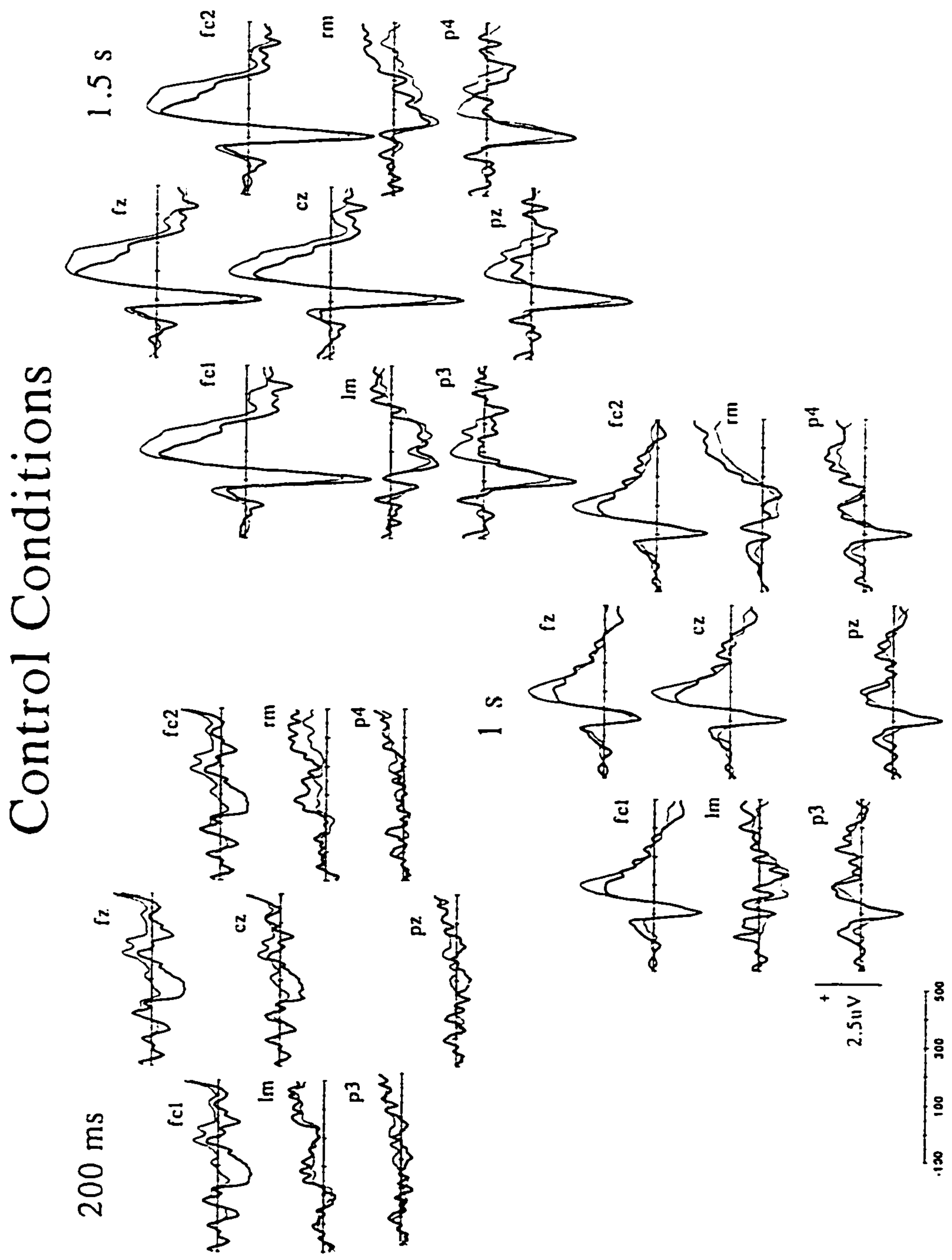


Figure 3

Difference waves at Fz, Cz, Pz, FC1, FC2, P3, P4, LM, and RM in three conditions when low tones were presented alone (Control/200 ms, Control/1.5 s, and Control/1 s).

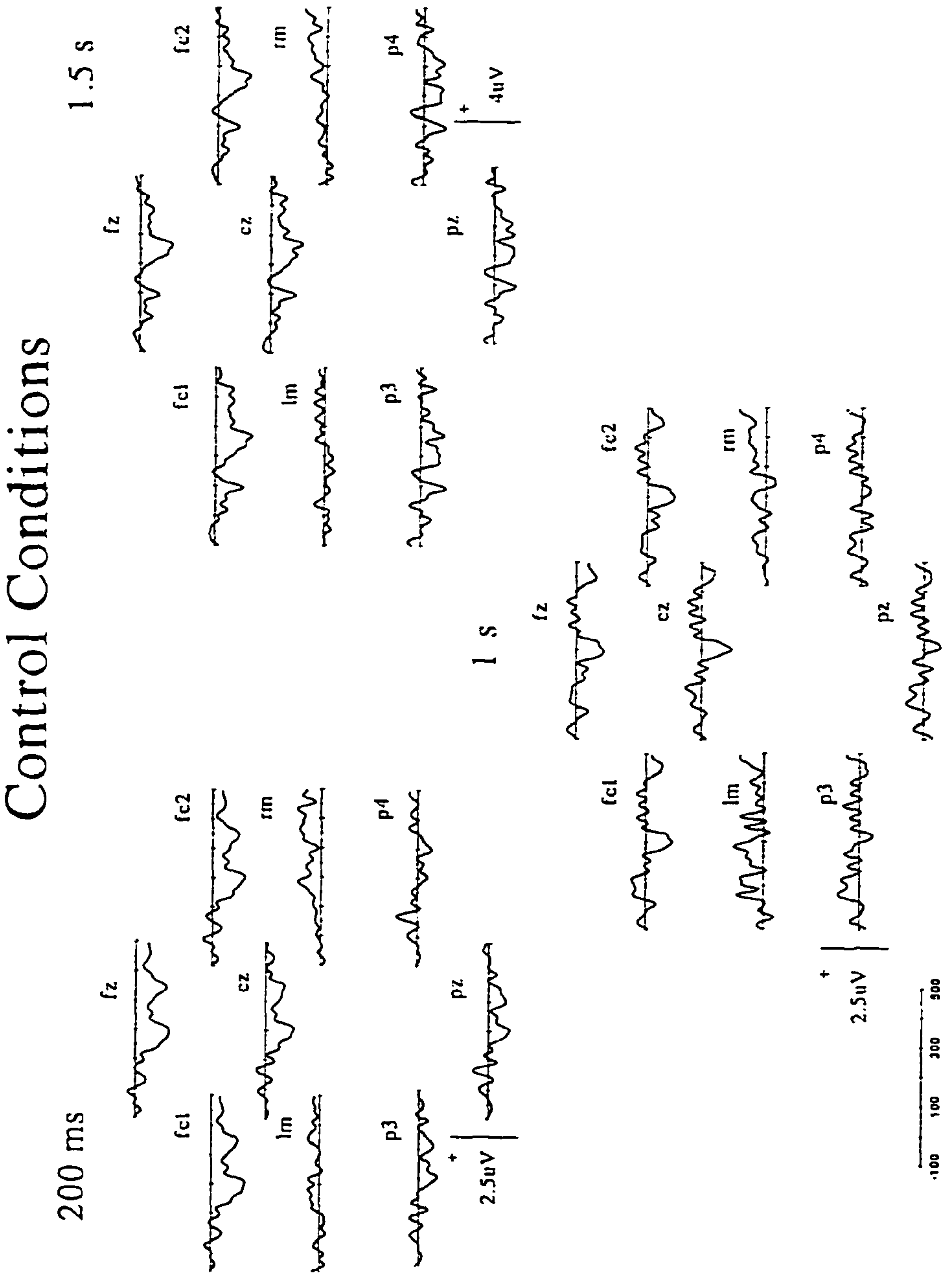


TABLE 1. Mean amplitude in µV (and standard deviation) of the Difference Waveform and the Standard and Deviant ERPs measured in the latency window of the MMN for Experiment 1.

	Electrode	Standard	Deviant	Difference	p
	Fz	.50 (.57)	-.54 (.78)	-1.04 (.59)	**
Alternating/100ms	FC1	.38 (.74)	-.48 (.91)	- .86 (.76)	**
(low tones)	FC2	.55 (.61)	-.33 (.82)	- .88 (.74)	**
	LM	.48 (.66)	.63 (.52)	.14 (.41)	
	RM	.43 (.73)	.24 (.74)	- .16 (.66)	
	Fz	.07 (.54)	-1.13 (.85)	-1.20 (1.14)	**
Control/200ms	FC1	.04 (.58)	-1.14 (.76)	-1.20 (1.07)	**
	FC2	.16 (.53)	-0.92 (.82)	-1.08 (1.06)	**
	LM	.40 (.77)	0.70 (.86)	.30 (.80)	
	RM	.32 (.62)	0.98 (.63)	.65 (.51)	**

* <.05

** <.01

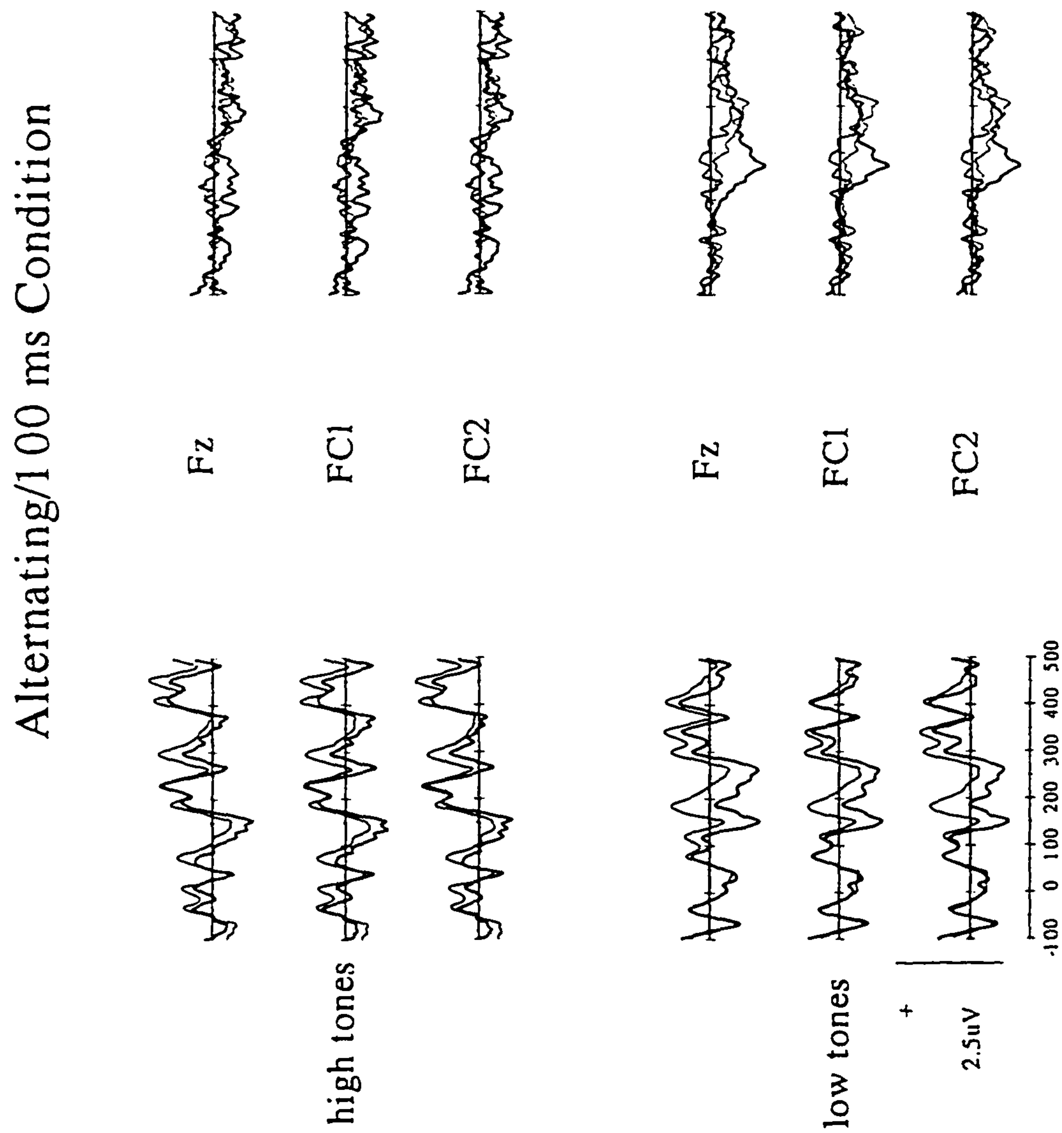
elicited by the deviant within the high tones sequence (F[1,9] = .45, p = .52).

Figure 4 also presents the grand mean difference waveforms (right column), obtained by subtracting the ERPs to the standard from the ERPs to the deviant separately for each stream. An MMN was elicited for the low stream, seen most prominently in the frontal electrodes. The negative deflection peaking at about 175 ms, delineates the MMN component. Notice that MMN obtained to the low deviant in the Alternating/100ms Condition is similar in amplitude and latency to the MMN elicited in the Control/200 ms condition (see Figure 3). However, the inversion at the mastoids, typically accompanying the MMN component, is attenuated in the Alternating/100 ms Condition compared to the inversion obtained in the Control/200 ms Condition. The presence of the MMN was established by the overall significant difference found between the ERPs elicited by the standard and deviant waveforms (measured in the latency range of the MMN) in a two-way repeated measures ANOVA, F (1,9) = 22.5, p = .001. Tukey HSD post hoc comparisons confirmed the difference at the frontal electrode sites where the MMN is most prominently seen, but not at the mastoid sites.
Table 2 presents the grand mean amplitudes of the standard and deviant ERPs obtained in the latency range of the MMN. MMN mean amplitudes are also provided in Table 2. These data show that an MMN can be elicited when two streams are presented, but only in one stream.

To ascertain whether topographical differences existed between the Control/200 ms and the Alternating/100 ms conditions,

Figure 4

<u>Alternating/100 ms condition of Experiment 1</u>. Standard (thin line) and deviant (thick line) ERPs at Fz, FC1, and FC2 (left column) for the high (top) and low (bottom) tones. Difference waves (thick line) with mastoids overlain (thin lines) at Fz, FC1, and FC2 (right column) for the high (top) and low (bottom) tones.



potentially accounting for the differential effects found at the mastoids, the data were scaled and a repeated measures ANOVA with factors of condition and electrode was conducted on the scaled data. The results of this analysis revealed a significant interaction between condition and electrode, F(2,18) = 4.8, p = 0.022, Greenhouse Geisser correction p = 0.034.

Control/1.5 s condition

As can be seen in Figure 2 (upper right), the ERPs elicited by the standard tones contained a negative component (N1) that peaked at 100 ms, was largest at Cz. A positive component (P2) peaked around 200 ms and was also largest at Cz. The N1 - P2 response was prominent because the interstimulus interval was sufficient (1.5 s).

The difference between the amplitude of the standard and the deviant ERPs in the region of the MMN, when all nine subjects were included, was not significant. When each subject was examined individually, four of the nine subjects had MMNs. A separate repeated measures ANOVA with factors of stimulus type and electrode (measured in the latency range of the MMN) was calculated on each individual subject using the number of runs as entities. This analysis revealed the presence of the MMN for each individual where an MMN was visibly detected: Subject 1 (S1): F(1,9)=7.1, p=.026. S2: F(1,9)=7.2, p=.025. S3: F(1,8)=33.1, p<.001. S4: F(1,9)=8.2, p=.019. Figure 3 (upper right) shows the difference waveforms for the group of the four subjects who had MMNs. The issue of the duration of the memory underlying MMN generation is considered further in the discussion.

Alternating/750 ms condition

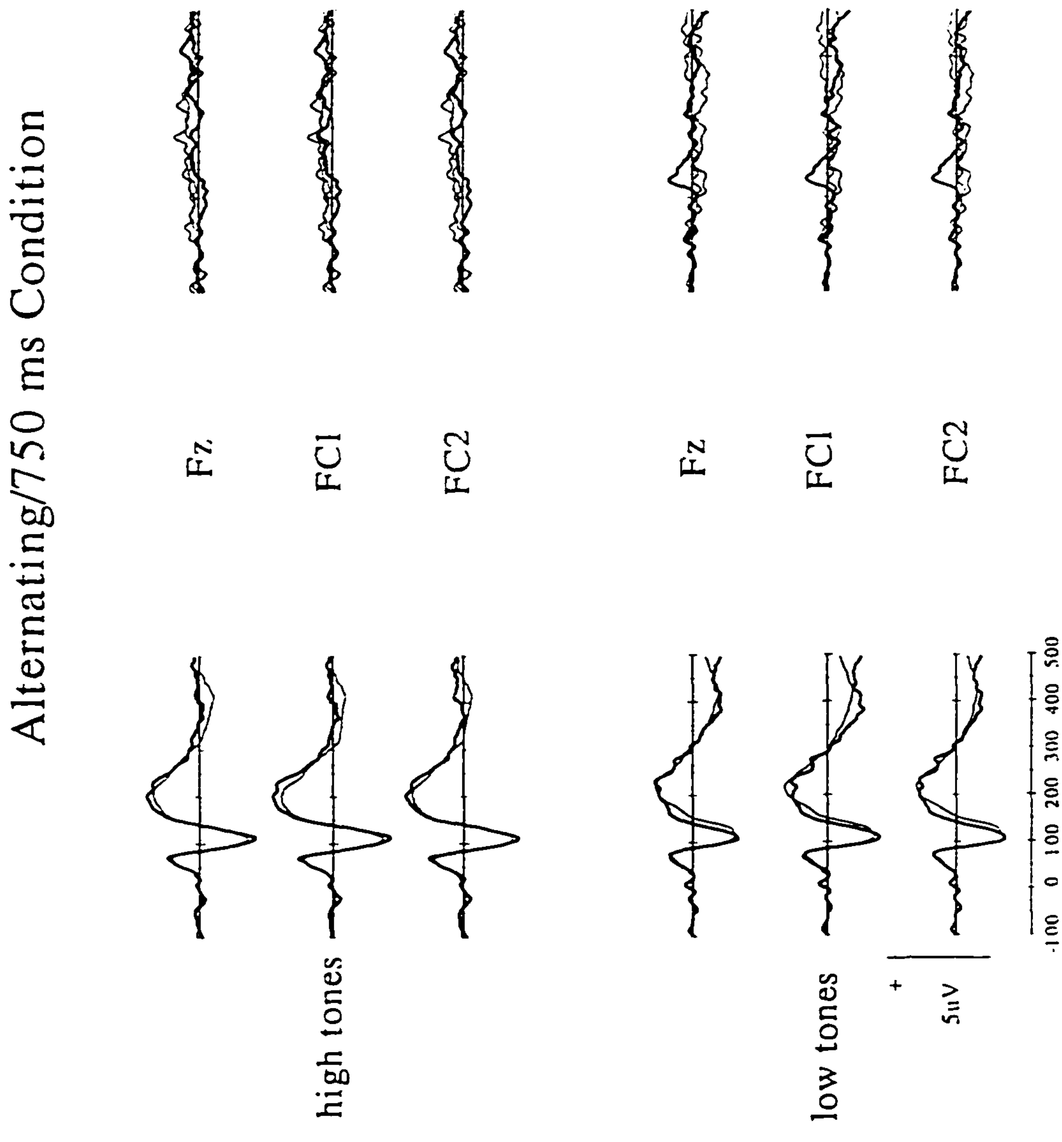
In this condition, the ERPs elicited by the standard tones contained a negative component (N1) that peaked at 100 ms, and was largest at Cz. A positive component (P2) peaked around 200 ms and was also largest at Cz. The N1 - P2 response was prominent because the interstimulus interval was sufficient (750 ms). As can be seen in Figure 5, for the low tones, the response to the standard tones was separated from the deviant tones in a negative direction (left column), creating a positive peak in the subtraction waveforms (right column). Likewise, for the high tones, there was no indication of an MMN.

Discussion

An MMN can be obtained to a three-tone standard and deviant sequence presented isochronously (the low tones only in the Control/200 ms condition). This result extends the findings of Schröger, Paavilainen, & Näätänen (1994) who obtained MMNs to changes occurring within a repeating tone pattern (consisting of five different frequency elements) with no silent intervals between them (see also Winkler & Schröger [1995]). In contrast, other MMN studies using stimulus sequence designs separated tonal patterns with intertrain (Schröger, 1994) or interpair (Saarinen, et al., 1992; Paavilanen, et al., 1995) intervals.

Figure 5

<u>Alternating/750 ms condition of Experiment 1</u>. Standard (thin line) and deviant (thick line) ERPs at Fz, FC1, and FC2 (left column) for the high (top) and low (bottom) tones. Difference waves (thick line) with mastoids overlain (thin lines) at Fz, FC1, and FC2 (right column) for the high (top) and low (bottom) tones.



The offsetting interval may facilitate the detection of the pattern of tones, not possible with an isochronous rhythm.

When the high tones were embedded in the low tones, in the Alternating/750 ms condition, no MMN was elicited. One possible explanation is that the high tones interfered with the emergence of the three-tone sequence within the low (or high) tones when alternated at the rate of one per .75 s. Another possibility is that the duration of the memory underlying the MMN was exceeded in this case (as explained in the introduction), since the low tones (or high tones) occurred once every 1.5 s.

The Control/1.5 s condition was run separately to determine whether the three-tone standard sequence exceeded the limits of the memory underlying the MMN system. An MMN was obtained in four of the nine subjects. This indicates that the memory can persist long enough in some subjects to elicit an MMN, but not all. It is likely that the duration of the memory is variable among people. Evidence that memory varies individually can be found in a study designed to investigate whether the duration of the memory underlying MMN generation is shorter in children than adults (for detecting a change in tonal frequency; Gomes, Sussman, Ritter, Kurtzberg, Cowan, & Vaughan, submitted). In addition to their main finding of age-related differences across the subject groups (there was a positive correlation between age and duration of the memory), the data indicate that there were individual memory differences within the groups as well.

Additional data showing individual differences were collected in our laboratory as pilot data for another experiment

(Control 1 s). These data were collected using the same stimulus parameters as the current experiment except the pace of the tones was one per second in the control condition, and one per 500 ms in the alternating condition. Half of the eight subjects obtained MMNs to the deviant sequence in the control condition and half did not. Figures 2 and 3 (center bottom) display the four subjects who had MMNs. None of the subjects who obtained an MMN in the control had MMNs when the tones were alternating high and low tones. An ANOVA for repeated measures conducted on the four subjects who had MMNs established that the ERPS to the standard were significantly different from the ERPs to the deviant, in the range of the MMN, $F(1,3)= 21.8$, $p=.018$. None of the subjects in the main experiment had MMNs in the Alternating/750 ms condition.

Taken together, these data show that for a total of eight different subjects who had significant MMNs when the low tones were presented alone at a slow pace, none had MMNs for alternating high and low tones. Therefore, the lack of an MMN may be attributed to interference of the within-stream sequences by the alternation of the high and low tones and not to constraints of the memory, at least for some subjects. Since the absence of an MMN in the Alternating/750 ms condition was not likely due to limits in the duration of the memory needed for this paradigm, we concluded that the alternation of the high and low tones interfered with the emergence of the high- and low-pitched tonal sequences in the Alternating/750 ms Condition.

An ANOVA for repeated measures with factors of condition and electrode was conducted on the scaled data of the three control conditions (Control/200 ms, Control 1.5 s, and Control 1 s). The absence of an interaction F(10,30)= .87, p=.572 in this analysis established that there were no significant differences between the MMNs in the three conditions.

When the same alternating sequence was run at a faster pace, an MMN was obtained. This was presumably due to the sorting associated with streaming. That is, when the tones were alternated at this pace they did not interfere with one another because high- and low- tone streams emerge pre-attentively. Hence, the within stream patterns appear to have emerged prior to, or at, the level of the MMN system. These results demonstrate that that the streaming effect is governed by pre-attentive mechanisms of the auditory system.

The MMN obtained in the Control/200 ms condition had a more typical scalp distribution than the MMN obtained in the Alternating/100 ms condition. The grand mean difference waves obtained in the Control/200 ms and Alternating/100 ms conditions were similar in both amplitude and latency. However, the inversion in polarity at the mastoid sites differed between these conditions. The MMN in the control condition revealed a typical inversion at the mastoids, whereas there was no significant reversal in polarity in the mastoids in the Alternating/100 ms condition. The notable distinction between the two conditions, possibly contributing to this difference, is that an MMN was elicited within a single stream of sound (a low tone stream) in the Control/200 ms condition and an MMN was elicited within the context of two streams of sound (a high tone stream and a low tone stream) in the Alternating/100 ms condition. The significant interaction of the ANOVA conducted on the scaled data provides supporting evidence, in this study, that different neural generators may have subserved the MMN process in the control and the experimental conditions.

In the Alternating/100 ms condition, an MMN was expected in both the low tone and high tone streams. An MMN was obtained to the low tones deviant but not to the high. Since the low tones deviant always preceded the high tones deviant and an MMN was obtained to the low tones stream only, we speculated that the MMN system may have been subject to processing constraints. A second experiment was conducted specifically to address the issue of whether only one MMN occurred because there was not enough time for the MMN system to process both deviants.

In summary, when alternating high and low tones occur at a rapid pace, the tones are sorted to separate streams of sound. This sorting process facilitates the ability to identify the order of the within stream sequences while impeding the ability to identify the order of across stream sequences (Bregman, 1990). Recall, when Bregman & Campbell (1971) presented high and low tones fast enough to produce the streaming effect, subjects mostly reported the order of the tones occurring within streams rather than across streams. In this study, the MMNs obtained in the fast-paced alternating conditions show that the ability to detect within stream sequences over across stream sequences was facilitated. The three-tone deviant sequences could be detected as different than the three-tone standard sequences as a function of the streaming effect. When the high and low tones alternated at a slower pace, the three-tone within stream standard sequences did not emerge, no MMNs were obtained.

Experiment 2. Processing constraints and the MMN system.

Introduction

In Experiment 1, an MMN was obtained to the low-tones deviant but not to the high-tones deviant when the stimuli were presented at a fast pace which induced the streaming effect. An MMN was expected for both the low- and high-tone streams when streaming occurred since the MMN indexes pre-attentive processing and pattern deviance occurred in both streams. One aspect of the paradigm that may have contributed to these results is that deviants in Experiment 1 consisted of a pattern of three tones and may have enlisted different processing mechanisms than when simple deviations of features of tones are used. However, since the low tones deviant always preceded the high tones deviant and an MMN was obtained to the low tones stream only, we speculated that the MMN system may have been subject to processing constraints. Experiment 2 was conducted to address the issue of whether only one MMN occurred because there was not enough time for the MMN system to process both deviants in the context of streaming.

The purpose of Experiment 2 was to test whether two MMNs were not obtained in Experiment 1 because the interval between the across-stream deviance was too small for the MMN system to process both. If the global properties of a tonal sequence influence the MMN process such that an MMN can only be elicited by the first of two deviant events that occur in a row across two streams of sound, then widening the time between across-stream deviance may make an MMN appear to the second deviant as well.

We hypothesized that if the same stimulus sequence were used as in Experiment 1 (i.e., the Alternating/100 ms Condition) with a wider interval between the low-tones deviant and high-tones deviant, two MMNs would be obtained. This would show that streaming sorts the tones to separate sources pre-attentively such that the MMN system can detect the deviance in both streams. Additionally, an MMN to both stream deviants in this experiment would support the hypothesis that the process that underlies MMN generation is subject to processing constraints. The MMN system may be limited in its ability to automatically track all the changes occurring within different streams of sound if they occur too closely in time.

Methods

Subjects

Eleven subjects (two males) ages 21-45 years of age participated in the experiment. Subjects were seated in a comfortable chair and instructed to ignore the stimuli by reading a book of their choice.

Experimental Procedure

The stimuli were six pure tones (400 Hz, 450 Hz, 500 Hz, 1150 Hz, 1250 Hz, and 1350 Hz) presented binaurally with insert earphones. Each tone was 50 ms in duration (rise and fall time 7.50 ms) and had an intensity of 75 dB SPL. The stimulus sequence employed in Experiment 1 (Alternating/100 ms condition) was used in Experiment 2 with the following modification. The time between the occurrence of the across-stream deviants was increased by one standard cycle of six tones. Eight blocks of stimuli, with a total of 200 of each type of deviant (high and low), were collected for each subject.

ERP Recording

The electrical brain activity was recorded using DC-coupled amplifiers, with a low-pass filter setting of 40 Hz. The digitization rate was 400 Hz. An epoch duration of 600 ms was used, which includes a 100 ms pre-stimulus baseline. Electrode recordings were obtained at the following sites: Fpz, Fz, Cz, Pz, Oz, Fp1, Fp2, F3, F4, F7, F8, FC1, FC2, P3, P4, LM, and RM (left and right mastoids, respectively). All recordings were referenced to the nose. Vertical ocular potentials were monitored with a bipolar electrode configuration using Fp1 and an external electrode placed below the left eye. Horizontal eye movements were monitored using electrodes F7 and F8. Trials on which electrical activity exceeded ±100 µV were automatically rejected. The remaining averaged ERPs were examined for residual artifact.

Data Analysis

ERPs elicited by the first tone of each standard three-tone sequence were averaged together across the runs for each subject, separately for the high and low tones. Likewise, the ERPs elicited by the first tone of the deviant three-tone sequence were averaged together across the runs, separately for each subject, and each set of tones (high and low).

The grand mean ERPs were used for the purposes of display. Grand mean difference waveforms were calculated by subtracting the ERPs from the standard from those of the deviant, separately for each set of high and low tones. The peak latency of the MMN was selected in the grand mean difference waveforms. A latency window from 25 ms before to 25 ms after the peak latency of the MMN in the grand means was used to measure the amplitude of the ERPs elicited by the standards and deviants for each subject and each condition. Peak latency was selected as 154 ms for the high tones MMN and 176 ms for the low tones MMN.

The data were statistically analyzed using a two-way analysis of variance (ANOVA) for repeated measures with factors of stimulus type and electrode. The mean voltages, in the 50 ms window taken around the peak of the MMN were used to determine whether the ERPs to the standard and deviant differed significantly at Fz, FC1, FC2, LM, and RM. Tukey HSD post-hoc comparisons were then used to determine statistical significance at individual electrode sites.

Results

Figure 6 displays the grand averages of the ERPS elicited by the standard and deviant tones, separately for the low and the high streams are shown on the left column. The N1-P2 components can be seen in the standard ERPs. They are not distinctive because the interval between the tones was short (100 msec). The

N1-P2 components from subsequent stimuli can also be seen in this epoch period since the period extends for 500 msec poststimulus onset. The deviant waveforms separate from the standard beginning about 125 msec for the high tones and 135 for the low tones, delineating the MMN.

The difference waveforms, obtained by subtracting the standard ERPs from the deviant ERPs, separately for each stream, are displayed in Figure 6 (right). A negative deflection can be seen in the difference waves at Fz, FC1, and FC2, peaking at about 175 ms in the low stream and about 155 ms in the high stream (Figure 6, right column) delineating the MMN components.

An MMN was obtained in both streams, established in a two-way ANOVA for repeated measures with factors of stimulus type and electrode, calculated on the low (F [1,10] = 7.1, p =.024) and high tones (F [1,10] = 6.3, p=.031)separately in the latency window of the MMN. Tukey HSD post hoc comparisons were conducted to confirm the presence of the MMN at electrode sites Fz, FC1, FC2, LM, and RM. Table 2 presents the grand mean amplitudes and standard deviations of the standard and deviant ERPs measured in the latency range of the MMN. The mean amplitudes of the difference waves are also reported.

Figure 6

<u>Experiment 2</u>. Standard (thin line) and deviant (thick line) ERPs elicited by the high tones (left column, top) and difference waves (thick line) with mastoids overlain (thin line; right column, top) at Fz, FC1, and FC2. Standard (thin line) and deviant (thick line) ERPs elicited by the low tones (left column, bottom) and difference waves (thick line) with mastoids overlain (thin line; right column, bottom) at Fz, FC1, and FC2.

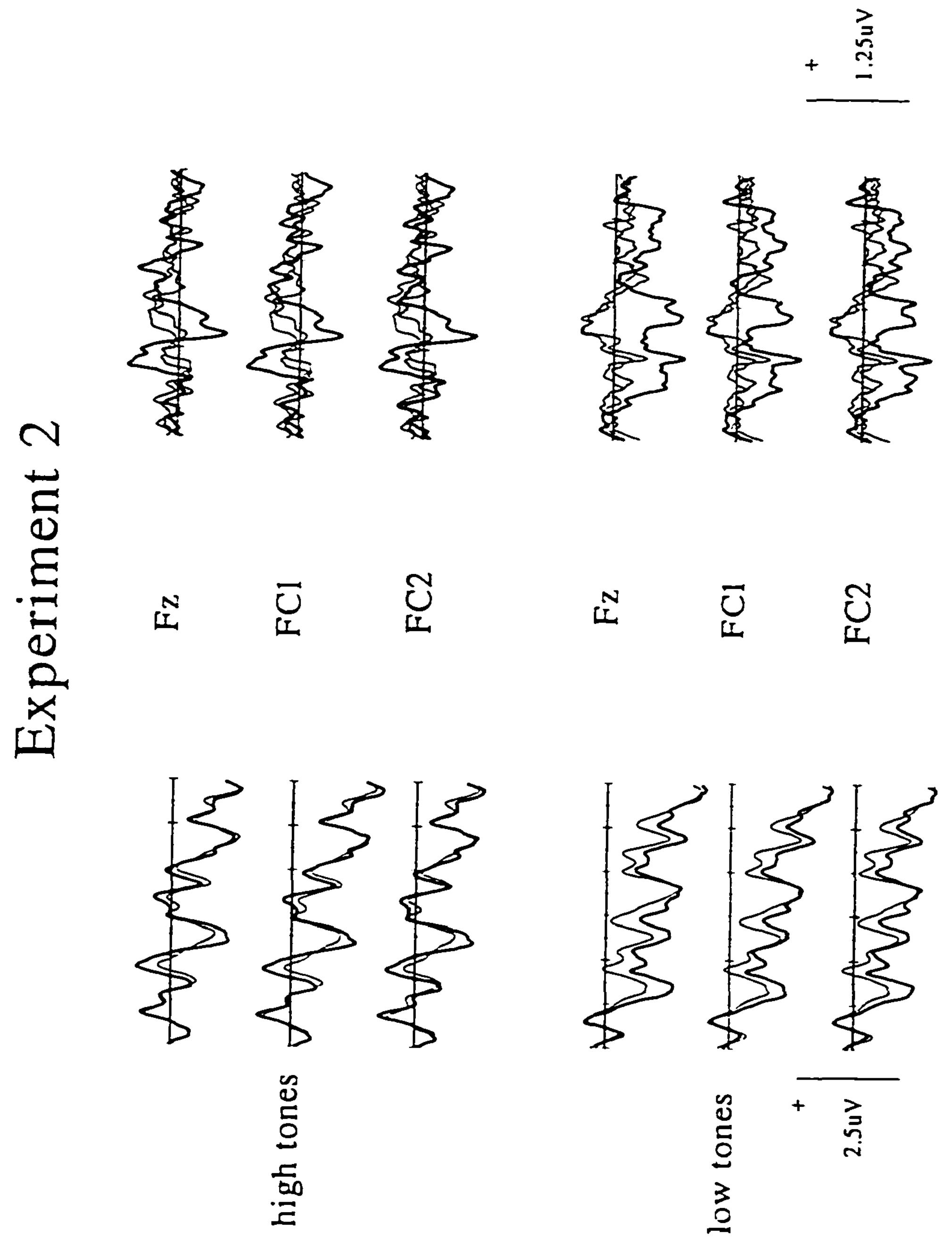


Table 2. Mean amplitude in µV (and standard deviation) of the Difference Waveform and the Standard and Deviant ERPs measured in the latency window of the MMN for Experiment 2.

	Electrode	Standard		Deviant		Difference		p
	Fz	-.46	(.44)	-1.16	(.92)	- .70	(.92)	**
	Cz	-.43	(.53)	- .58	(.60)	- .16	(.74)	**
	FC1	-.59	(.39)	-1.12	(.78)	- .52	(.70)	**
Low tones	FC2	-.40	(.53)	- .90	(.85)	- .51	(.95)	**
	LM	-.43	(.48)	- .17	(.55)	.25	(.40)	**
	RM	-.17	(.92)	.01	(1.03)	.25	(.58)	**
	Fz	- .86	(.82)	-1.24	(.98)	- .38	(.69)	**
High tones	Cz	- .68	(.87)	-1.10	(.92)	- .42	(.91)	**
	FC1	-1.00	(.75)	-1.30	(.86)	- .30	(.66)	**
	FC2	- .72	(.87)	-1.11	(.95)	- .38	(.65)	**
	LM	- .15	(.53)	.14	(.76)	.29	(.44)	**
	RM	.06	(.81)	.11	(.86)	.05	(.40)	*

* <.05

** <.01

Discussion

Experiment 2 was conducted to try to clarify the results obtained in Experiment 1 concerning why only one MMN was obtained in the streaming condition. The results of Experiment 1 were somewhat puzzling since we expected that if the streams segregated pre-attentively two MMNs would be obtained. An additional six-tone standard cycle separated the low tones deviant from the high tones deviant was added between the occurrence of the low- and high-tones deviants and an MMN was obtained in both streams. These results extend the findings of Experiment 1 that the sorting of streams to separate sources occurs pre-attentively when alternating high and low tones are presented at a fast enough rate to induce the streaming effect.

The two MMNs obtained in Experiment 2 also seem to explain why only one MMN was obtained in Experiment 1. Apparently, there was not enough time between the occurrence of the three-tone deviants, across streams, for the MMN system to process both of them. The results of Experiment 2, therefore, indicate that the MMN system may be subject to processing constraints in the context of streaming. Another consideration is that it may take more time to process a three-tone standard than a single tone standard. Both aspects of the paradigm used in Experiment 1 (the three-tone standard and the two streams of sound) may have influenced how the deviants were processed in respect to time.

Experiment 3. Attention-dependent mechanisms of auditory stream segregation

Introduction

The mismatch negativity (MMN), a component of event-related potentials (ERPs), indexes early, automatic responses to changes in auditory stimulation, providing information about pre-attentive auditory processing and the representations registered in auditory sensory memory (for reviews see Näätänen, 1992; Ritter, Deacon, Gomes, Javitt, & Vaughan, 1995). The MMN is believed to be the outcome of a comparison process, commonly elicited when an incoming stimulus differs from the memory of repetitive tones (standards) occurring in the recent acoustic past. The differing tones (the deviants) can vary in frequency, intensity, or duration from the standard tones. They can vary along single or multiple acoustic dimensions (Levanen, Hari, McEvoy, & Sams, 1993; Schröger, 1995; Schröger, 1996), by sequential order (Schröger, 1994; Schröger, Näätänen, & Paavilainen, 1996; also see Experiment 1), or by a change in the abstract representation of pairs of standard tones (Paavilainen, Saarinen, Tervaniemi, & Näätänen, 1995; Saarinen, Paavilainen, Schröger, Tervaniemi, & Näätänen, 1992). This pre-attentive comparison process can operate on the spectral, temporal, and spatial information that is stored in the memory that underlies the MMN system. The MMN process is considered pre-attentive because attention is not required to produce it. For instance, MMNs were obtained in the above-mentioned studies while the subjects ignored the stimuli (e.g., reading a book).

The MMN is a negative wave, which is maximal over the fronto-central regions of the scalp and varies in latency in relation to the difficulty or timing of the discrimination between the standard and the deviant. The latency of the MMN increases as the discrimination gets more difficult. The amplitude of the MMN increases as the discrimination gets easier.

MMN and attention

Näätänen originally proposed that the amplitude of the MMN is largely insensitive to manipulations of attention (Alho, Sams, Paavilainen, Reinikainen, & Näätänen, 1989; Mäntasylo, & Näätänen, 1987; Näätänen, 1991; Näätänen, 1992). Woldorff, Hackley, & Hillyard, 1991 were the first to show an attentional effect on the MMN system for intensity deviants. In a follow-up study using the Woldorff et al. (1991) paradigm, Näätänen, Paavilainen, Titinen, Jiang, & Alho (1993) presented subjects with high frequency tones in one ear and low frequency tones in the other. Subjects were asked to attend to one ear and count the number of designated difficult-to-detect deviants (either frequency or intensity) occurring in that ear. Another condition used the same demanding dichotic paradigm, except subjects were asked to ignore the stimuli. The amplitudes obtained for the frequency-deviant MMNs were similar for the attended and unattended stimuli, as well as for the ignored stimuli. Therefore, the MMN process for frequency-deviants was unaffected by the direction of attention. The amplitude of the MMN elicited by the deviants that differed from the standards in intensity, on the other hand, were affected by manipulations of attention. When attention was strongly focused toward one ear (necessitated by the demand of the task), the intensity-deviant MMN was significantly reduced in amplitude for the responses obtained from the unattended ear. However, an MMN was obtained to the intensity-deviants when subjects ignored the stimuli altogether with an amplitude that was not significantly different than the amplitude of the intensity-deviant MMN obtained for the attended channel. Thus, it appears that when a high degree of attention is required in one direction, the amplitude of the MMN is reduced for intensity changes occurring for the unattended stimuli.

Alain & Woods (1997) also demonstrated that attention can modulate the amplitude of the MMN. They presented two alternating high tones of different frequencies to one ear and two alternating low tones of different frequencies to the other, with breaks (by repetition) in the alternation constituting a deviant. Deviants occurred within the tones presented to both the attended and unattended ears. In another condition, ERPs were collected while subjects ignored the stimuli. The results were similar to the results of the Näätänen, Paavilainen, et al. (1993) study with regard to intensity deviants. The amplitude of the MMNs obtained for the unattended channel were considerably smaller than those obtained in the attended channel, whereas the MMNs obtained during the ignore condition were not.

Attention can modulate the MMN component in an additional way: by inducing it or increasing its amplitude (Kraus, McGee, Carrell, King, Tremblay, & Nicol, 1995; Näätänen, Schröger, Karakas, Tervaniemi, & Paavilainen, 1993). In a study by Näätänen, Schröger (1993), standard stimuli were composed of eight 50-msec segments that each differed in frequency (creating one standard stimulus 400 msec in duration). The sixth segment of the deviant was higher in frequency relative to the sixth segment of the standard. The study was presented in three ignore phases and two active discrimination phases. Discrimination phases occurred after the first and second ignore phases, in which subjects were asked to press a key every time they heard a deviant stimulus. The results were divided into three types of behavioral responses. "Non-improvers" refers to those subjects whose performance (detecting the deviant sixth segment of the stimuli) did not improve across the two discrimination phases. No MMNs were obtained in any of the ignore phases for these subjects. "Improvers" refers to those subjects whose performance was not good in the first discrimination phase yet improved in the second discrimination phase. In this group, no MMN was obtained in the first phase, was obtained in the second ignore phase, and increased in amplitude in the third ignore phase. "Good non-improvers" refers to those subjects whose performance was good in the first discrimination phase and remained good in the second discrimination phase. In this group, MMNs were obtained in the first ignore phase and the amplitude remained similar throughout all ignore phases, whereas the latency of the MMN decreased from the first to the third ignore phase. A second experiment was conducted with no active discrimination phases to determine whether the increased exposure to the stimuli by itself could effect similar results. The MMNs exhibited no significant amplitude changes across the three phases. The authors concluded that attention directed to the stimuli made the representation of the standard more accurate. Thus, attention to the stimuli presumably produced an increased ability to automatically detect the deviation in the complex stimuli, as manifested by an increase in amplitude or decrease in latency of the MMN.

In the Näätänen, Paavilainen, et al. (1993) study, the MMN elicited by the intensity deviants in the unattended channel was reduced, or abolished. It may be reasoned from this that the modulation was the result of an attenuation of the system that generates the MMN. That is, the information about the changes in loudness level were represented (i.e., all incoming information was analyzed at least at the feature level) but that the withdrawal of attention affected the amplification system of the MMN process to a degree in which the amplitude was reduced (Näätänen, Paavilainen, et al., 1993). Or, it could be reasoned that the modulation was a result of an early gating process, such that the representation of loudness was not distinctive enough for the brain to detect changes in the loudness level occurring in the unattended channel (Woldorff, et al., 1991). By contrast, in the Näätänen, Schröger, et al., (1993) study, directed attention to the stimuli was postulated by the authors to result in a more accurate representation of the standard stimuli, such that when subjects subsequently ignored the stimuli there was an increase in the amplitude and decrease in the latency of the MMN in a sub-group of the subjects. Collectively, the results of these studies indicate that attention can affect the amplitude and latency of the MMN.

The purpose of Experiment 3 was to determine whether focusing attention on a subset of concurrent stimuli could alter the manner in which the brain organizes the processing of the stimuli such that an MMN would be produced.

Auditory scene analysis (Bregman, 1990) is a term used to describe a process by which the auditory system decomposes the mixture of sounds arriving at the ears into meaningful segments or groupings. Thus, the task of the brain is to disentangle the mixture of sounds to their original sources, keeping them distinct. Cues for this sorting process can be provided by similarities in the properties of the acoustic energy, such as the frequency range of the sounds, their spatial location, intensity, or rate at which the sounds occur. The sequential integration of tones may occur on the basis of <u>shared</u> properties, whereas the segregation of tones may occur on the basis of <u>contrasted</u> properties. Whether the sound is sequentially integrated, or separated into distinct sound sources, is influenced by the context of the adjacent sounds. For example, if a sequence of tones alternates across high and low frequency ranges at a rapid pace, the perception of the sequence splits into two separate sound sources, one made up of the high tones and one of the low (the streaming effect; Bregman, 1990). If the same sequence occurs at a slow pace, alternating high and low pitches are perceived. The grouping, in this case, would depend on the rate at which the tones occur, as well as the frequency separation between them. Whether they are processed as one or two streams is dependent upon the context within which the stimuli occur.

The results of Experiment 1 suggest that alternating high and low tones segregated into two streams pre-attentively when occurring at 100 msec intervals but not at 750 msec intervals, when subjects ignored the stimuli. When the tones were presented at the fast pace, an MMN was obtained by the deviant sequences occurring within both the high- and the low-tone streams. Since subjects ignored the stimuli, the presence of the MMN during the streaming effect indicated that the segregation of the tones occurred automatically, at or before the level of the MMN system. On the other hand, when tones were presented at a slow pace, no MMNs were obtained for either the high or low tones. Thus, the alternation of the high and low tones interfered with the emergence of the within-stream sequences. Segregation did not occur automatically at the slow pace, yet did occur automatically at the fast pace. These results led us to ask whether attention to either the high or low tones presented at a slow pace could produce segregation, thereby altering the processing of the stimuli at a pre-attentive level, and generating an MMN.

Accordingly, in the present study, sequences of alternating high and low tones (as described above) were presented in attend and ignore conditions at a slow stimulus rate which was not expected to produce streaming automatically, to investigate whether the MMN would indicate differential processing as a function of attention. The rate of alternation between the high and low tones was held constant across both conditions, while the state of attention was varied. We speculated that when subjects ignored the stimuli, no MMNs would be elicited by the within-stream deviant sequences, whereas with attention focused on a subset of the tones, MMNs would be elicited by the within-stream deviant sequences.

Methods

Subjects

Eleven subjects (eight females) between the ages of 24 and 43 years, with reportedly normal hearing, were paid for their participation in the experiment. Three subjects were dropped from the study because they were unable to perform the task during the attention phase of the study.

Experimental Procedure

Subjects were seated in a comfortable chair. The stimuli were six pure tones (400 Hz, 450 Hz, 500 Hz, 1150 Hz, 1250 Hz, and 1350 Hz) presented binaurally through insert earphones. Each tone was 50 msec in duration, including a 7.5 msec rise/fall time, with an intensity of 75 dB SPL.

High (1150 Hz and above) and low (500 Hz and below) frequency tones were alternated at a constant SOA of 500 msec. A rising sequence of the three high frequency tones and a rising sequence of the three low frequency tones were alternated (e.g., L1, H1, L2, H2, L3, H3; where L1 equals 400 Hz and H1 equals 1150

Hz). This six-tone cycle constituted the standards and occurred on 87% of the trials. A deviant (falling) three-tone sequence (e.g., L3, L2, L1) occurred on 13% of the trials, half within the low tones and half within the high tones. The deviants (25 per run for the low tones and 25 per run for the high tones) occurred randomly within the fourteen runs created for the study. All of the runs were randomized to ensure that sequences were not predictable when subjects attended to the tones. Seven runs each were used for the ignore and attend condition, and the order of the runs was counterbalanced across subjects. The standard and deviant sequences are presented in Figure 7.

There were two parts to the study. In the first part, subjects were instructed to ignore the stimuli by reading a book of their choice (Ignore condition). Since it was necessary to determine that no MMN would be elicited in the Ignore condition, it was run first for all subjects. Subjects then took a break as long as needed.

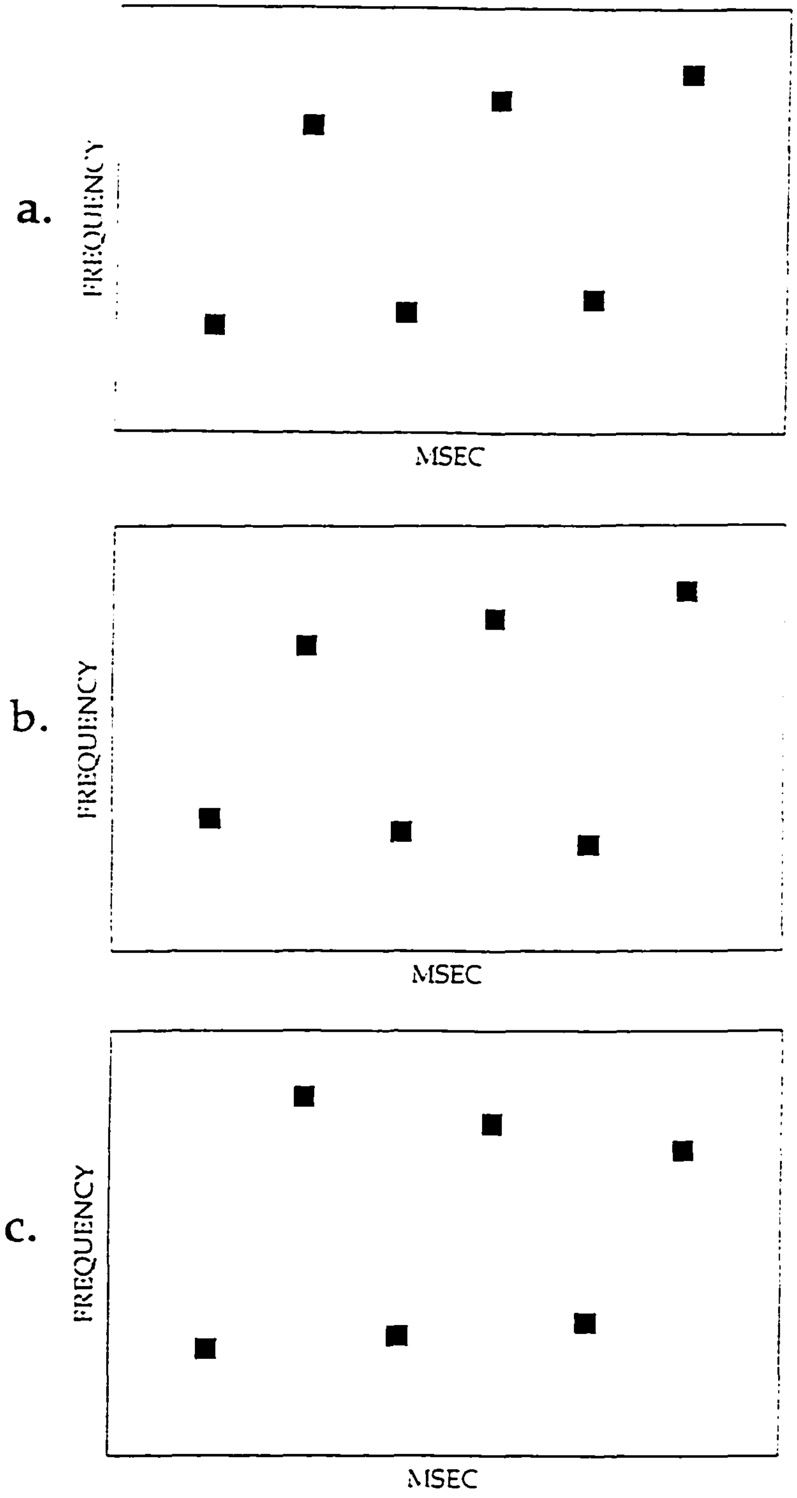
In the second part of the study, subjects were instructed to attend to the high tones and ignore the low tones, pressing a key every time they heard a deviant high-tone sequence (Attend condition). A practice session was given in two phases. In the first phase, the high tone sequence was presented alone at the rate of stimulation the high tones occurred in the alternating sequence (one tone per second). Subjects were instructed to listen for a three-tone rising standard sequence and tell when they heard a three-tone falling deviant sequence. When it was clear that the subjects could hear the standards and deviants within the high tones sequence, the second phase was conducted. In the second phase of the practice session, an alternating sequence of high and low tones similar to that to be used during the recording session was presented. Subjects were now instructed to pay attention to the high tones only while ignoring the low tones, and to press the keypad every time they heard the deviant (falling) high-tone sequence. When subjects understood what to do and could perform the task, recording proceeded. Short breaks were given as needed after each run.

ERP Recording

The electrical brain activity was recorded using direct-coupled (DC) amplifiers, with a low-pass filter setting of 40 Hz, and a digitization rate of 500 Hz. The epoch duration was 600 msec. A 500 msec poststimulus epoch was used along with a 100 msec prestimulus baseline. Recordings were obtained at the following electrode sites: Fpz, Fz, Cz, Pz, Oz, Fp1, Fp2, F3, F4, F7, F8, FC5, FC6, FC1, FC2, T3, T4, C3, C4, CP5, CP6, CP1, CP2, T5, T6, P3, P4, O1, O2, LM, and RM (left and right mastoids, respectively). The nose was used as a reference. Horizontal eye movements were monitored using electrodes F7 and F8. Vertical eye movements were monitored with a bipolar electrode configuration using Fp1 and an external electrode placed below the left eye. Artifact rejection was set to automatically reject activity exceeding ±100 µV. The averaged ERPs remaining were examined for residual artifact. ERPs were digitally filtered off-line with a bandpass of 1-30 Hz.

Figure 7

Example of a standard cycle of six tones (a.), a deviant occurring in the low tones (b.), and a deviant occurring in the high tones (c.).



Data Analysis

In Experiment 1, the MMN was elicited by the first tone of the three-tone deviant sequence. On this basis, these data were similarly analyzed. ERPs elicited by the first tone of each standard sequence were averaged together across the runs for each subject, separately for the high and low tones, in each condition. Likewise, the ERPs elicited by the first tone of the deviant sequence were averaged together across the runs, separately for each subject, each set of tones, in each condition.

The grand mean ERPs were used for the purposes of display. Grand mean difference waveforms were calculated by subtracting the ERPs elicited by the standard from those elicited by the deviant, separately for each set of high and low tones and each condition. The peak latency of the MMN was selected at Fz in the grand mean difference waveforms as 237 msec for the unattended tones in the Attend condition. The amplitude of the ERPs elicited by the standards and deviants for each subject in each condition were measured at Fz in a latency window from 25 msec before to 25 msec after the peak latency of the MMN in the grand mean difference waveforms.

The data were statistically analyzed using a two-way analysis of variance (ANOVA) for repeated measures with factors of stimulus type (standard and deviant) and electrode (Fz, Cz, FC1, FC2, LM, and RM) to determine whether the ERPs associated with the standard were significantly different than the ERPs associated with the deviant in the latency range of the MMN.

Tukey post-hoc comparisons were then used to determine statistical significance at individual electrode sites. Since there was no evidence of an MMN for either the high or the low tones in the ignore condition, the mean voltages, in the 50 msec window taken around the peak of the MMN of the unattended stream in the Attend condition were used to determine whether the ERPs to the standard and deviant differed significantly at Fz, Cz, FC1, FC2, LM, and RM in the Ignore condition.

To compare differences in scalp distributions between the ERPs obtained for the unattended stream with the ERPs obtained by the attended stream in the Attend condition, mean voltages were measured around the peak negativity in each stream separately. Peak latency was chosen as 213 msec for the attended channel and 263 msec for the unattended channel. The data were scaled (McCarthy & Wood, 1985) and then evaluated using the factors of channel (attended-unattended) and electrode (all 32 recording sites were included in the analysis) in a two-way repeated measures ANOVA.

An alpha level of .05 was used. Huynh-Feldt corrections were reported when appropriate.

Results

Subject report

At the end of the Ignore phase, subjects were asked how they heard the tones, if they noticed. Subjects reported that when they noticed they heard alternating high and low pitches. At the end of the practice phase, subjects were asked if they noticed the three-tone sequences during the Ignore phase. No subjects noticed, and were surprised when told that the tones they were now attending were the same type sequences as the tones they had been ignoring. All subjects reported that they could segregate the high from the low tones, and that it took some time at the start of each run to segregate the tones. The task, finding the high tones deviant within the three-tone standards, varied in difficulty level from subject to subject. However, all subjects reported that highly focused attention on the high tones was required to complete the task on each run of the session. That is, undivided attention was necessary to keep track of the standard three-tone pattern within the high tones.

Ignore condition

Figure 8 displays the group averaged standard and deviant ERPs obtained separately for the high (top) and low (bottom) tones at Fz, Cz, Pz, FC1, FC2, LM and RM. The typical N1-P2 components elicited by the standards can be clearly seen, with peak latencies for the high tones of 106 msec (N1) and 170 msec (P2), and for the low tones of 108 msec (N1) and 190 msec (P2). The N1 amplitude, measured at Fz, was larger for the high tones than for the low tones ($\underline{t}$=3.54 [7 df]; $p < .01$). The difference waves, obtained at the same electrodes, are displayed in Figure 9. Some small negativities are present in the waves for both the high and the low tones. However, there was no significant difference between the standard and deviant ERPs for either the low tones (F [1,7] = 1.3, p = .29) or the high tones (F [1,7] =

2.0, p=.26). Thus, no MMNs appear to have been elicited when subjects ignored the stimuli.

Attend condition

Figure 10 displays the group averaged standard and deviant ERPs obtained separately for the attended (top) and unattended (bottom) tones at Fz, Cz, Pz, FC1, FC2, LM and RM. The N1-P2 components elicited by the unattended tones can be seen in the standard and deviant waveforms. A broad negative deflection, denoting the MMN, follows the N1-P2 components in the deviant waveforms. The ERPs elicited by the standard attended tones exhibit an N1 and P2 followed by a late positivity displaying two peaks. In the deviant waveforms, N1 and P2 are followed by

Figure 8

Ignore condition. Grand averaged standard (thin line) and deviant (thick line) waveforms obtained for the high tones (top) and the low tones (bottom) separately at Fz, Cz, Pz, FC1, FC2, LM, and RM.

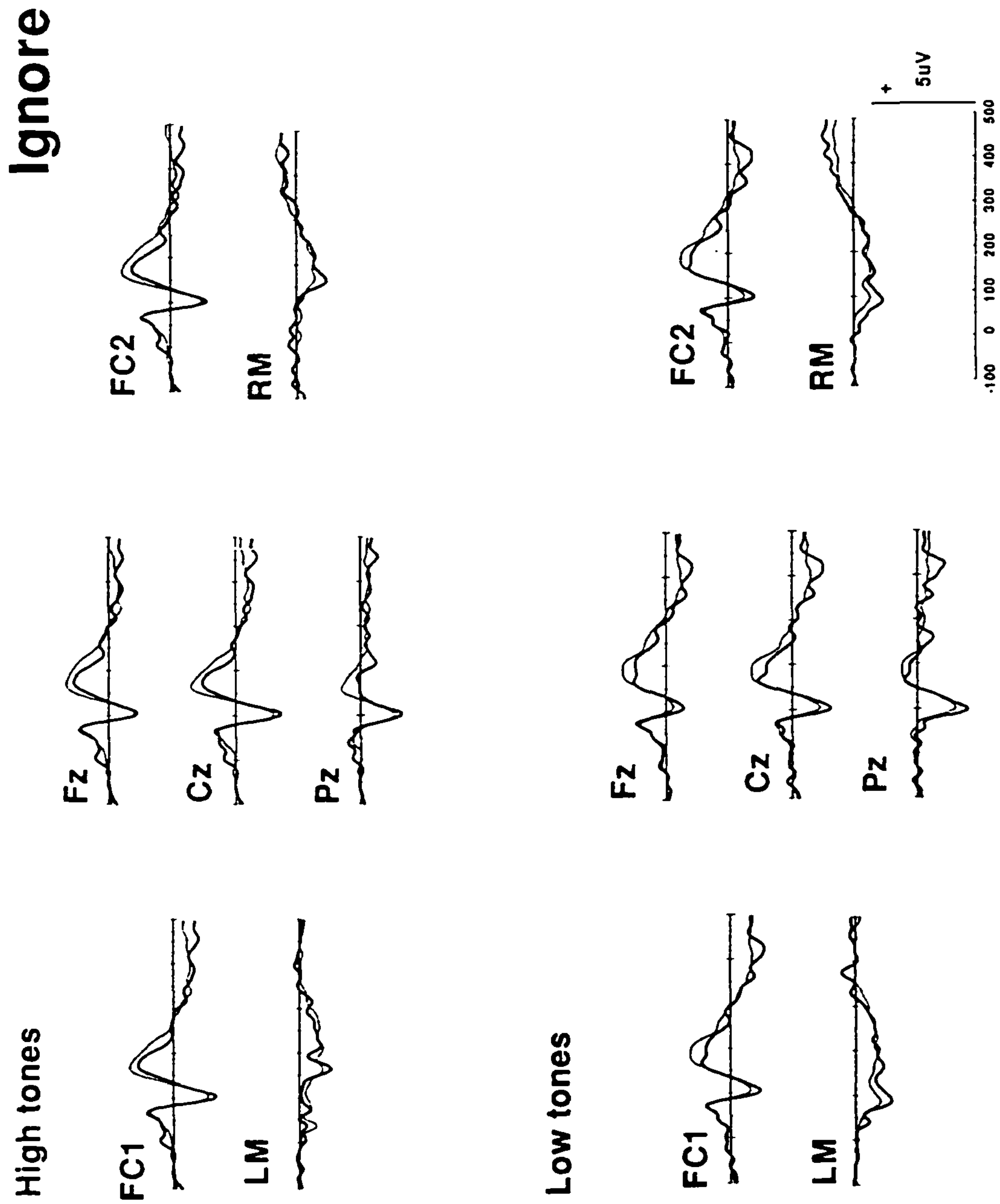
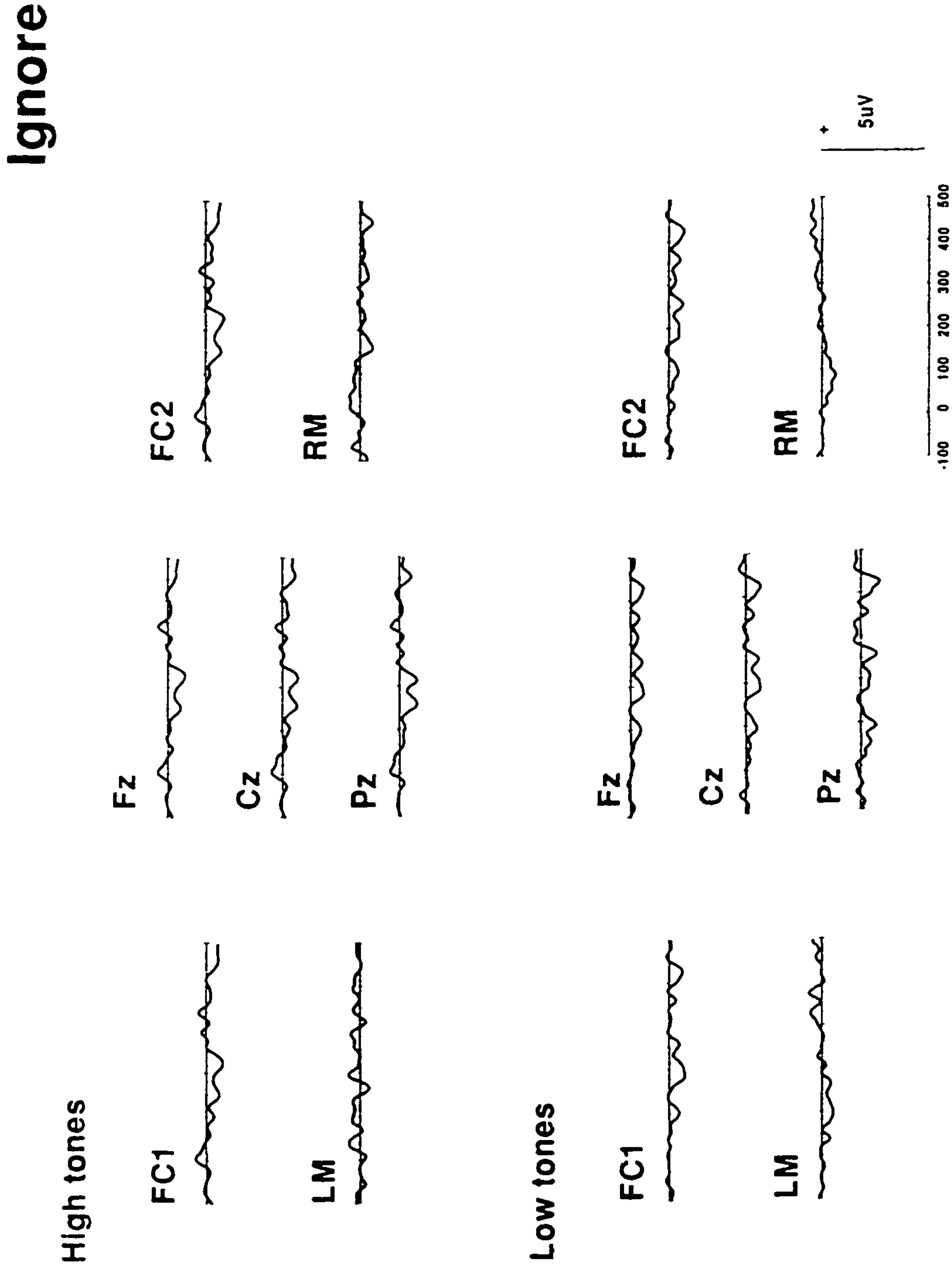


Figure 9

Ignore condition. Grand averaged difference waveforms (deviant minus standard ERPs) obtained for the high tones (top) and the low tones (bottom) separately at Fz, Cz, Pz, FC1, FC2, LM, and RM.



another negative deflection and a large positive deflection (P3), peaking at about 360 msec. N1 amplitude, measured at Fz, was larger for the attended tones than for the unattended tones (*t*=8.99 [7 df]; $p < .001$). Notice that the P3 component, associated with conscious target detection, is present in the deviant waveforms elicited by the attended tones but not the unattended tones.

Figure 11 displays the difference waves obtained by subtracting the ERPs for the standards from those for the deviants in each condition. In the attended condition, MMNs were elicited by the deviants in the unattended stream (F [1,7] = 14.06, $p < .01$). Tukey HSD post hoc comparisons resulted in significance at the frontal electrode sites but not at the mastoid sites. No significant reversal in polarity was obtained. Table 3 presents the grand mean amplitudes of the standard and deviant ERPs measured in the latency range of the MMN. The peak amplitudes of the MMN component obtained in the same latency window are also provided. The positive-going waves that can be seen in the unattended difference waves at the midline and FC1 and FC2 are caused by the standard ERPs going more negative than the deviant ERPs at the end of the epoch (see in the unsubtracted waveforms in Fig. 10). The MMN elicited by the unattended tones indicates that segregation was brought about by attention.

A significant interaction was obtained on the scaled data indicating a difference in the scalp topography obtained in the region of the peak negativity by the ERPs in the attended and the unattended streams (F [1, 31] = 3.75, $p = 0.03$). A post-hoc investigation of the electrode sites by scalp region indicated that the frontal, central, and temporal recording sites were contributing to this difference.

Figure 10

Attend condition. Grand averaged standard (thin line) and deviant (thick line) waveforms obtained for the high tones (top) and the low tones (bottom) separately at Fz, Cz, Pz, FC1, FC2, LM, and RM.

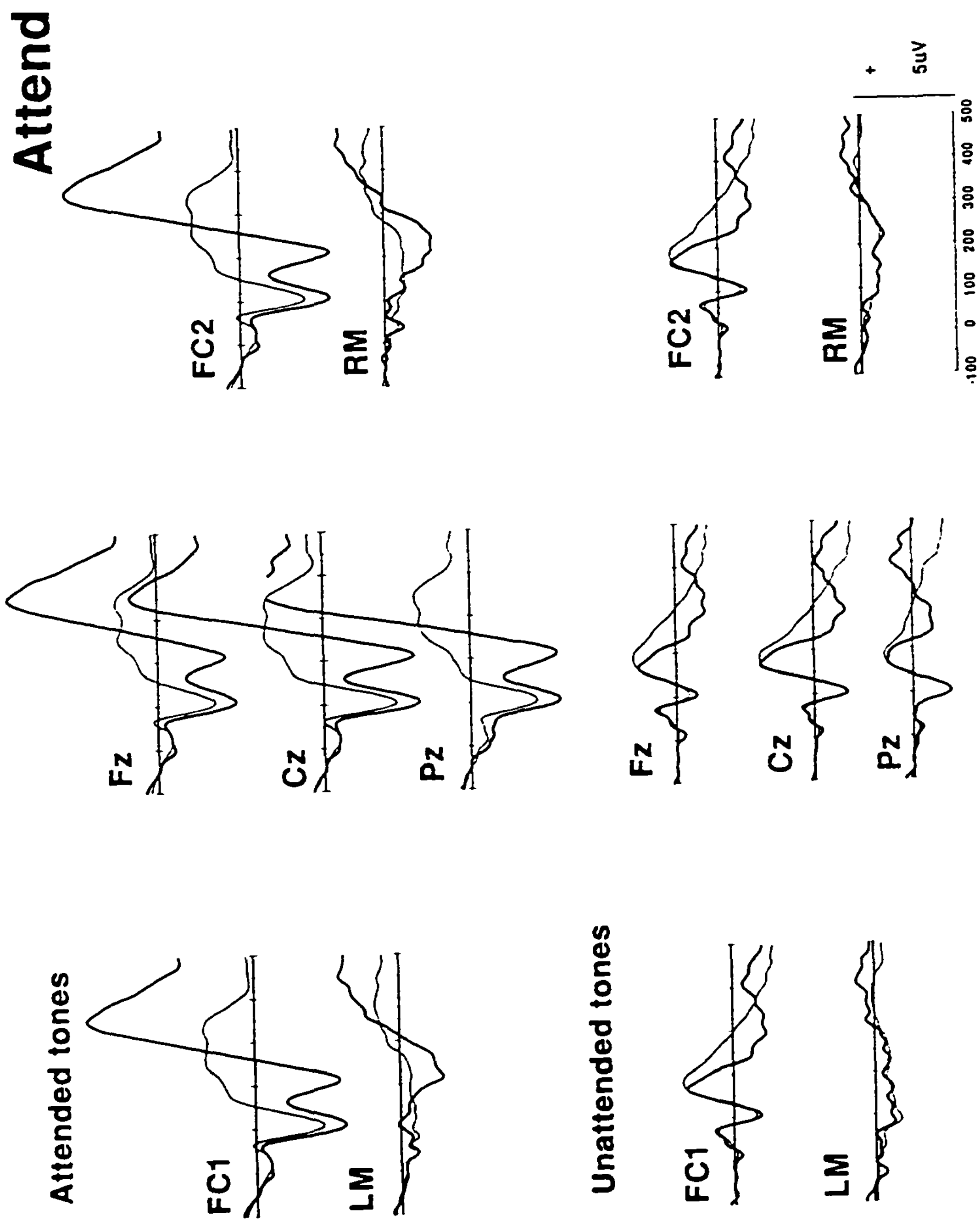


Figure 11

Attend condition. Grand averaged difference waveforms (deviant minus standard ERPs) obtained for the attended tones (top) and the unattended tones (bottom) separately at Fz, Cz, Pz, FC1, FC2, LM, and RM.

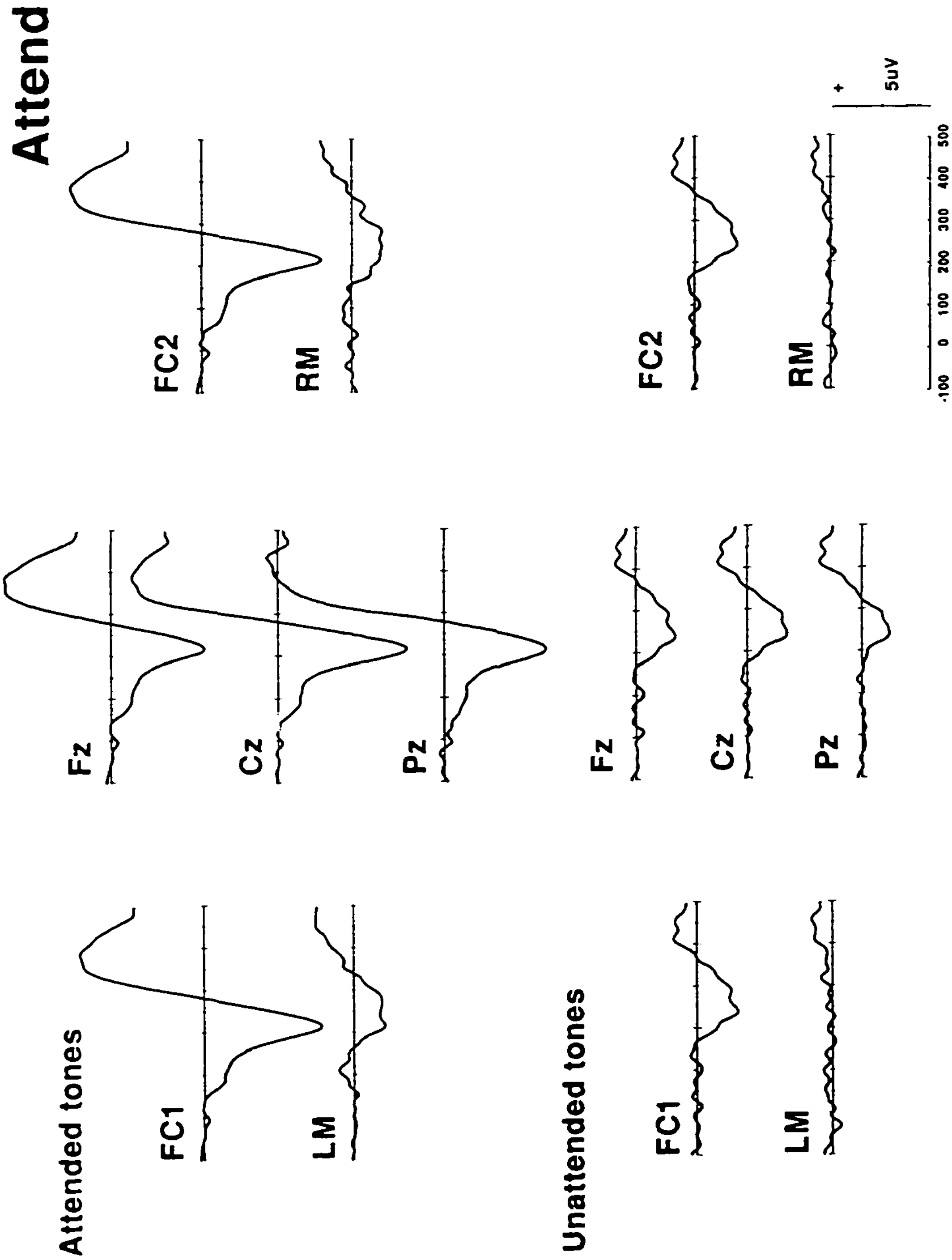


Table 3. Mean amplitude in µV (and standard deviation) of the Standard and Deviant ERPs and the Difference Waveform measured in the latency window of the MMN for the unattended tones in the attend condition for Experiment 3.

Electrode	Standard	Deviant	Difference	p
Fz	1.37 (0.8)	-0.41 (1.5)	-1.78	**
Cz	1.26 (0.9)	-0.48 (1.4)	-1.74	**
FC1	1.31 (0.9)	-0.54 (1.6)	-1.86	**
FC2	1.38 (0.7)	-0.55 (1.5)	-1.93	**
LM	-0.68 (0.5)	-0.59 (1.2)	-0.09	
RM	-0.85 (0.5)	-0.95 (0.9)	0.10	

** <.01

Discussion

The results of this study demonstrate that selective attention can alter the organization of sensory input. Attention to a subset of sequentially patterned tones can induce segregation so that automatic detection of the deviant sequences is initiated. This was contrasted with the results obtained when subjects ignored the stimuli and no MMNs were elicited. The brain can organize acoustic information differently when selectively attending than when ignoring.

The MMN obtained in the unattended stream indicates that the input to sensory memory was altered (compared to the ignore condition) as a function of attention. There is a relationship between the pre-attentive processes associated with generation of the MMN component and the attentional mechanisms enlisted for segregating the high from the low tones. How pre-attentive and attentive mechanisms can operate simultaneously can be seen in the well-known example of the cocktail party phenomenon. During a cocktail party, the listener can decide which voice, or conversation, to listen to while ignoring the rest of the ongoing party noise. The cues which help the listener distinguish one conversation from the others, such as the location from which the voice is coming from or the pitch and loudness of the voice, are usually processed pre-attentively. That is, we listen to the content of the speaker's message without mixing up the acoustic characteristics of the speaker's voice with other voices in the room. This is an example of how an attentional process (i.e., the decision to listen to a particular voice) can influence a pre-attentive process (i.e., the subsequent selection by the brain of the ongoing target conversation).

This study supports the notion that both pre-attentive and attentive mechanisms play a role in auditory stream segregation. Bregman (1990) distinguishes between primitive and schema-driven processes that govern stream segregation. Segregation that is based on primitive processing occurs outside the focus of attention and is determined by stimulus characteristics. The streaming effect that is induced by rapid alternation of high and low tones is an example of stream segregation elicited through primitive processing (see Experiment 1). Schema-driven processes, on the other hand, rely on attention (and/or past knowledge). A study by Dowling (1973) is an example of schema-driven stream segregation. He overlapped a familiar melody with a background melody of the same frequency range. Subjects could not hear the familiar melody without instruction to listen for it, most likely due to the interference of the melodies with one another because they occurred within the same range. Subjects easily heard the familiar melody when instructed to listen for the familiar melody <u>prior</u> to presentation of the overlapped melodies. Dowling concluded that prior instruction provided a schema that guided identification of the target melody. In other words, the segregation of the two melodies occurred as a function of schema-driven attention since the melody was not noticed when subjects attended the combined melodies without instruction.

The relationship between the primitive processes and schema-driven processes can be seen in the ERPs. In Experiment 1, when subjects ignored sequences of high and low tones similar to those used in this study, streaming, as evidenced by the MMN obtained to the deviant sequences within each stream, occurred at a fast but not at a slow rate of stimulation. The streaming effect occurred without attention and therefore is considered to depend upon a primitive process. In the current study, the relatively slow stimulus rate used did not induce segregation of the high and low tones automatically, and no MMNs were obtained when subjects ignored the stimuli. When active attention led to perception of the three-tone sequence in the attended stream, MMNs were elicited to the deviant sequence in the unattended stream. The presence of MMNs to the deviant sequences in the unattended channel indicates that schema-driven processes can alter the organization of the sensory input, thereby producing a discriminative effect comparable to that occurring with streaming induced by "primitive" processes. These findings suggest that it will be fruitful to examine physiological similarities and differences between the primitive and schema driven mechanisms of auditory stream segregation.

Although this study was not designed to directly compare the physiological processes that occurred in the attended and unattended channels, difference in these processes can be clearly seen in Figs. 10 and 11. The P3 component appears when subjects attend deviant (or target) stimuli, and generally does not appear when subjects ignore or do not attend the stimuli (see Donchin, Ritter, & McCallum, 1978 for a review). Compare, in Fig. 10, the ERPs elicited by the deviant attended tones (top) with the

ERPs elicited by the deviant unattended tones (bottom). A clear P3 component, occurring at about 350 msec and maximal at Pz, can be seen in the deviant waveforms for the attended tones, but not so for the unattended tones. This indicates that subjects were selectively attending the high tones[1]. The findings in the attended channel are generally consistent with earlier studies and have been examined in detail elsewhere [e.g., Alho, et al., 1989; Näätänen, 1992; Näätänen, Paavilainen, et al., 1993; Novak, et al., 1990). What is important for the present study is the clear presence of MMN in the unattended channel, with the absence of any of the ERP features that characterize active discrimination.

We can conclude that the discriminative effect indexed by the MMN in the unattended channel represents an automatic process operating on the stimulus pattern contained in the low-pitched tone sequence. The segregation of high- and low-pitched tones that supports this automatic discrimination is obviously dependent upon the active segregation of the high-pitched tones mediated by attention to them. However, this attentional segregation permits the operation of an apparently independent automatic mechanism mediated by the MMN system. In other words, the attentional effect appears manifest in the unattended channel

---

[1] Another way to determine whether subjects selectively attend stimuli is by examining an endogenous component that is associated with selective attention called the processing negativity (PN) or the negative difference wave (Nd). The component can be delineated by subtracting the standard ERPs obtained for the unattended channel from the standard ERPs obtained from the attended channel. In the current study, a processing negativity was not observed. Since the attended and unattended tones were alternated, they were predictable. Consequently, differences that might be seen between the attended and unattended standard ERPs would be difficult to evaluate since they could be due to differential arousal associated with attended and unattended stimuli.

as a consequence of the reorganization of the sensory input. The exact locus and time course of this restructuring of the sensory stream organization remains to be determined.

References

Alain, C., & Woods, D.L. (1997). Attention modulates auditory pattern memory as indexed by event-related brain potentials. Psychophysiology, 34, 534-546.

Alho, K., Paavilainen, P., Reinikainen, K., Sams, M., & Naatänen, R. (1986). Separability of different naegative components of the event-related potential associated with stimulus processing. Psychophysiology, 23, 613-623.

Alho, K., Sams, M., Paavilainen, P., Reinikainen, K., & Näätanen, R. (1989). Event-related brain potentials reflecting processing of relevant and irrelevant stimuli during selective listening. Psychophysiology, 26, 514-528.

Alho, K., Tervaniemi, M., Huotilainen, M., Lavikainen, J., Titinen, H., Ilmoniemi, R.J., Knuutila, J., & Näätänen, R. (1996). Processing of complex sounds in the human auditory cortex as revealed by magnetic brain responses. Psychophysiology, 33, 369-375.

Alho, K., Woods, D. L., & Algazi, A., Processing of auditory stimuli during auditory and visual attention as revealed by event-related potentials. Psychophysiology, 31 (1994) 469-479.

Bregman, A.S. Auditory Scene Analysis. MIT Press, Cambridge, MA, 1990.

Bregman, A.S. (1978). Auditory streaming is cumulative. Journal of Experimental Psychology: Human Perception and Performance, 4, 380-387.

Bregman, A.S. (1990). Auditory Scene Analysis. Cambridge, MA: MIT Press.

Bregman, A.S., & Campbell, J. (1971). Primary auditory stream segregation and perception of order in rapid sequences of tones. Journal of Experimental Psychology, 89, 244-249.

Broadbent, D.E. (1958). Perception and Communication. New York: Pergamon Press.

Cowan, N., Winkler, I, Teder, W., & Näätänen, R. (1993). Memory prerequisites of the mismatch negativity in the auditory event-related potential (ERP). Journal of Experimental Psychology: Learning, Memory, and Cognition, 19, 909-921.

Donchin, E., Ritter, W., & McCallum, W.C. Cognitive psychophysiology: The endogenous components of the ERP. In E. Callaway, P. Tueting, & S.H. Koslow (Eds.), Event-related Brain Potentials in Man, Academic Press, New York, 1978, pp. 349-441.

Dowling, W.J., The perception of interleaved melodies. Cognitive Psychology, 5 (1973) 322-337.

Giard, M.-H., Perrin, F., Pernier, J., & Bouchet, P. (1990). Brain generators implicated in processing of auditory stimulus deviance: A topographic event-related potential study. Psychophysiology, 27, 627-640.

Gomes, H., Bernstein, R., Ritter, W., Vaughan, H.G. Jr., & Miller, J. (in press). Storage of feature conjunctions in transient memory. Psychophysiology.

Gomes, H., Deacon, D., Ritter, W., & Vaughan, H. G., Jr. (in preparation). Effect of changes in stimulus frequency and stimulus rate in the auditory system: Implications for models of the neural mechanism subserving the mismatch negativity.

Gomes, H., Sussman, E., Ritter, W., Kurtzberg, D., Cowan, N., & Vaughan, H.G. Jr. (submitted). Electrophysiological evidence of developmental changes in the duration of auditory sensory memory.

Javitt, D., Doneshka, P., Zylberman, I., Ritter, W., & Vaughan, H.G. Jr. (1993). Impairment of early cortical processing in schizophrenia: an event-related potential confirmation study. Biological Psychiatry, 33, 513-519.

Javitt, D.C., Schroeder, C.E., Steinschneider, M., Arezzo, J.C., & Vaughan, H.G., Jr. (1992). Demonstration of mismatch negativity in the monkey. Electroencephalography and Clinical Neurophysiology, 83, 87-90.

Jones, M.R. (1976). Time, our lost dimension: Toward a new theory of perception, attention, and memory. Psychological Review, 83 (5), 323-355.

Jones, M.R., Kidd, G., & Wetzel, R. (1981). Evidence for rhythmic attention. Journal of Experimental Psychology: Human Perception and Performance, 7 (5), 1059-1073.

Jones, M.R., Maser, D.J., & Kidd, G.R. (1978). Rate and structure in memory for auditory patterns. Memory and Cognition, 6, 246, 258.

Kraus, N., McGee, T., Carrell, T.D., King, C., Tremblay, K., & Nicol, T. (1995). Central auditory system plasticity associated with speech discrimination training. Journal of Cognitive Neuroscience, 7, 25-32.

Levanen, S., Hari, R., McEvoy, L., & Sams, M. (1993). Responses of the human auditory cortex to changes in one vs. two stimulus features. Experimental Brain Research, 97, 177-183.

McCarthy, G., & Wood, C.C. (1985). Scalp distributions of event-related potentials: An ambiguity associated with analysis of variance models. Electroencephalography and clinical Neurophysiology, 62, 203-208.

Mäntasylo, S., & Näätänen, R. (1987). The duration of a neuronal trace of an auditory stimulus as indicated by event-related potentials. Biological Pscyhology, 24, 183-195.

Näätänen, R. (1991). Mismatch negativity outside strong attentional focus: A commentary on Woldorff, et al.(1991). Psychophysiology, 28, 478-484.

Näätänen, R. (1992). Attention and Brain Function. Hillsdale, NJ: Erlbaum.

Näätänen, R., Gaillard, A.W.K., & Mäntysalo, S. (1978). Early selective attention effect on evoked potential reinterpreted. Acta Psychologica, 42, 313-329.

Näätänen, R, Paavilainen, K., Alho, K., Reinikainen, & Sams, M. (1987). Interstimulus interval and the mismatch negativity. In C. Barber & T. Blum (Eds.), Evoked potentials III (pp. 392-397). London: Butterworths.

Näätänen, R., Paavilainen, P., Titinen, H., Jiang, D., & Alho, K. (1993). Attention and mismatch negativity. Psychophysiology, 30, 436-450.

Näätänen, R., & Picton, T. (1987). The N1 wave of the human electric and magnetic response to sound: A review and an analysis of the component structure. Psychophysiology, 24, 375-425.

Näätänen, R., Schröger, E., Karakas, S., Tervaniemi,M., & Paavilainen, P. (1993). Development of a memory trace for a complex sound in the human brain. NeuroReport, 4, 503-506.

Neisser, U. (1967). Cognitive Psychology. New York: Appleton-Century-Crofts.

Nordby, H., Roth, W.T., & Pfefferbaum, A. (1988). Event-related potentials to breaks in sequences of alternating pitches or interstimulus intervals. Psychophysiology, 25, 262-268.

Norman, D.A. (1967). Temporal confusion and limited capacity processors. Acta Psychologica, 27, 293-297.

Nousak, J.K., Deacon, D., Ritter, W., & Vaughan, H.G., Jr. (1996). Storage of information in transient auditory memory. Cognitive Brain Research, 4, 305-317.

Novak, G., Ritter, W., & Vaughan, H.G., Jr., & Wiznitzer, M.L. (1990). Differentiation of negative event-related potentials in an auditory discrimination task. Electroencephalography and Clinical Neurophysiology, 75, 255-275.

Paavilainen, P., Alho, K., Reinikainen, K., Sams., M., & Näätänen, R. (1991). Right-hemisphere dominance of different mismatch negativities. Electroencephalography and Clinical Neurophysiology, 78, 466-479.

Paavilainen, P., Saarinen, J., Tervaniemi, M., & Näätänen, R. (1995). Mismatch negativity to changes in abstract sound features during dichotic listening. Journal of Psychophysiology, 9, 243-249.

Ritter, W., Deacon, D., Gomes, H., Javitt, D.C., & Vaughan, H.G. Jr. (1995). The mismatch negativity of event-related potentials as a probe of transient auditory memory: A review. Ear & Hearing, 16, 52-67.

Saarinen, J., Paavilainen, P., Schröger, E., Tervaniemi, & Näätänen, R. (1992). Representation of abstract attributes of auditory stimuli in the human brain. NeuroReport, 3, 1149-1151.

Sams, M., Alho, K., & Näätänen, R. Short-term habituation and dishabituation of the mismatch negativity of the ERP. Psychophysiology, 21(4), 434-441.

Sams, M., Hari, R., Rif., J., & Knuutila, J. (1993). The human auditory sensory memory trace persists about 10 s: Neuromagnetic evidence. Journal of Cognitive Neuroscience, 5 (3), 363-370.

Schröger, E., (1994). An event-related potential study of sensory representation of unfamiliar tonal patterns. Psychophysiology, 31, 175-181.

Schröger, E. (1995). Processing of auditory deviants with changes in one vs. two stimulus dimensions. Psychophysiology, 32, 55-65.

Schröger, E. (1996). Interaural time and level differences: Integrated or separated processing? Hearing Research, 96, 191-198.

Schröger, E., Näätänen, R., & Paavilainen, P. (1992). Event-related brain potentials reveal how non-attended complex sound patterns are represented by the human brain. Neuroscience Letters, 146, 183-186.

Schröger, E., Paavilainen, P., & Näätänen, R. (1994). Mismatch negativity to changes in a continuous tone with regularly varying frequencies. Electroencephalography and Clinical Neurophysiology, 92, 140-147.

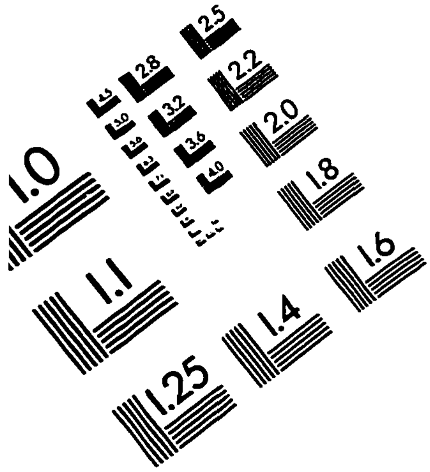
Schröger, E., Tervaniemi, M., Wolff, C., & Näätänen, R. (1996). Preattentive periodicity detection in auditory patterns as governed by time and intensity information. Cognitive Brain Research, 4, 145-148.

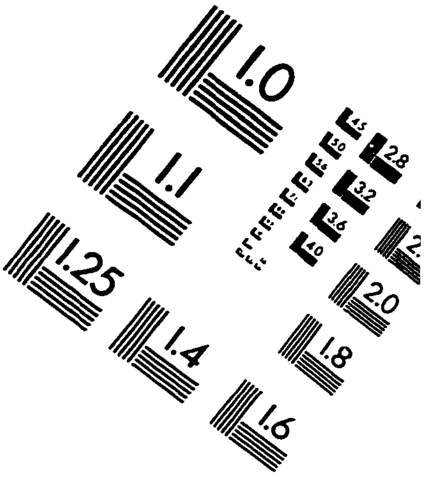
Winkler, I., Cowan, N, Csépe, V., Czigler, I., & Näätänen, R. (1996). Interactions between transient and long-term auditory memory as reflected by the mismatch negativity. Journal of Cognitive Neuroscience, 8 (5), 403-415.

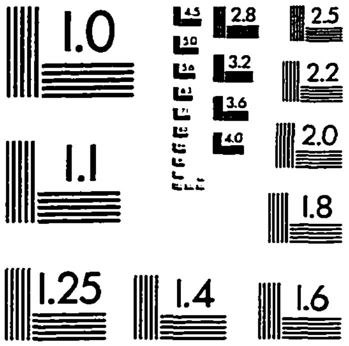
Winkler, I., & Schröger, E. (1995). Neural representation for the temporal structure of sound patterns. NeuroReport, 6, 690-694.

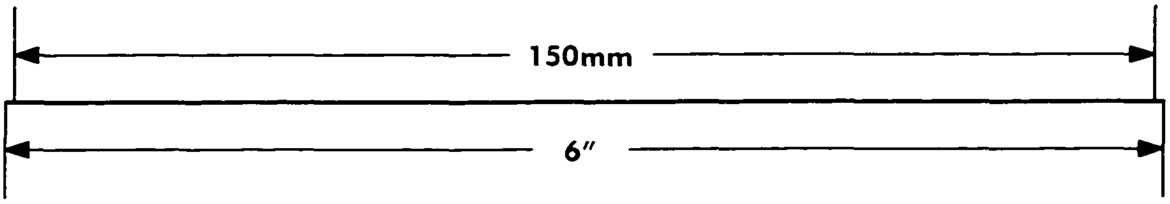
Woldorff, M.G., Hackley, S.A., & Hillyard, S.A., The effects of channel-selective attention on the mismatch negativity wave elicited by deviant tones. Psychophysiology, 28 (1991) 30-42.

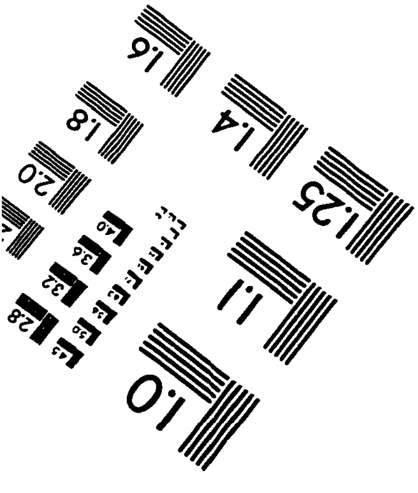
IMAGE EVALUATION TEST TARGET (QA-3)

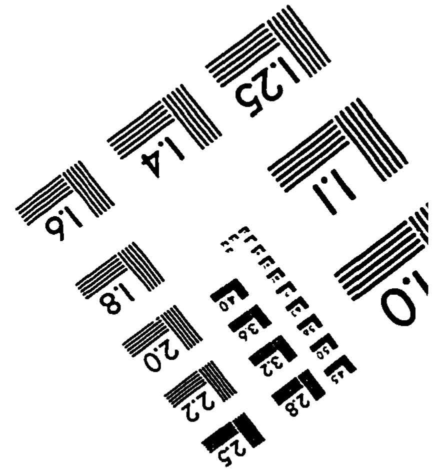












APPLIED IMAGE . Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989