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.

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.

ProQuest Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

UMI®

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

A

MISMATCH NEGATIVITY ELICITED TO VOWELS IN CHILDREN AND ADULTS AND ITS ASSOCIATION TO BEHAVIORAL PERFORMANCE

by

MARA L. MORR

A dissertation submitted to the Graduate Faculty in the Program of Speech and Hearing Sciences in partial fulfillment of the requirements of the degree of Doctor of Philosophy, The City University of New York.

2002

UMI Number: 3047248

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

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

May 01, 2002
Date

Chair of Examining Committee

5/3/02
Date

Executive Officer

Diane Kurtzberg

Winifred Strange

Brett Martin
Supervisory Committee

Abstract

MISMATCH NEGATIVITY ELICITED TO VOWELS IN CHILDREN AND ADULTS AND ITS ASSOCIATION TO BEHAVIORAL PERFORMANCE

by

Mara L. Morr

Advisor: Valerie L. Shafer

Objectives: The aims of this dissertation are: 1) To examine the neural correlates of automatic discrimination, as indexed by mismatch negativity (MMN), of phonetically-similar, short-duration vowels ([I]-[ɛ]) in typically-developing school-age children and adults (Experiments 1 and 2). 2) To examine the relationship between MMN and behavioral performance (Experiments 1 and 2). 3) To determine whether MMN is an index of acoustic or phonetic processing (Experiment 1). 4) To examine the effect of attention on brain discrimination (Experiment 2). 5) To determine whether complexity of the paradigm affects the brain's discriminative processes (Experiment 1 vs. 2).

Design: Vowels ([I]-[ɛ]) were presented using oddball paradigms in two experiments. In Experiment 1, two conditions were presented in which two deviants fell across- and one within the phonetic-category from the standard. In Experiment 2, a one deviant oddball paradigm was used. In one condition (Attend), the subjects actively discriminated a non-target tonal deviant embedded in the auditory stream. In a second condition (Passive), the subjects ignored the stimuli and watched a silent video. Identification and discrimination abilities were also examined in both experiments.

Results: In both experiments, essentially similar behavioral perceptual abilities were found for the children and adults, yet the neurophysiological indices of discrimination differed across groups. Significantly greater variability of the amplitude of the difference waveforms were found for the children compared to the adults in both experiments. In Experiment 2, attention to the auditory stream slightly modified the MMN in both the children and adults, although the effect differed across groups.

Conclusions: These findings support the claim that the brain's discriminative processes continue to mature during the school-age years and that under certain test conditions automatic discriminative mechanisms and attention-dependent behavioral processes are not related. Due to limited research, little is known about MMN maturation and its elicitation in individual subjects. Even less is known about the relationship between MMN and auditory processing or language development. Response variability across subjects and poor signal-to-noise ratios limit the clinical use of MMN at this time. Future studies will need to be conducted to address these issues before MMN can be considered clinically useful.

Acknowledgments

The research for the present dissertation was conducted at the Kennedy Center at the Albert Einstein College of Medicine. This dissertation was part of a larger research project funded by NIH Grant DC00223.

During my research I had the pleasure of working with many different people who influenced me both on a personal and professional level. I would first like to thank Valerie L. Shafer for her guidance and friendship during the preparation of this dissertation. I am grateful that I had the opportunity to work with her because I was introduced to areas of study that I normally would not have approached. Her ideas are creative and she has a natural enthusiasm for her work. I have learned a great deal from working with her.

I am also grateful to Diane Kurtzberg for sharing with me her vast knowledge of developmental electrophysiology. I have learned a great deal from her, including how rewarding and enjoyable a career in developmental electrophysiology can be.

I would also like to thank Winifred Strange for her influence during this dissertation. She is an expert in psychophysical vowel perception and as such challenged me throughout my dissertation.

A heartfelt thank you needs to be given to Brett Martin for her insightful comments. Her efforts and support were greatly appreciated.

This dissertation would not have been completed without the friendship and support of Karen Sheridan, Hilary Gomes, Michael Schur, and Nancy Turgen. I would also like to thank Elyse Sussman for being a good friend and colleague. Diana Cintron, Loretta Garin, and Judith Kreuzer are the backbones of the lab. I thank them for their support and many, many laughs. Heartfelt gratitude needs to be given to Brian Cairns for his time, efforts, and advice on statistical analyses.

A special thanks also needs to be given to my mother Jenny, my uncle Leon, and my brother Ed who provided me with the love, support, and the perspective of remaining on a specific time frame by always asking me "Aren't you done yet?".

Mara L. Morr
2002

Table of Contents

List of Tables

List of Figures

List of Appendices

1. Specific Aims

A large number of investigations have focused on studying the neurophysiological correlates of speech discrimination in adults. Few, however, have examined these processes in children. By examining speech processing in children we can learn more about the development of speech and language and its relationship to brain development. It is important to develop a model of the brain mechanisms that underlie phonetic processing in typical language developing (TLD) children, because we can then use it to understand deviant or delayed processing in children with language impairments (e.g., specific language impairment [SLI]). Event-related potentials (ERPs) are one method that can be used to examine the brain mechanisms activated during auditory and speech processing.

ERPs are measures of electrical brain activity time-locked to sensory, motor, or cognitive processing. The advantage of using ERPs to investigate auditory processing is that they allow for a fine-grained temporal analysis of neurophysiological brain activity. They can be used to evaluate the processing of stimuli that differ minimally on various acoustic-phonetic cues and that are difficult to discriminate behaviorally. ERPs can also be used to examine spatiotemporal differences of neural activity recorded from the scalp across subject groups. Scalp potential mapping provides information about the location of maximal brain activity recorded on the surface of the head. Differences in these surface patterns can be related to differences in underlying brain mechanisms. Recently, a few investigations have examined ERP correlates of the development of speech processing using a limited set of speech sounds and electrode sites. Inconsistent results concerning the maturation of ERPs, specifically MMN, have emerged. MMN is a cortical potential that indexes the discrimination of sound (including speech stimuli).

One goal of this dissertation is to create a neurophysiological model of vowel perception by TLD children for comparison to children with deviant or delayed language processing (e.g., children with SLI). In this dissertation, vowel sounds that have not been previously used to examine speech processing, as indexed by MMN, were presented to child and adult listeners. We used an experimental design incorporating both electrophysiological and behavioral measures in the same subjects to examine the relationship between the underlying pre-attentive neural mechanisms activated during speech processing and behavioral performance. A 32-channel electrode array was used, which allowed for spatiotemporal analysis of underlying brain activity in vowel processing in the children and adults.

The aim of Experiment 1 was to evaluate how adults and school-age TLD children process phonetically-similar vowel contrasts ([I]-[ε]) of short duration using both behavioral (identification and discrimination) and electrophysiological (MMN) methods. We chose to examine the processing of phonetically-similar, brief vowels in TLD children to establish normative data for comparison with data from children with SLI in future studies. Behavioral research suggests that children with SLI have difficulty processing vowels (Tallal and Piercy, 1975; Frumkin and Rapin, 1980; Leonard, McGregor, and Allen, 1992; Stark and Heinz, 1996). Re-synthesized, edited naturally-produced vowel sounds were chosen for presentation as opposed to purely synthetic vowels, because the re-synthesized vowels maintain a natural quality. It is unclear at this time whether the brain responds differently to purely synthetic vs. more natural-sounding speech stimuli. For this reason, the more realistic stimuli were chosen.

We chose the ERP component, MMN, as the dependent measure because it can be used to examine neurophysiological mechanisms underlying discrimination. Both across- and within-phonetic-category comparisons were used to elicit MMN in order to determine whether MMN is an index of differences in processing phonetic as well as acoustic properties.

For the purposes of this dissertation, we define acoustic processes as the processing of stimuli on a physical and psychophysical scale (e.g., frequency, pitch, intensity, duration). Phonetic processing is the ability to discriminate and/or identify stimuli in a fashion that is not predicted entirely by the physical or psychophysical properties of the speech sound. For example, categorical perception is considered to be phonetic processing. A listener can find it difficult to perceive the difference between two exemplars of the same phonetic category even though they differ acoustically (e.g., two exemplars of /da/ that differ by 200 Hz in the starting frequency of the second formant). In contrast, the same listener can easily discriminate the difference between two exemplars of two different phonetic categories that differ to the same degree as the within-category difference (e.g., 200 Hz difference in the starting frequency of the second formant for /ba/ vs. /da/).

If MMN is an index of acoustic processing, then MMN latency and amplitude should show a direct relationship to the magnitude of the acoustic difference between the standard and deviant stimuli. If MMN is an index of phonetic processing, then MMN latency and amplitude should reflect behavioral patterns of speech processing, such as categorical perception. A complete description of MMN will be provided in the next section.

Experiment 2 was designed to evaluate whether attention is needed for children to show a mature MMN. The question arose from the results of Experiment 1. In the first experiment, the children and adults showed similar behavioral identification and discrimination of the stimuli (when [ɛ] served as the standard), but differences in the amplitude, latency and topography of the MMN (in a task that did not require attention. In one condition (Passive) of Experiment 2, ERPs were recorded to the stimuli as the subject's attention was directed elsewhere (i.e., watching a video). In a second condition (Attend), MMN was elicited while the subject attended to the auditory stream. In this condition, the subject's task was to actively discriminate a non-target deviant by pressing a button. Behavioral data using the same stimuli were also collected. The aims of these experiments were the following:

1) to compare the neurophysiological correlates of discrimination (as indexed by MMN) for typically-developing school-age children and adults (Experiments 1 and 2).
2) to determine the relationship between MMN and behavioral performance (Experiments 1 and 2).
3) to determine whether MMN is an index of phonetic or acoustic processing (Experiment 1).
4) to determine whether attention can affect the MMN response (Experiment 2).
5) to determine whether the complexity of the paradigm affects the discriminative processes (Experiment 1 vs. 2).

Below is a review of pertinent investigations using MMN to examine discriminatory abilities in children and studies that have implemented both neurophysiological and behavioral measures. A review of the behavioral data of SLI children's processing of vowel sounds will also be presented because the stimulus choice in this dissertation was motivated by results from this literature. This section is followed by the Methods and Results from Experiments 1 and 2. In the final section, a general discussion is presented.

2. Background and Significance

2.1 MMN as a Clinical Tool

MMN is an index of an automatic cortical discriminative response (for review see Näätänen, Paavilainen, Tiitinen, Jiang, and Alho, 1993). It is typically obtained when stimuli are presented in an oddball paradigm, in which a train of repetitive identical (standard) stimuli are occasionally replaced by differing (deviant) stimuli, and can be elicited while the subject's attention is directed elsewhere (e.g., reading a book). MMN is derived by subtracting the response to the standard from that of the deviant. It can be used to assess a listener's discriminative abilities to both non-speech and speech stimuli. For this reason, there has been a great deal of interest in determining whether MMN can be used for the assessment of children with language impairments (e.g., Kurtzberg, Vaughan, Kreuzer, and Fliegler, 1995; Kraus, Koch, McGee, Nicol, and Cunningham, 1999; Shafer, Morr, Kreuzer, and Kurtzberg, 2000).

A number of factors, however, can compromise the diagnostic value of MMN. MMN amplitude decreases as the similarity between the standard and deviant increases

(Picton, Alain, Otten, Ritter, and Achim, 2000). Thus the signal-to-noise ratio of MMN to stimuli that differ slightly may be too small to use as a reliable tool. It can also be difficult to identify the presence of MMN in individual subjects (Kurtzberg et al., 1995), a required characteristic of any clinical tool. Furthermore, under certain test conditions behavioral performance is not directly related to MMN (e.g., Kraus, McGee, Micco et al. 1993). Before MMN can be considered useful in the clinical setting, it is important that we understand the relationship between findings obtained on behavioral measures of speech processing and MMN.

Recently, several studies have found that attention modulates MMN amplitude (e.g., Woldorff, Hackley, and Hillyard, 1991; Szymanski, Yund, and Woods, 1999; a complete discussion of this literature will be presented below). In a study with children, Gomes, Molhom, Ritter, Kurtzberg, Cowan, and Vaughan (2000) have reported an enhancement of MMN with active discrimination of difficult, but not of moderately-difficult or easy tonal changes. If it can be shown that MMN elicitation with active discrimination is reliably larger in children compared to MMN elicited passively, then MMN may be clinically useful. One of the goals of this dissertation was to determine whether attention affects the magnitude, latency or topography of MMN.

Before any electrophysiological measure can be used to evaluate children with language impairments, we need to understand typical perceptual development. The experiments in this dissertation used behavioral and neurophysiological methodology to examine how spectrally similar, short duration vowel stimuli ([I]-[ɛ]) presented in isolation are processed by TLD school-age children and adults.

2.2 MMN in Children

Over the past few years, several experiments have used MMN to examine the brain's discriminative processes in children using a variety of stimulus parameters. MMN has been examined in 7 to 11 year olds in response to consonant + vowel (CV) stimuli that differed across initial consonant phonemic boundaries (/ga/ standard, /da/ deviant; Kraus, McGee, Sharma, Carrell, and Nicol 1992; Kraus, McGee, Carrell, Sharma, Micco, and Nicol, 1993), and that differed acoustically within a phonemic category (/da$_1$/-(/da$_2$/; Kraus, McGee, Micco, Sharma, Carrell, and Nicol, 1993). These studies did not report differences in MMN latency between children and adults. Kraus, McGee, Carrell et al. (1993) and Kraus, McGee, Micco et al. (1993) did, however, find larger MMN magnitudes (peak-to-offset amplitude and area) in children compared to adults. Kraus et al. (1999) examined MMN onset latency, area, and duration in 6- to 15-year-old children for stimulus pairs /da/-/ga/ and /ba/-/wa/. In general, no significant differences were observed across the children as a function of age. In an experiment described in Csépe (1995)[1], MMN was generally similar between 8- to 10-year-old children and adults. MMN peaked at similar latencies to both tonal and vowel changes in the children and adults. The MMN peak amplitude to CV syllables was observed at later latencies than that of tones in both age groups. In a second experiment described by Csépe (1995), however, the MMN was larger in children than adults in response to tonal changes.

In contrast to the above findings, other researchers have reported a developmental decrease in MMN latency. Korpilahti and Lang (1994) evaluated children 7 to 13 years of age. Significant negative correlations were observed between MMN latency and age in response to durational (50 ms standard, 110 ms deviant; 50 ms standard, 500 ms deviant) and frequency changes (500 Hz standard, 553 Hz deviant) in tonal stimuli. Significant negative correlations between MMN latency and age in pre-school and school-aged children in response to tonal differences (1000 Hz standard, 1200 Hz deviant) have also been observed by other researchers (Shafer et al., 2000). The children in this study showed significantly later MMN peak latencies than the adults. MMN peak latency was observed to decrease by approximately 11 ms/year as age increased. Gomes, Sussman, Ritter, Kurtzberg, Cowan, and Vaughan (1999) observed maturational differences in auditory sensory memory, as indexed by MMN. In this study they presented trains of eight tonal stimuli (1000 Hz standard, 1200 Hz deviant) to children aged 6-7, 8-10, and 11-12 years and adults. The stimulus trains were separated in one condition by a 1 s intertrain interval (ITI) and in another condition by an 8 s ITI. The first tone of half of the trains was a standard, while the first tone of the other half was a deviant. The remaining stimuli within the train were always standards. MMN latency was found to decrease as age increased. In addition, MMN was not elicited in the younger child groups (6-7 and 8-10 years) in the 8 s ITI condition.

In sum, the electrophysiological literature available at this time reveals conflicting results on the maturation of MMN latency. The absence of maturational latency differences in some experiments and its presence in others may be due to a number of experimental factors. In general, the studies that did not show maturational effects used synthetic speech stimuli[2]. Currently it is unclear whether the brain responds differently to synthetic and naturally-produced sounds. Furthermore, the studies that showed a maturational effect of MMN latency and used a typical oddball paradigm of one standard and one deviant used relatively rapid ISIs (Korpilahti and Lang, 1994: 350 ms ISI; Shafer et al., 2000: 750 ms ISI). Those that did not show a maturational effect used longer ISIs of 1 to 1.7 s (Kraus et al., 1992; Kraus, McGee, Carrell et al., 1993; Kraus, McGee, Micco et al., 1993; Kraus et al., 1999[3]). Gomes et al. (1999) showed an MMN latency effect using trains of stimuli at long ITIs of 1 or 8 s. The ISI between the stimuli within the train, however, was 250 ms. Therefore, the authors' report of an MMN latency effect may be consistent with the studies that used fast ISIs. Alternatively, it is possible that the brain may have grouped the stimuli within the train as a pattern (Sussman, Ritter, and Vaughan, 1998a), which would therefore be considered a more complex listening condition. Thus, the latency effect may be associated with the complexity of the listening condition rather than the ISI. Additional investigations are needed to determine which of these factors contribute to the differences observed across studies.

2.3 MMN Association with Behavioral Performance

MMN amplitude has been related to an adult listener's ability to perceive a tonal deviant when presented in an oddball paradigm using one standard and one deviant (Sams, Paavilainen, Alho and Näätänen, 1985) or when presented in tonal patterns (Schröger, Näätänen, and Paavilainen, 1992; Schröger, Paavilainen, and Näätänen, 1994). When a deviant was not perceived during the behavioral discrimination task, no MMN was elicited (Sams et al., 1985). When discrimination was found to be poor, MMN amplitude was reduced (Schröger et al., 1992; Schröger et al.,1994). MMN has also been elicited in response to within-phonetic-category vowel differences that subjects behaviorally discriminated (Sharma and Dorman, 1998).

Winkler et al. (1999) examined the relationship between speech discrimination and MMN in adult listeners. Finnish monolingual speakers, Hungarians fluent in Finnish, and monolingual Hungarians were tested. The vowels [e] vs. [æ] (found in Finnish) were expected to be perceived as different vowels by the Finnish speakers, while the Hungarian speakers were expected to perceive both [e] and [æ] as the Hungarian phoneme [ɛ]. Vowels found in both Finnish and Hungarian ([e] vs. [y]) was also examined. The total duration of the vowels was 165 ms. MMN was found to all contrast pairs ([e] vs. [æ] and [e] vs. [y]) for all test groups, except for the monolingual Hungarians in response to vowels [e]-[æ]. On an identification task of vowels [e] vs. [æ], the Finns and bilingual Hungarians were faster and more accurate at identifying [e]-[æ], compared to the monolingual Hungarians. The monolingual Hungarian listeners performed at chance levels. Thus, cortical representations of the Finnish phonemes in memory were evident only for those speakers who showed evidence of behavioral identification.

Kraus et al. (1996) evaluated MMN in typically-developing (TD) children and children with learning-problems (LP; diagnosed with either a learning disability, attention deficit disorder, or both), aged 6 to 15 years. The consonant contrasts /ba/-/wa/ and /da/-/ga/ were presented. The TD children showed significantly smaller just-noticeable-differences (JND) on a behavioral task than the LP children to pairs of CV syllables that varied along a continuum by either the duration of the formant transitions of the initial consonant (/ba/-/wa/) or by the spectral properties of the formant transition of the initial consonant (/da/-/ga/). Both child groups discriminated the /ba/-/wa/ syllables better than the /da/-/ga/ contrast. A greater difference in performance was observed across groups to the /da/-/ga/ comparison than to the /ba/-/wa/ discrimination. This finding would suggest that the LP children are more impaired in their processing of spectral properties (/da/-/ga/) compared to duration characteristics (/ba/-/wa/). Thus, the extent of the reduced JND scores found for the LP children varied according to the acoustical change manipulated in the continua.

Kraus and colleagues (1996) compared electrophysiological findings for a subgroup of good and poor perceivers of the CV contrast /da/-/ga/, all of whom could discriminate the contrast /ba/-/wa/ equally well. Results revealed that MMN was similar across groups to CV contrasts /ba/-/wa/. Robust MMN responses were also elicited by the good /da/-/ga/ perceivers. MMN, however, was absent in the poor perceivers in response to the stimulus pair /da/-/ga/. The authors suggest that the deficits of the learning-impaired children occur prior to 'conscious perception' since MMN was elicited without attention to the stimuli. Furthermore, these findings suggest a relationship between the behavioral and electrophysiological responses. They suggest that MMN can be used in the clinical setting for differential diagnosis of LP.

The authors examined a subgroup of good and poor perceivers of the CV contrast /da/-/ga/, all of whom could discriminate the contrast /ba/-/wa/ equally well. While there is some support for a relationship between behavioral performance and MMN based on these findings, it would have been desirable to examine MMN in poor perceivers of /ba/-/wa/. Clearly, there were some poor perceivers of the /ba/-/wa/ contrast since the TD children were found to have significantly smaller JNDs to this contrast compared to the LP children. If absent MMN responses had been found for the poor perceivers of the

/ba/-/wa/ contrast, this would confirm the relationship between behavioral performance and MMN.

It would also have been a more elegantly designed study had they examined LP children who performed well in discriminating both /da/-/ga/ and /ba/-/wa/ to determine whether the underlying neurophysiologicval activity indexed by MMN was similar for the LP and TD children. Such a finding would suggest that the MMN may be useful in the clinical setting.

In contrast to the above findings, other studies have not shown an association between MMN and behavioral findings. MMN was elicited in adults in response to stimulus contrasts that differed across (/da/-/ga/) and within phonemic boundaries (/da_1/-/da_2/; Sharma, Kraus, McGee, Carrell, and Nicol, 1993; Dalebout and Stack, 1999). Sharma et al. (1993) elicited an MMN in the within-category condition that was similar in latency, amplitude, and area to the MMN elicited to the across-boundary speech sounds. Since the within-category stimuli differed acoustically, but not phonetically, we would have expected a smaller or absent MMN compared to the MMN elicited to the across-phonemic boundary stimuli. In the study conducted by Dalebout and Stack (1999), the subjects could not behaviorally discriminate the within-category stimuli (/da_1/ vs. /da_2/), yet MMN was still elicited.

MMN has also been found in school-age children to within-category speech sounds /da_1/-/da_2/ (Kraus, McGee, Micco et al., 1993). MMN latency and duration for these children was similar to adults (Sharma et al., 1993). The MMN magnitude (peak-to-peak amplitude and area), however, was significantly larger in the children than the adults. Results of a discrimination task of these within-category sounds revealed chance performance for the children (53.2%) and slightly better performance for the adults (64.6%). The finding of a robust MMN in both groups, but near chance levels of performance on the behavioral task, suggests that MMN indexes differences in the physical rather than phonetic properties. Furthermore, the adults seemed to behaviorally discriminate the sounds slightly better than the children, yet their MMNs were smaller. This difference in MMN amplitude across groups is likely attributed to maturational differences in the ERPs.

Other studies have compared behavioral and electrophysiological findings in children. However, the relationship between the neurophysiological and behavioral results was not uniform across stimulus types. Kraus et al. (1999) examined 6-to 15-year-old TLD children and adults in response to stimulus pairs /da/-/ga/ and /ba/-/wa/. No developmental differences were observed in the same/different JND scores to pairs of /da/-/ga/ syllables, which differed by the third-formant onset frequency along a 40 step (10 Hz each step) continuum. JND scores in response to /ba/-/wa/ syllables, which varied by the duration of the first and second formants in 30 steps of one ms each, decreased slightly with age. MMN, however, showed no difference in latency, amplitude, or area across age groups.

Bradlow et al. (1999) evaluated TD (typically-developing) and LP (learning problems; diagnosed with either a learning disability, attention deficit disorder, or both) 6- to 16-year-old children in response to CV syllables /da/-/ga/ and /ba/-/wa/. Two /da/-/ga/ continua were created. In the first continuum, a 40 ms formant transition and a 60 ms steady state period were used creating a CV stimulus of 100 ms. In the second continuum, the formant transition was extended to 80 ms, creating a total stimulus duration of 140 ms. The formant transition duration of the /ba/-/wa/ continuum varied from 10 (/ba/) to 40 ms (/wa/). The total stimulus duration was kept constant at 100 ms. For the behavioral discrimination task two pairs of stimuli were presented. The task of the subject was to indicate which of the two pairs of stimuli were different to determine JND. The EEG was recorded to stimuli that were just noticeably different, as determined by normal adult listeners.

Similar JND scores, ERPs to the standard and deviant, and MMNs were observed for the TD and LP children in response to the /ba/-/wa/ stimuli. Behavioral findings to the 40 and 80 ms /da/-/ga/ stimuli revealed larger JNDs for the LP compared to the TD children, which suggested poorer discrimination abilities. Furthermore, transition length had no effect on performance in either group. The electrophysiological data revealed reduced MMN areas for the LP group compared to the TD children to the short, 40-ms transition duration stimuli. Enhanced MMN responses were found in the LP children to the longer 80-ms formant transition, compared to the MMN elicited by the same children to the 40 ms transition stimuli. The children with typical language skills, however, showed no enhancement of MMN magnitude to the longer transition stimuli. Thus, the MMN was found to be similar across groups to the 80-ms formant transition stimuli.

In sum, transition length had no effect on the behavioral or electrophysiological responses of the TD children suggesting a relationship between behavioral and neurophysiological responses. The observation of similar MMN magnitudes for the 40 vs. 80 ms transition /da/-/ga/ responses is interesting since one would expect an increase in amplitude as the standard and deviant become acoustically more different. It may be the case that speech stimuli are processed differently than non-speech stimuli (i.e., tones) or that the same acoustic properties in different stimuli are processed to different extents. Research has shown larger MMNs to speech stimuli from a listener's native language (e.g., Winkler et al, 1999). Studies have also shown different orientations of the generators of MMN related to acoustic properties, such as intensity, frequency, and duration (for review see Alho, 1995). Further research is needed to examine how neural mechanisms indexed by MMN process different sounds and about how they develop in children compared to adults. For the LP children, while the lengthened formant transition enhanced the MMN response, their behavioral discrimination scores did not improve. This finding reveals a dissociation between behavioral and electrophysiological responses.

It is possible that the discrepancy reported between the neurophysiological and behavioral findings across groups in the Bradlow et al. (1999) study may be an effect of the stimulus onset asynchrony (SOA; or onset-to-onset rate of presentation). Tallal and Piercy (1973) proposed that children with certain learning disabilities have difficulty processing stimuli presented at rapid rates. The SOAs used in the electrophysiological condition in Bradlow et al. (1999) were slower (710 ms) for the /ba/-/wa/ stimuli than for the 40 and 80 ms formant transition /da/-/ga/ stimuli (SOA=590 ms). Lengthening the formant transition would not improve behavioral performance if the SOA were too fast to allow the brain adequate time to process the pairs of stimuli. Unfortunately, it is impossible to evaluate this possibility because the SOAs used for the behavioral testing were not reported.

Research has also shown that MMN magnitude can increase in adults with learning/training and can transfer to stimuli other than the training stimuli (Tremblay, Kraus, Carrell, and McGee, 1997). Thus, alternatively, a learning effect may have occurred. The order of presentation of the test conditions used in the present study was not discussed by the authors (i.e., behavioral or electrophysiological testing first; 40 or 80 ms transition /da/-/ga/ stimuli presented first). Therefore, if the behavioral condition was always presented first, a learning effect may have occurred for the following ERP condition. That is, practice with the stimuli in the behavioral condition may have led to improved discrimination in the subsequent ERP experiment. In contrast, if the behavioral tasks were presented last, this may account for the absence of improvement in performance for the LP children as transition length increased from 40 to 80 ms for the /da/-/ga/ stimuli. Tallal and Piercy (1975) examined dysphasic children and observed improved behavioral performance to initial stop consonant contrasts /ba/-/da/ as formant transition length was increased from 43 to 95 ms. It is possible that the 80 ms increase used by Bradlow et al. (1999) was insufficient for behavioral improvement. More research is needed to determine to what extent the formant transition needs to be increased in order to improve performance in children with language and learning impairments.

Čeponienė, Service, Kurjenluoma, Cheour, and Näätänen (1999) grouped 7- to 9-year-old children into low and high performers on a pseudoword repetition task. The task of the subject was to repeat the nonsense sound[4]. A same/different behavioral task was presented using both tones (1000 Hz vs. 1100 Hz) and speech stimuli (/baga/-/baka/). Electrophysiological data was recorded to the same sounds. In addition, two different ISIs (350 and 2000 ms) were used in both the behavioral and electrophysiological measures.

On the discrimination task, the high repeaters showed better discrimination of the tones and speech stimuli than the low repeaters. In addition, the high repeaters showed significantly better performance than the low repeaters in discriminating the tones at the long ISI. Electrophysiological findings revealed no difference between the groups in MMN amplitude or latency to the tonal stimuli. MMN was also larger in both groups to the tones presented at the shorter ISI. In response to the speech stimuli the low repeaters showed no MMN in either ISI condition, whereas the high performers showed an MMN response for both ISIs. No effect of ISI was observed for the latency or amplitude of the MMN for the high repeaters. Thus, an association was observed between behavioral and electrophysiological measures for speech stimuli, but not for tones.

In sum, there appears to be conflicting evidence on whether MMN is associated with behavioral findings. Further studies are needed to determine under what test conditions behavioral findings correlate with electrophysiological findings. Furthermore, more research is needed comparing children and adults to determine whether the relationship between behavioral and electrophysiological responses changes with age. This dissertation will serve to add to this body of literature by using both neurophysiological and behavioral measures.

2.4 MMN in Response to Vowel Contrasts

To date, only a few studies have used an oddball paradigm to elicit MMN in order to examine vowel discrimination. MMN-like negativities have been reported to vowel contrasts in newborns and very young infants (e.g., Cheour-Luhtanen et al., 1995; Cheour et al., 1998). MMN has also been elicited to vowel stimuli in adults (e.g., Aalotonen, Niemi, Nyrke, and Tuhkanen, 1987; Aaltonen, Eerola, Lang, Uusipaikka, and Tuomainen, 1994; Sharma and Dorman, 1998). The neural correlate of vowel discrimination has not been examined in older children. Behavioral research has shown vowel perceptual deficits in children with language deficits (Tallal and Piercy, 1975; Frumkin and Rapin, 1980; Leonard et al., 1992; Stark and Heinz, 1996). For this reason it is important to develop a model of vowel processing in TLD children. Following is a discussion of the findings from behavioral studies that evaluated vowel perception in children with SLI. This section provides the basis for our motivation to study vowel processing and our choice of vowel contrasts.

2.5 Behavioral Data to Vowel Contrasts in Children with SLI

Most studies that have examined speech discrimination in children with SLI have focused on consonant contrasts. Research has suggested that children with SLI have difficulty perceiving certain contrast pairs (e.g. /ba/-/da/) because their formant transitions are brief in duration and/or rapidly changing (e.g., Tallal and Piercy, 1973, 1974, 1975). This temporal deficit has been hypothesized to be responsible for the difficulty in processing both non-verbal and verbal stimuli (Tallal, Stark, Kallman, and Mellits, 1980). Others have argued that children with SLI have difficulty processing speech sounds that are phonetically-similar (e.g., Mody, Studdert-Kennedy, and Brady, 1997) or that are brief in duration and occur in unstressed word or sentence positions (e.g., grammatical morphemes; Leonard et al., 1992). However, at normal speech rates, vowel sounds can be short in duration and produced at rapid rates of articulation. Under these circumstances, vowels are not generally 'steady-state'. In addition, in English two vowels can be acoustically-similar, but be assigned to different phonetic categories. For example, in English the vowels [ɪ] and [ɛ] are acoustically-similar in their F1 and F2 formant frequencies, but belong to different phonetic categories.

Research suggests that under certain test conditions, children with SLI show poor vowel perceptual abilities. Based on the few behavioral studies that are available, it appears that inferior vowel perception in SLI children is observed under the following conditions: 1) isolated vowels that are brief in duration, 2) vowels that are relatively shorter than the surrounding phonetic material, 3) vowels that are phonetically-similar, or 4) vowels that are presented at rapid ISIs (Tallal and Piercy,1975; Leonard et al., 1992; Stark and Heinz, 1996; Frumkin and Rapin, 1980). These studies are discussed below.

Tallal and Piercy (1975) presented vowel + vowel (VV) stimuli that were created to mimic the durational components of a CV stimulus, but that did not possess initial formant transitions. The 43-ms initial steady-state vowel was similar in duration to a formant transition found in a stop CV stimulus. The initial vowel was immediately followed by a second vowel that was 207 ms in duration and was similar in duration to the steady-state portion of the remaining CV syllable. Children with language impairments showed poorer performance on identification, two-element temporal ordering, and same-different discrimination tasks in response to the VV syllables. These results suggest that perceptual performance in the language-impaired children can be degraded when a brief vowel is embedded in a complex stimulus.

Leonard et al. (1992) also provide data that language-impaired children have difficulty processing speech sounds of short duration, but only when they are situated adjacent to a stimulus of longer duration. That is, children with SLI were unable to identify speech sounds when the duration of the contrastive segments was relatively brief compared to the duration of the rest of the stimulus. This relative briefness is an intrinsic characteristic of grammatical morphemes (e.g., "the"). For example, when TLD and SLI children aged 4.6-5.7 years were presented with 100 ms phonetically-different vowel pairs [I]-[u], no difference was observed between the groups on a target identification task. However, when the same children were presented with 775 ms stimuli contrasts /dab-i-ba/-/dab-u-ba/ that differed only by the medial 100 ms vowel, all of the SLI children were unable to reach criterion. The majority of the TLD children, however, were able to perform at criterion levels.

Others have argued that it is the phonetic-similarity of a vowel pair and not its duration that influences perceptual performance of children with language impairments (LI; Stark and Heinz, 1996). Vowel pairs [ɑ]-[I] (phonetically different) and [ɛ]-[æ] (phonetically similar) were presented. Two test conditions were created: long (total duration= 40 to 240 ms) and short duration (5 to 40 ms). The task was to identify the vowel at the shortest possible duration. If the child reached criterion he/she continued on to a two-element temporal ordering test. If the child failed to reach criterion he/she continued on to a change/no change discrimination task of two successively presented vowel sounds. The purpose was to determine the shortest duration needed to temporally order or discriminate the vowels.

In general, no difference in performance was observed between the groups in the identification of the phonetically-different vowel pair. The LI children did, however, require a longer vowel duration to temporally order the vowels compared to the TLD children. In response to the spectrally-similar vowels, the LI children performed worse on the tasks compared to the TLD children, except on the change/no change discrimination test. The TLD children also showed evidence that the spectrally-similar vowels were more difficult to identify than the phonetically-different vowels. In sum, the language impaired children demonstrated greater difficulty in the identification compared to the discrimination of the similar vowels.

The findings reported by Tallal and Piercy (1974), however, differ from those observed by Stark and Heinz (1996). Tallal and Piercy (1974) evaluated the processing of long duration phonetically-similar vowel contrasts (total duration= 250 ms; [ɛ]-[æ]) using identification and temporal ordering tasks. In general, similar behavioral performance was observed for the LI and control children. It is possible that the complexity of the task combined with the similarity of the vowel sounds presented by Stark and Heinz (1996) influenced the performance of the LI children. Future studies are needed to determine whether SLI children have vowel perceptual difficulties due to the phonetic-similarity of the vowels, the brevity of the speech stimuli, or a combination of the two factors. One purpose of this dissertation is to provide information concerning how TLD children process brief phonetically-similar vowels so that we can then examine the processing of these stimuli in children with SLI.

Frumkin and Rapin (1980) found different patterns of vowel processing deficits in children with and without phonological impairments. Spectrally different vowel stimuli ([a]-[u]) were presented to dysphasic children with severe reading and spelling impairments. The dysphasic children with normal phonology showed difficulty in temporally ordering pairs of vowels ([a]-[u]) separated by short ISIs and poor perception of short duration vowels (e.g., 40 ms) when presented in either isolation (identification task) or in pairs (temporal ordering task). No difference in vowel identification performance was observed between the dysphasic children with abnormal phonology and a group of normal control subjects. The dysphasics with abnormal phonology were found to have a deficit in temporally ordering short duration pairs of vowels presented at short ISIs. This is not to say, however, that dysphasic children with abnormal phonology have better perception of speech sounds than dysphsics with normal phonology. CV syllables were also presented in this study. The dysphasics with abnormal phonology showed more difficulty in the processing of CV speech sounds, which had rapid formant transitions, in both isolation and in pairs. The authors indicated that the results for this group of children were consistent with those observed by Tallal and Piercy and thus support the temporal processing deficit model. Frumkin and Rapin (1980) suggested different underlying deficits for the two language impaired subject groups. More specifically, the authors proposed that deficient auditory short-term memory or an impaired neural mechanism specific to vowel perception contributed to the impaired vowel processing observed for the language impaired children with normal phonology. This explanation remains to be confirmed with further research.

Tallal & Stark (1981) found no differences for children with and without language impairments in discriminating short duration (40 ms), phonetically-similar vowels ([ɛ]-[æ]). However, the similar behavior observed across groups may be associated with the choice of behavioral task (discrimination vs. identification). The majority of studies using vowels showed greater vowel perceptual deficits for the language impaired children on identification, rather than discrimination tasks. A study conducted by Sussman (1993), using CV syllables, also showed that identification and not discrimination deficits were associated with language impairment. Furthermore, discrimination ability was found to be associated with chronological age. If Tallal & Stark (1981) had used an identification task, deficits in vowel perception may have been observed.

In summary, there is evidence that under certain test conditions, children with SLI show poor vowel perception abilities. It is important to examine vowel, as well as consonant perception, because these phonetic units are also necessary for differentiating lexical items.

In this dissertation the results of two experiments will be presented. In both experiments vowel perception abilities of TLD children and adults in response to phonetically-similar, short duration vowel sounds ([I]-[ε]) were examined. These vowels were chosen because we expect this contrast to be particularly challenging for children with SLI. These experiments will serve as the basis for future studies examining children with SLI.

3. Experiment 1

3.1 General Overview

This experiment was undertaken to examine how typically-developing 8- to 10-year-old children compare to adults in their perception of brief vowels using both behavioral and electrophysiological measures. Behavioral identification and discrimination tasks and passive brain discriminative responses, indexed by MMN, were recorded to spectrally similar, brief vowels [I] and [ε]. Both identification and discrimination tasks were presented because the behavioral literature at this time suggests that children with SLI are more likely to have difficulty in the identification than the discrimination of speech sounds. We designed the experiment to elicit MMN because a number of investigations suggest that it may serve as a useful clinical tool for identifying auditory processing deficits (e.g., Kraus et al., 1999). The experimental design of the present dissertation incorporated both behavioral and electrophysiological measures. The relationship of MMN to behavioral performance remains controversial and thus, requires further investigation.

We were also interested in examining whether MMN was an index of phonetic or acoustic processing. This second goal is accomplished by using both within- and between-phonemic-category deviants in the oddball paradigm. Re-synthesized, natural speech sounds were used instead of synthetic stimuli because they may possess acoustic properties specific to speech not typically present in synthetically-produced speech sounds. We hypothesized that: 1) The children would show similar categorical behavior (i.e., identification) and discrimination performance as the adults. This pattern of performance was observed by Sussman (1993). 2) The children would show longer MMN latencies compared to the adults. This prediction is based on previous MMN investigations that have observed maturational differences when stimuli are presented at relatively rapid ISIs (Korpilahti and Lang, 1994; Shafer et al., 2000). 3) MMN amplitude and latency would reflect the behavioral responses of the children and adults. The conflicting findings of previous investigations (reviewed above) suggest that this last hypothesis may not be confirmed.

3.2 Methods

3.2.1 Subjects

Two subject groups, child and adult, participated. The children's ages ranged from 8;8 to 10;5 years (mean=9;5, standard deviation (SD)=0;6). A total of ten children participated (eight males and two females). An additional two children were excluded due to excessive movement during the ERP testing. The adults' age ranged from 22;10 to 36;6 years (mean=28;7, SD=4;0). A total of nine adults participated (four males and five females). One additional adult was excluded due to excessive alpha produced during EEG recordings. Subjects were monolingual, had no history of language, learning, or hearing impairments, developmental delays, neurological deficits, chronic otitis media, or serious medical conditions. Child subjects were in the appropriate grade for their age and received no support services. The Clinical Evaluation of Language Fundamentals (Third Edition; CELF3) was used to examine the expressive and receptive language abilities of the children. The Test of Nonverbal Intelligence (TONI) was used to assess their nonverbal skills. The expressive language skills and non-verbal skills of one child subject (Subject 1) were examined using a different test battery. The CELF formulated sentences section was used to examine the child's expressive language skills, while the Stanford Binet test was used to assess his nonverbal ability. All test scores for child participants were reviewed by a speech-language pathologist and identified as being in the range of typical speech-language development. Expressive and receptive language standard scores were 90 or better and the nonverbal IQ standard scores were greater than 80 (see Table 1 for a summary of the test scores). The expressive language scores of Subject 1 were found to be in the 75th percentile, which is considered a high average score. His nonverbal IQ was also found to be above average. At the time of testing, each subject's hearing sensitivity was screened from 500-4000 Hz at 20 dB HL to rule out a hearing deficit[5].

3.2.2 Stimuli

A re-synthesized, naturally-produced isolated vowel sound (Λ) of an adult female was edited to produce the vowel stimuli. This vowel sound was recorded and digitized at 10,000 Hz on a DAT tape and edited to 250 ms in total duration using the Computerized Speech Lab/LPC Parametric Manipulation Synthesis Program software (CSL/ASL). The ASL software was also used to compute formant frequencies and bandwidths. F1 and F2 formant center frequencies of the schwa were edited to create a continuum from [I] to [ε]. The bandwidth of the original vowel was retained to maintain naturalness. The F1 formant frequency was increased by 25 Hz steps from 450-650 Hz, while the F2 formant frequency decreased by 30 Hz steps from 2220-1980 Hz. Formants F3 and F4 were constant throughout the nine-step continuum at approximately 2714 and 3175 Hz, respectively. In order to create the brief vowel stimuli ([I]-[ε]) to be used in this experiment, the 50-ms center of the vowels were extracted, and edited to begin and end with rise and fall times of 5 ms, respectively. The intensity of the stimuli was set at 86.5 dBpeSPL. The stimuli were delivered binaurally through EAR Eartone 3A insert earphones. Table 2 shows the F1 and F2 formant frequencies of the stimuli used in the experiment (stimulus numbers 3, 5, 7, and 9)[6]. The vowel identification associated with each step on the continuum was tested in a previous study using adult listeners (Liebenthal, Lee, Shafer, Kurtzberg, and Vaughan, in preparation) and is also displayed in

Table 2. Stimulus 3 and 5 were perceived as [I], whereas 7 and 9 were perceived as [ɛ]. Stimulus 5 and 7 fell close to the phonemic boundary.

3.2.3 Procedures

The order of the behavioral and electrophysiological conditions was counterbalanced across subjects. Rewards (e.g., colored pencils, rubber balls) were provided to the children throughout testing to maintain continuous attention. After explaining the experiment to the parent(s) and child, the parent signed a parental consent form and the child signed a child assent form. After explaining the study to the adult participants, an adult consent form was signed.

Behavioral

A familiarization condition was provided before each behavioral test to ensure that the subject understood the task. Each familiarization task was presented one to two times. For the identification task, the subject was directed to press one button for [I] and another button for [ɛ] after each speech sound. If the subject failed to press any button following each of the vowel sounds, the subject was re-instructed, and the familiarization task was presented again. Feedback was provided only if the participant made a high number of errors during the familiarization task. For the discrimination task, the subject was told to press a button when a change (i.e., the deviant) from the standard was perceived. If the participant failed to press the button to the within-category deviant in the first practice session for the discrimination task, then the within-boundary deviant was identified for the subject within the stream of speech sounds during the second practice session. Failure to discriminate the within-category deviant during the practice session did not exclude the participant from continuing in the experiment.

Identification

The children labeled stimulus 3, 5, 7, and 9, while the adults were asked to identify the entire nine-step continuum. The children were only presented with the four test stimuli because it was determined that they would not be able to maintain consistent attention for the duration of the identification of the entire nine-step continuum. Each stimulus was presented fifteen times, for a total of 60 stimuli to the children and 135 stimuli to the adults. The vowel sounds were presented at an SOA of 2 s. The task of the subject was to press one button when [I] was heard and another button for [ε]. Reaction times were recorded for each subject.

Target Discrimination

Stimuli were presented using an oddball paradigm. In this paradigm one stimulus type (the deviant) is presented less frequently than another stimulus type (the standard). Two different test conditions were created. In one condition, stimulus 9[ε] served as the standard and 7[ε], 5[I], and 3[I] served as the deviants. In the second condition, stimulus 3 served as the standard and 5, 7, and 9 served as the deviants. Within both conditions, one of the deviants fell within the same phonemic category, whereas the other two fell outside of the phonemic category of the standard. Twenty stimuli of each deviant and 248 of the standard stimuli were presented. In both conditions an SOA of 2 s was used. Each condition was divided into two runs. The task of the subject was to press a button when a change from the standard stimulus (i.e., the deviant) was perceived. Reaction times were recorded in both tasks for all subjects. Reinforcement (thumbs up for correct responses vs. a 'no' gesture for incorrect responses) was provided to the responses of the child subjects. This reinforcement helped keep the attention of the child on the task.

Electrophysiological

The same oddball conditions used in the behavioral discrimination task were used in the electrophysiological condition, with two alterations: 1) the SOA was reduced from 2 s to 600 ms and 2) the subject was asked to ignore the speech sounds and to watch a silent video. Captions were usually needed to capture the attention of the adults, but were unnecessary for the children.

Recording Procedures

All subjects were fitted with an electro-cap (Electro-Cap Products). Electrophysiological activity was recorded from 31 electrode sites (superset of the International 10-20-electrode system; see Figure 1). The nose served as the reference, P09 as the ground, and differential recordings between FP2 and an electrode placed slightly below the outer canthus of the right eye served to monitor eye movements. Electrode impedance was measured and usually maintained below 5 kOhms. For the children who could not tolerate excessive scalp cleaning, impedance did not exceed 10 kOhms.

The EEG was amplified 30,000 times with the filter bandpass set at .05 to 100 Hz using Nicolet amplifiers. Data were acquired using a Neuroscan PC-based system in continuous mode and digitized at 512 Hz per channel. The channels were observed during data acquisition to monitor for muscle movement and electrical artifact. Five hundred stimuli were presented within each run. Each deviant was presented at a 7%

probability for a total deviant occurrence of 21%. Each subject received five runs for each condition for a total of 2500 stimuli per condition (standard=1975 trials; each deviant=175 trials). The continuous EEG was post-processed off-line into epochs of standard and deviant stimuli. Analysis time was 500 ms with an additional 50 ms pre-stimulus baseline against which measurements of amplitude were obtained. The individual epochs were baseline corrected by subtracting the mean voltage of an individual epoch from itself. Any epoch that exceeded +/- 100 μV was rejected before averaging. The averaged waveforms were filtered from 1 to 15 Hz and baseline corrected to set the pre-stimulus mean amplitude to zero.

3.2.4 Analysis

Behavioral

The significance of the behavioral responses was tested using mixed ANOVAs. For the identification task, group (children and adults) x identification was tested when [I] was identified as the vowel for the four stimuli 3, 5, 7, and 9. Only one response category was tested for the four stimuli because the other response can be derived from this data. Missed responses were less than 2% for each stimulus. The responses to the four stimuli (3, 5, 7, 9), as opposed to the nine-step continuum, were compared because both groups classified these stimuli. For the discrimination task, group x target discrimination was tested separately when [I] served as the standard and when [ε] served as the standard. For the analysis of discrimination performance, the ANOVAs were calculated from Arc Sin transformed data scores. The data were transformed to create a distribution that better matches the assumption of normality required by ANOVA. The false alarm responses (i.e., the responses to the standard) were then subtracted from the hit responses (i.e., the responses to the deviant). Tukey HSD and Tukey Unequal N HSD (when group was a factor) post-hoc tests were used to follow-up significant effects.

Reaction times were also examined for each behavioral task using mixed ANOVAs (group x reaction time). For the identification task, the reaction times for only stimulus 3 and 5 for vowel sound [I] and for 7 and 9 for vowel sound [ɛ] were analyzed because only these stimuli had a sufficient number of responses. For the target discrimination task, the reaction times to the standard stimulus were not included in the analyses because there were too few responses. Tukey HSD and Tukey Unequal N HSD (when group was a factor) post-hoc tests were used to follow-up significant effects.

Electrophysiological

ERP Waveforms

The average amplitudes of the ERPs to the standard and deviant for seven 30 ms time periods (100-130, 131-160, 161-190, 191-220, 221-250, 251-280, 281-310 ms) were calculated. For the first level of analysis, within-group ANOVAs were conducted comparing stimulus by time to determine whether MMN was elicited to each deviant. These analyses were conducted for eleven electrode sites (Fz, Cz, Pz, C3, C4, FC5, FC6, CP5, CP6, left mastoid [LM], right mastoid [RM]). Fz was chosen because this electrode site has often been reported in the literature as the location where MMN is maximal. The mastoids were included in the analyses because MMN has been found to invert at the mastoids under certain test conditions. The remaining electrode sites were chosen because the topographical analyses suggested a negativity in these regions at the latency of MMN. The central sites C3, Cz, and C4 were selected because inspection of the ERP waveforms suggested that the negativity was maximal centrally. Several tests were conducted for this first level of analysis in order to identify the time and location that MMN was elicited in order to use for group comparisons. This strategy allowed us to limit statistical comparisons for the between-group testing to those sites and times that showed MMN.

MMN was derived by subtracting the response to the standard from that of the deviant. The latency of the peak amplitude of the MMN was identified from the subtraction waveforms for each subject. MMN was identified in the difference waveform as the most negative deflection between 150-250 ms. This window for peak identification was chosen because MMN has been observed to typically occur at latencies between these values in response to speech stimuli (e.g., Aaltonen et al., 1987). To determine whether MMN differed across groups, 2-way mixed ANOVAs examining MMN amplitude were calculated comparing group (children/adult) by time. These analyses were conducted only for the times and electrode sites that showed significant MMN responses in the within-group comparisons.

Tukey HSD and Tukey Unequal N HSD (when group was a factor) post-hoc tests were used to follow-up significant effects. The Greenhouse-Geisser adjusted univariate test was used to correct for violations of specificity for factors with more than two levels (i.e., time). The Greenhouse-Geisser correction computes reduced degrees of freedom to account for the fact that the multiple levels are correlated and not independent from one another. Epsilon (ε) and corrected p values will be reported.

Scalp Current Density Maps

Scalp current density (SCD) analysis of the MMN was performed using EEGFOCUS (2.0 MEGIS Software GmbH). SCD maps provide the location of maximal source current divergence at the scalp, which is indicative of the location of sources on the surface of the cortex and the orientation of this current. Spatiotemporal patterns can be compared across groups and test conditions using SCD analyses. The specific location of the intracranial generator, however, cannot be determined from SCD maps.

The software, used to create SCD maps, computes the second spatial derivative to determine the foci of inward and outward current flow on the scalp (i.e., Laplacian estimation). The current distributions are reference independent (Perrin, Bertrand, and Pernier, 1987; Pernier, Perrin and Bertrand, 1988). EEG recordings produce passive spread of currents throughout the scalp. The SCD analysis removes the passive lateral spread of electrical current and thus gives a better indication of the region of maximal activity at the scalp. In this dissertation, the voltage grand mean difference waveforms at the peak negativity of the MMN were used to create the SCD Maps. The maximal point, in the expected time frame of the MMN, in the Laplacian estimations was selected to create the SCD maps. The amplitude of the SCD maps was set at 0.5 $\mu V/cm^2$.

4. Results

4.1 Behavioral

4.1.1 Identification

Grand mean identification and reaction time values were calculated for the children and adults (see Figure 2; adult values on top and child values on the bottom).

One child was excluded from this analysis because the subject showed an unusually large number of missed responses (greater than 14%). A significant main effect of stimulus was found (F(3,48)=303.21, p=0.000000). Post-hoc tests showed that the identification of stimulus 3 was significantly different ($p<0.05$) from stimulus 5, 7, 9 and stimulus 5 from 7 and 9. No group differences were found. Reaction times did not differ significantly across groups (F(3,48)=1.10, p=0.36).

Thus, similar findings were observed for the adults and children in the identification responses and reaction times of the responses to the vowels ([I]-[ɛ]). The identification of stimulus 3 and 5 were found to significantly differ from the labeling of stimulus 7 and 9. The difference in the responses for 5 and 7 was quite large suggesting that the category boundary lies between these two stimuli. While the identification of stimulus 3 significantly differed from 5, the difference was smaller (13%) than the difference between 5 and 7 (greater than 50%). This suggests that the category boundary falls between stimulus 5 and 7. The significant difference between 3 and 5 suggests that they may not be equally good exemplars of the vowel sound [I][7].

4.1.2 Target Discrimination

ANOVAs were calculated from Arc Sin transformed data scores. Group x stimulus analyses were tested separately when [I] served as the standard and when [ɛ] served as the standard. Grand mean discrimination and reaction time values were calculated for the children and adults and can be seen in Figure 3 (adult values on top and child values on the bottom). A main effect for group was significant when 3[I] served as the standard (F(1,17)=6.45, p=0.02), with the adults showing better discriminatory abilities compared to the children. A main effect for stimulus was observed when 9[ɛ] served as the standard (F(2,34)=91.22, p=0.000000) and when 3[I] served as the standard (F(2,34)=127.69, p=0.000000).

Post-hoc tests (p<0.05) showed that when stimulus 9[ɛ] was the standard, responses to stimulus 7[ɛ] were significantly different from responses to stimulus 3[I] and 5[I]. No significant difference was found between stimulus 3 and 5. When 3 was the standard, responses to stimulus 5 were significantly different from those to stimulus 7 and 9. No significant difference was seen between responses to 7 and 9. These results suggest that in both test conditions both age groups discriminated the vowels across the boundary better than the deviants that fell within the same phonetic-category as the standard.

When reaction time was analyzed, a significant interaction was found when 9[ɛ] served as the standard (F(2,34)=3.60, p=0.04). Post-hoc tests (p<0.05) revealed that the adults were significantly faster than the children at responding to stimulus 3 and 5. Significant main effects of group (F(1,17)=9.34, p=0.007) and stimulus (F(2,34)=30.99, p=0.000000) were found when 9[ɛ] was the standard and when 3[I] served as the standard (group: F(1,17)=9.85, p=0.006; stimulus: F(2,34)=35.95, p=0.000000). The main effects of group revealed that on average the adults responded significantly faster compared to the children.

Post-hoc tests (p<0.05) of the main effect of stimulus showed that when 9[ɛ] served as the standard, reaction time was significantly slower for responses to stimulus 7[ɛ] compared to 3[I] and 5[I], but there was no difference between 3 and 5. When 3 served as the standard, reaction time was significantly slower for stimulus 5 compared to 7 and 9, but no difference was observed between 7 and 9.

In sum, both age groups discriminated the vowels across the boundary better than the within phonetic-category deviants. In general, the adults showed better discriminatory performance than the children when 3[I] served as the standard. In addition, on average, the adults responded significantly faster than the children. However, both groups showed faster reaction times to the vowel deviants that were acoustically more different from the standard (i.e., the across-boundary deviants).

4.2 Electrophysiology

4.2.1 ERPs to the Standard and Deviant

Electrode site C3 was chosen for illustrative purposes because MMN was generally largest over the left hemisphere in the grand mean waveforms for both age groups. The grand mean ERPs at C3 to the standard and deviant stimuli of both conditions can be seen in Figure 4 for both the children (black) and adults (gray). The ERPs to the stimuli in the condition where 9[ɛ] served as the standard is on the left and to the condition where 3[I] was the standard is on the right. Maturational differences in the morphology of the waveforms in response to the standard and deviant were observed. Across both conditions the adults showed the mature P1-N1-P2 component complex. The children, however, showed a large positivity between 100-150 ms ($P_{100-150}$) followed by a negativity at 200-250 ms ($N_{200-250}$) in response to both the standard and deviant. This morphology has been observed in children in other studies when stimuli are presented at relatively rapid rates (e.g., Čeponienė, Cheour, and Näätänen, 1998; Shafer et al., 2000).

4.2.2 Difference Waveforms

The ERP response to the deviant is more negative than the ERP to the standard for the greatest acoustical difference of 9[ɛ] vs. 3[I] (see the top graphs of Figure 4). As the acoustical difference between the standard and deviant becomes smaller, this negativity decreases in amplitude (see middle and bottom graphs of Figure 4).

The grand mean difference waveforms for both conditions are shown in Figure 5 at C3 for both the children (black) and adults (gray). These waveforms suggest that a negativity was elicited in the children that was both later in peak latency and smaller in amplitude in both test conditions compared to the adults. In the adults, the intermediate, across-boundary deviant stimuli elicited smaller negativities compared to the responses elicited to the extreme deviants. When 9 served as the standard, a negativity was not evident to the intermediate across-category deviant (5[I]) in the child listeners. The negativity elicited to the extreme deviant stimulus (deviant=9, standard=3) appears unexpectedly smaller than the response to the intermediate deviant stimulus (deviant=7) in the children. The negativity to the extreme stimulus is expected to be larger because of the greater acoustical difference between the standard and deviant. This unexpected finding may be attributed to amplitude variability in the children. One child subject in particular greatly decreased the grand mean difference waveforms elicited to the extreme deviant. Statistical analyses will clarify whether the two stimuli differ in amplitude. A distinct negativity was not elicited to the within-boundary stimuli for any group.

4.2.3 Within-Group Anova's Assessing Amplitude Across Time

Within-group ANOVAs were conducted comparing stimulus (standard/deviant) by time (seven time intervals) to determine whether MMN was elicited to each deviant presented. These analyses were conducted for eleven electrode sites (see Methods). Only significant findings including stimulus (standard/deviant) will be reported.

Condition 1: Standard=9[ε]

Deviant=3[I]

Significant interactions of stimulus by time were found in the adults at Fz (F(6,48)=6.30, p=0.00003, ε=0.48), Cz (6,48)=9.40, p=0.00003, ε=0.35), Pz (F(6,48)=6.82, p=0.003, ε=0.33), C3 (F(6,48)=12.96, p=0.0002, ε=0.35), C4 (F(6,48)=9.36, p=0.00002, ε=0.40), FC5 (F(6,48)=8.57, p=0.001, ε=0.43), FC6 (F(6,48)=10.29, p=0.00006, ε=0.47), CP5 (F(6,48)=9.01, p=0.004, ε=0.30), and CP6 (F(6,48)=4.88, p=0.01, ε=0.40). A significant main effect of stimulus was found in the adults at Fz (F(1,8)=20.20, p=0.002), Cz (F(1,8)=19.42, p=0.002), Pz (F(1,8)=13.90, p=0.006), C3 (F(1,8)=18.47, p=0.003), C4 (F(1,8)=45.89, p=0.0001), FC5 (F(1,8)=8.54, p=0.02), FC6 (F(1,8)=42.88, p=0.0002), CP5 (F(1,8)=8.03, p=0.02), and CP6 (F(1,8)=10.47, p=0.01). Post-hoc tests of the significant interaction of stimulus by time revealed significant differences (p<0.05) of the ERPs to the standard and deviant for the adult listeners from 101-250 ms at Fz, C3, C4, FC6, from 131-250 ms at Cz, Pz, FC5, CP5, and CP6. No significant interactions or main effects were found for the children at any electrode site, indicating no MMN was elicited.

In sum, a widely distributed MMN (i.e., deviant more negative than the standard) was elicited at frontal, central, and parietal electrode sites in the adult listeners. The negativity was significant from 101-250 ms, with the duration of the negativity varying depending on the electrode site analyzed. No MMN was found for the children at any electrode site.

Deviant=5[I]

No significant interactions or main effects were found for the adults at any electrode site. A significant interaction of stimulus by time was found for the children at C4 ($F(6,54)=3.63$, $p=0.00000$, $\varepsilon=0.31$). Post-hoc tests ($p<0.05$) failed to show differences between the ERP to the standard and deviant at any given time interval at C4. Thus, the interaction revealed only slight differences in the amplitude of the ERPs to the standard and deviant across time. In sum, no significant negativity or positivity was elicited in either test group.

Deviant=7[ε]

The adults showed a significant main effect of stimulus at Pz ($F(1,8)=12.67$, $p=0.007$), with CP6 ($F(1,8)=4.79$, $p=0.06$) approaching significance. A significant effect was also found for the children at Cz ($F(1,9)=6.74$, $p=0.03$) and FC5 ($F(1,9)=6.58$, $p=0.03$), with C3 ($F(1,9)=5.12$, $p=0.05$) approaching significance. However, the ERP to the deviant was found to be more positive than the ERP to the standard for both groups. Thus, no MMN was elicited in either the children or adults.

Condition 2: Standard=3[I]

Deviant=9[ε]

A significant interaction of stimulus by time was found for the adults at Fz ($F(6,48)=6.51$, $p=0.00002$, $\varepsilon=0.51$), Cz ($F(6,48)=5.31$, $p=0.00003$, $\varepsilon=0.40$), C3 ($F(6,48)=6.86$, $p=0.0002$, $\varepsilon=0.35$), C4 ($F(6,48)=5.38$, $p=0.00003$, $\varepsilon=0.41$), FC5 ($F(6,48)=7.30$, $p=0.001$, $\varepsilon=0.36$), and FC6 ($F(6,48)=7.34$, $p=0.00009$, $\varepsilon=0.52$). A significant main effect of stimulus was found for the adults at Fz ($F(1,8)=7.41$, $p=0.03$), Cz ($F(1,8)=7.51$, $p=0.03$), C3 ($F(1,8)=6.91$, $p=0.03$), and RM ($F(1,8)=11.12$, $p=0.01$), with LM (F(1,8)=4.83, p=0.06) approaching significance. Post-hoc tests of the significant interaction of stimulus by time revealed significant differences (p<0.05) of the ERPs to the standard and deviant for the adult listeners from 131-220 ms at Fz, C3, FC5, and FC6, and from 131-190 ms at Cz and C4.

A significant interaction of stimulus by time was found for the children at RM (F(6,54)=5.32, p=0.0001, ε=0.23). Post-hoc tests (p<0.05) of the interaction revealed that the ERP to the deviant was more positive than the ERP to the standard from 161-250 ms. The children also showed a significant main effect of stimulus at LM (F(1,9)=14.15, p=0.004), which was attributed to the ERP to the deviant being more positive than the ERP to the standard.

In sum, the ERP to the deviant was more negative than the ERP to the standard at centrolateral sites for the adult listeners. The duration of the negativity (i.e., MMN) extended from 131-220 ms, varying in duration depending on the electrode site. The ERP to the deviant was more positive compared to the response to the standard at the mastoids in approximately the same time intervals. No significant MMNs (i.e., deviant more negative than the standard) were observed at superior sites in the children.

Deviant=7[ε]

A significant interaction of stimulus by time was found for the adults at Cz (F(6,48)=4.16, p=0.0001, ε=0.34), C3 (F(6,48)=6.57, p=0.0003, ε=0.34), FC5 (F(6,48)=5.77, p=0.002, ε=0.36), and CP5 (F(6,48)=5.22, p=0.01, ε=0.29). Post-hoc tests of the significant interaction of stimulus by time revealed that the deviant was significantly more negative than the standard (p<0.05) from 131-220 ms at C3, from 161-

220 at Cz, and from 161-190 ms at FC5 and CP5. No significant interactions or main effects were found for the children at any electrode site, indicating no MMN was elicited.

In sum, left hemispheric, centrolateral MMN responses (i.e., deviant more negative than the standard) were found in the adults, with the duration of the negativity varying, depending on the electrode site, from 131-220 ms. No significant MMN was found for the children at any electrode site.

Deviant=5[I]

A significant main effect of stimulus was found for the adults at LM (F(1,8)=6.50, p=0.03), which was attributed to the ERP to the deviant being more positive than the ERP to the standard. No other significant effects, including stimulus, were observed for the adults. No significant interactions or main effects were found for the children at any electrode site. Thus, no MMN was elicited for either the children or adults.

Summary of Findings

In general, the within-group ANOVAs revealed that across both test conditions significant MMNs were found at frontal, lateral, and parietal sites for the adults to the extreme stimulus differences (standard=9, deviant=3; standard=3, deviant=9) and to the intermediate across-boundary vowel in Condition 2 (standard=3, deviant=7). No significant MMN was found for the adults to the intermediate across-category vowel in Condition 1 or to the within-boundary vowels in either test condition. In Condition 1, the MMN range extended from 101-250 ms, while in Condition 2 the duration of the MMN extended from 131-220 ms. This difference can be seen in the grand mean difference waveforms (see Figure 5).

For the child listeners, no significant MMN was found in either test condition. This finding is surprising because an MMN appears to be present at the expected latency of the MMN in the grand mean difference waveforms (see Figure 5) and in the SCD maps (to be discussed below in the section Scalp Current Density Maps; see Figure 6). Examination of the standard deviations revealed greater variability in the children compared to the adults. This increased variability led to the failure to identify significant MMN responses in the children.

4.2.4 Between-Group ANOVAs Assessing MMN Amplitude Across Time

Only the time intervals and electrode sites that were found to include a significant difference between the standard and deviant for the within-group ANOVAs, and that did not show a significant difference in variability across group, will be examined using 2-way mixed ANOVAs.

Condition 1: Standard=9[ε]

Deviant=3[I]

The following electrode sites and time intervals were examined because they satisfied the requirements of homogeneity of variance: Fz (131-160, 161-190), Cz (131-160), C3 (131-160, 161-190), FC5 (131-160, 161-190), and CP5 (131-160). A significant main effect of group was found for Fz (F(1,17)=5.02, p=0.04), C3 (F(1,17)=8.25, p=0.01), and FC5 (F(1,17)=12.70, p=0.002) for the time intervals examined (131-160 and 161-190 ms). The main effect of time approached significance at CP5 (F(1,17)=4.24, p=0.06) for time interval 131-160 ms. No significant interactions were found.

In sum, the main effect of group indicates that the adults and children differed. The adults showed a negative deflection in the difference waveform (Fz: mean=-1.29, SD=1.13; C3: mean=-1.50, SD=1.21; FC5: mean=-1.12, SD=1.22), while the children showed a positivity (Fz: mean=0.24, SD=1.78; C3: mean=0.12, SD=1.52; FC5: mean=0.58, SD=1.07).

Deviants=5[I]; Deviants=7[ε]

No significant MMN was found in the within-group analyses for either the children or adults. Thus, between-group analyses were not conducted.

Condition 2: Standard=3[I]

Deviant=9[ε]

The following electrode sites and time intervals were examined because they satisfied the requirements of homogeneity of variance: Fz (191-220), C4 (131-160, 161-190), FC6 (131-160, 161-190, 191-220), LM (101-130, 131-160, 161-190, 191-220, 221-250), and RM (131-160, 161-190, 191-220, 221-250). A significant interaction of group by time was found for LM ($F(4,68)=4.04$, $p=0.01$, $\varepsilon=0.69$). Post-hoc testing showed that the difference waveform was more positive ($p<0.05$) for the children than the adults from 221-250 ms. A single time interval was examined for Fz from 191-220 ms and was found to be significantly different across groups ($F(1,17)=5.74$, $p=0.03$).

A significant main effect of time was found for RM ($F(3,51)=6.40$, $p=0.003$, $\varepsilon=0.72$) and LM ($F(4,68)=7.79$, $p=0.0004$, $\varepsilon=0.69$), with C4 ($F(1,17)=4.05$, $p=0.06$) approaching significance. Post-hoc testing ($p<0.05$) revealed that the positivity was greatest between 161-220 ms at the mastoids. At RM, the time periods 161-190 and 191-220 ms were significantly more positive than time interval 131-160 ms. At LM, the time periods 161-190 and 191-220 ms were significantly more positive than time interval 101-130 ms. No additional significant findings were observed for any electrode site.

Deviant=7[ε]

The electrode sites and time intervals that were found to be significant in the within-group analyses did not satisfy the requirements of homogeneity of variance. Thus, between-group analyses were not conducted.

Deviant=5[I]

No significant MMN was found in the within-group analyses for either the children or adults. Thus, between-group analyses were not conducted.

Summary of Findings

In sum, a negativity was found in the difference waveforms of the adults in Condition 1 to the extreme deviant (3[I]) at Fz, C3, and FC5 compared to a positivity observed in the children. This indicates that MMN was elicited in the adults and not the children at the given electrode sites examined. For the children, positive responses were found at the mastoids in Condition 2 to the extreme deviant 9[ε]. No additional deviants were examined.

4.2.5 Scalp Current Density Maps

An important finding in this dissertation is that the ERP responses of the children are more variable than the adults. This led to an absence of a significant MMN for the children in the within-group ANOVAs. One question arising from this observation is whether the variability in MMN amplitude is related to variability in the topography of the response. Therefore, we examined the topography of the difference waveform of each subject for the across-boundary deviants. We did not examine the within-boundary deviants because no negativity was found to these deviants in either test condition. See

Table 3 for a listing of the peak latencies used to create the grand mean and individual SCD maps.

The SCD maps of the grand mean difference waveforms revealed topographical differences between groups and across deviant types within a group. The adults showed bilateral frontocentral foci in both test conditions to the extreme across-category deviants (i.e., standard=9, deviant=3; standard=3, deviant=9), with stronger amplitude activation over the left central electrode sites (see Figure 6, left). The negativity (or inward current flow) is illustrated by white contours and the positivity (or outward current flow) by black contours. As the acoustical difference between the deviant and standard decreases, the amplitude of the focus of the negativity in the difference waveform decreases (shown as a lower density of contour lines; e.g., see the SCD map to the intermediate across-category deviant (7[ε]) in Condition 2).

The grand mean SCD maps for the children also showed bilateral foci. These foci are denser compared to the adult foci and probably reflect greater amplitude activity for the children compared to the adults (see Figure 6; right). Furthermore, in general the foci are denser over the left hemisphere compared to the right. In Condition 1 to the deviant 3[I], the children's foci are more lateral and posterior compared to the adults. The distribution of the negative and positive activity of the right focus of the children also differed from the adults suggesting a differing orientation of the neural generators across groups (e.g., the right positive focus [indicated by the black contours] for the children was more anterior compared to the adults). Source analysis using an equivalent current dipole method (e.g., BESA) would be necessary to model potential sources of this activation. A right hemispheric focus is maintained to both deviants. Since a significant negativity was not found for the children it is unclear whether this negative focus reflects the discriminative processes indexed by MMN. No distinct left hemispheric negative activity is observed in the SCD maps to the intermediate across-boundary deviant. In Condition 2, bilateral frontocentral foci can be seen in the SCD maps of the children to the extreme deviant (9). The distribution of the focal pattern is similar to that seen in the adults. A right central negative focus was observed to deviant 7[ε]. This focus was similar in location to the focus elicited to the extreme deviant (9). A left hemispheric focus was seen to deviant 7 that was more anterior than that elicited to deviant 9.

It is important to determine how many subjects were similar to the grand mean. It is possible that a small number of participants dominated the response in the grand mean. In addition, the F-tests of variance revealed greater variability in the amplitude of the ERP difference waveforms of the children compared to the adults. Examination of the individual SCD maps allows us to determine whether the greater variability in the children is due to variability in the topography of this difference waveform or is due to an absence of negativity at any superior sites for some child subjects. We were also interested in determining whether some of the child participants showed a topographical pattern similar to the adults.

Figure 7 (left) shows the SCD maps for each adult subject over the right and left hemispheres when 9[ε] served as the standard and 3[ɪ] the deviant. The SCD maps only to the extreme deviants in both test conditions will be presented because the intermediate across- and within-category deviants did not elicit robust MMNs in the adults. The most negative point in a 30 ms time interval was selected for creating the individual SCD maps (adults=176 ms [161-191 ms]; children=218 ms [203-233 ms]). This 30 ms time frame was chosen to include the peak negativity of the grand mean SCD maps (+/- 15 ms). This time interval of 30 ms is also used for the statistical comparisons in this dissertation.

All nine adult subjects showed negativity over the left hemisphere. Subjects 1-7 showed a similar response pattern to the grand mean SCD maps. Subjects 8 and 9, however, showed a topography that was more posterior compared to the other adults. The right hemispheric response was similar to the grand mean for seven of the nine subjects (1-6, 9), with the remaining two subjects (7-8) showing a more lateroanterior negative focus. In general, the right hemispheric topography was less uniform across subjects compared to the left hemispheric response pattern.

The focal patterns of the children (see Figure 7, right) were less uniform compared to the adults. Four of the ten children (1-4) showed negative foci for both hemispheres that were located within a similar region as in the SCD maps of the grand means. However, these four children differed in the location of the foci, in that no two children showed a similar negative/positive dipole distribution. For subjects 6, 9, and 10 the right hemispheric focus was similar to that observed in the grand mean SCD map. The left hemispheric focus was either more anterior (6), more inferior (9), or more anteroinferior (10) compared to the grand mean SCD map. Subjects 5 and 7 showed a left hemispheric focus similar to the grand mean, but no distinct right focus. Subject 8 showed a right hemispheric focus that was more anterior compared to the grand mean, however, no distinct left hemispheric focus.

Figure 8 (left) shows the SCD maps for each adult subject over the right and left hemispheres when 3[I] served as the standard and 9[ε] as the deviant (peak latency for the adults=175 ms [160-190 ms]; children=210 ms [195-225 ms]). A similar left hemispheric negative focus was found in all nine adults that resembled the grand mean SCD map. All nine adults also showed negativity over the right hemisphere. However, the location of the negative focus differed from that of the grand mean for several of the adults. Subjects 2 and 3 showed a negative focal point that was more frontal and superior, the negative focus of subjects 5 and 8 was more inferior, and the response of subjects 4 and 6 was more central.

The children's ERP responses were more uniform in Condition 2, compared to their responses in Condition 1. Eight of the ten children (1, 2, 4-8, 10) showed a similar negativity over left, superior sites compared to the grand mean SCD maps (see Figure 8, right). Subject 9 showed a left hemispheric focus that was more temporal and inferior then the focus illustrated in the grand mean. Subject 3 showed no distinct negativity over superior and temporal sites. Of the ten children, seven (1, 2, 4, 5, 7-9) showed a similar right hemispheric response compared to the grand mean. The three remaining subjects (3, 6, 10) showed a more frontal negative focus over the right hemisphere.

Summary of Findings

In sum, the majority of the adult subjects showed a similar scalp topography for the negative activity. The SCD topography for the children, however, was less uniform than for the adults. The variability of the topography across the child subjects contributed to their greater variability in voltage amplitude compared to adults. The children also showed a more uniform topographical response pattern when 3[I] served as the standard stimulus than when 9[ε] served as the standard.

5. Discussion

The behavioral data revealed somewhat similar performance levels on the identification and target discrimination tasks for the children and adults. Similar category boundaries and patterns of identification were found for the children and adults. Both age groups discriminated the vowels across the boundary better than the deviants that fell within the same phonetic-category as the standard. Both groups discriminated the target deviant equally well when 9[ɛ] served as the standard. However, the adults showed significantly better discrimination than the children when 3[I] served as the standard. Both groups showed similar reaction times in the identification task. In the target discrimination tasks, both groups showed faster reaction times to the across-category deviants than to the within-boundary deviants. However, on average across the stimuli presented, the adults were significantly faster at discriminating the deviant compared to the children.

The neurophysiological data suggested differences across groups in the underlying brain processing of the vowels [I] and [ɛ]. MMN was found for the adults in both test conditions. Significant MMN responses were observed to the extreme deviants in both conditions (standard=9 vs. deviant=3; standard=3 vs. deviant=9) and to the intermediate across-category deviant in Condition 2 (standard=3 vs. deviant=7) at frontal, lateral, and parietal sites. No significant MMN was found to the intermediate across-boundary deviant in Condition 2 or to the within-boundary vowels for either test condition. The SCD maps showed bilateral frontocentral foci in both test conditions to the extreme deviants, with larger amplitudes over the left central electrode sites. A left hemispheric dominance to speech stimuli has been reported in other ERP studies (e.g., Näätänen et al., 1997). In the adults, the intermediate deviant showed a similar, but weaker SCD topography compared to the greater stimulus difference. This similarity suggests that the same processes were used to discriminate both across-category deviants.

No significant MMN response was found for the child participants in either test condition. However, the grand mean difference waveforms of the children did show a negativity at the expected latency of the MMN (see Figure 5). This negativity was later in peak latencies and smaller in peak amplitudes for the children compared to the adults. The children's grand mean SCD maps also showed distinct negative foci over superior sites to the extreme across-category deviants. In certain instances the topography was similar for the children and adults (standard=3 vs. deviant=9). Similar to the adults, a left hemispheric dominance was observed in the SCD maps of the children. A left hemispheric maximum of the MMN to speech sounds is consistent with reports from other ERP studies in adults (Näätänen et al., 1997), children (Csépe, 1995), and infants (Pang, Edmonds, Desjardins, Khan, 1998). These similarities suggest that the negativity observed in the grand mean waveforms and the SCD maps is MMN.

The variability of the children's difference waveform responses was compared to the adults by using F-tests of variance. Variance was significantly greater for the children than the adults at the majority of the electrode sites examined, within the expected latency range of the MMN (see Appendix B for a summary of the F-value's). Thus, the variability of the responses of the children probably contributed to the absence of a significant MMN. The individual SCD maps also showed a more uniform focal pattern for the adults compared to the children (see Figures 7 and 8). We also observed greater variability in the peak latency of the negativity for the children than the adults (peak

MMN latency for the extreme across-boundary deviants in both test conditions: Standard=9[ɛ]: Adults MMN mean peak latency=193 ms [SD=20.02], Children=216 ms [24.12]; Standard=3[ɪ]: Adults=173 ms [17.61], Children=214 ms [49.71]). Peak MMN latency was found to be significantly more variable in the children compared to the adults ($F(10,9)=3.14$, $p<0.05$) when 3[ɪ] served as the standard, but not when 9[ɛ] was the standard. Within-group analyses revealed that the children's peak MMN latency was significantly more variable for Condition 2 (standard=3[ɪ]) than Condition 1 (standard=9[ɛ]; $F(10,10)=2.98$, $p<0.05$). The adults showed similar variance across conditions ($F(9,9)=3.18$, $p<0.05$). These findings suggest that the absence of significance for the MMN in children is due to greater variability in MMN amplitude and latency than that found for adults.

The finding of differences between the child and adult group further supports the argument that the mechanisms indexed by MMN continue to mature beyond the school-age years. However, the absence of a significant MMN in the children was unexpected. Several researchers have found an MMN to speech stimuli in children (e.g., Kraus, McGee, Micco et al., 1993; see the MMN in Children section). Thus, it remains to be determined what factors differed between the present experiment and the other child MMN studies. Below is a discussion addressing possible factors that may have contributed to this unexpected finding.

5.1 Why was a significant MMN not found for the children in Experiment 1?

Several studies have found significant MMN responses elicited to synthetic consonant contrasts in children. The latency of this MMN did not change as a function of age (Kraus et al., 1992; Kraus, McGee, Carrell et al., 1993; Kraus, McGee, Micco et al.

1993; Kraus et al., 1999). Some researchers have reported larger MMN magnitudes in children compared to adults (Kraus, McGee, Carrell et al., 1993; Kraus, McGee, Micco et al. 1993). In the present experiment, naturally-produced, re-synthesized, edited vowels were used. It may be the case, that more natural speech-like stimuli are processed differently by the brain than synthetically created speech sounds. Preliminary data collected by Maul, Morr, Shafer, and Kurtzberg (2001) found a similar pattern of results using naturally-produced re-synthesized consonant contrasts (/ba/-/da/). In their study, a distinct MMN was not present in the child group compared to the adult listeners. Instead, a late negativity was observed in the children. Behavioral performance was also similar across groups. In a study conducted by Vihla, Lounasmaa, and Salmelin (2000), naturally-produced Finnish vowels and two-frequency complex tones, that represented the F1 and F2 formant frequencies of the vowels, were presented. Larger mismatch magnetic field amplitudes were found in adult listeners to the complex tones compared to the vowels. These studies suggest that more natural speech-like stimuli are more difficult to discriminate by the brain mechanisms indexed by MMN.

It is possible that stimulus duration and not the naturalness of the stimuli would account for the differences observed between the present experiment and other studies. The total duration of the vowel stimuli presented in the present study was 50 ms. The CV syllables used by Maul et al. (2001) were 250 ms in total duration, but differed in the 50 ms formant transitions. However, other researchers found clear MMNs in children to CV stimuli that differed by a 40 ms formant transition (total duration of the stimuli=90 ms; e.g. Kraus et al., 1992). It is possible that it is a combination of these factors (i.e., brevity and naturalness) that led to differences across studies.

An alternative hypothesis for the absence of a significant child MMN in the present experiment, is that the rate of presentation in the present experiment (SOA=600 ms) was too fast to allow the child sufficient time to process the stimuli. A number of previously discussed studies used slower rates of presentation of 1 s or longer (Kraus et al., 1992; Kraus, McGee, Carrell et al., 1993; Kraus, McGee, Micco et al. 1993; Kraus et al., 1999). However, a few studies have used rates less than 1s and found MMN in children. For example, Čeponienė et al. (1999) elicited MMN in children to bisyllabic pseudowords using a relatively fast SOA of 720 ms (offset-to-onset interstimulus interval=350 ms). Bradlow and colleagues (1999) reported MMN in children to consonant contrasts presented at a SOA of 590 ms. Thus, rate of presentation does not appear to entirely account for the absence of a significant MMN in the children. Again, it may be the case that a combination of factors led to differences across studies.

Differences in automatic processing by the brain mechanisms underlying MMN may account for the variability in peak latency, amplitude, and topography of the MMN in children. MMN is believed to be generated from a number of sources which include the primary and secondary auditory cortices on the supratemporal plane and lateral posterior temporal gyrus, as well as, frontal cortex (for review see Alho, 1995; Steinschneider and Dunn, in press). It is possible that these different areas mature at different rates. Thus, the different topography found for children compared to adults may reflect differential refractoriness of the neuronal populations of these regions due to immaturity. Research that has examined rate of presentation on ERPs has shown greater refractoriness of the neuronal populations for children than adults (Čeponienė et al., 1998; Morr, Shafer, Davidson, Kreuzer, and Kurtzberg, in preparation). We have also observed topographical differences in MMN to tones in children between the ages of 4-10 years (Martin, Shafer, Morr, Kreuzer, and Kurtzberg, 2001). Thus, under certain conditions the child's MMN mechanism may not be mature enough to process the stimuli as efficiently as the adult. Alternatively, the absence of a clear MMN in the children may be associated with a masking effect by some other brain response (Morr, Shafer, Kreuzer, and Kurtzberg, 2002). However, there does not seem to be any evidence to support this latter hypothesis at this time. It will be important to determine how different underlying cortical sources contribute to the surface topography by examining the topography of the MMN under different task and stimulus conditions. The relationship of the different cortical mechanisms to behavioral responses also requires further investigation.

The complexity of the paradigm may have played a role in the failure to observe a significant MMN in the children. In the present study, one standard and three deviants were used. Studies that presented speech stimuli using simple oddball paradigms of one standard and one deviant have elicited MMN in school-age children and have found no maturational differences in MMN latency or amplitude (e.g., Kraus et al., 1992; Kraus et al., 1999), or found larger MMN amplitudes in children compared to adults (Kraus, McGee, Carrell et al., 1993; Kraus, McGee, Micco et al. 1993). Thus, limited memory capacity or inefficient pre-attentive processing may have occurred due to the complexity of the stimulus environment created by the test paradigm.

Inefficient pre-attentive processing of the MMN mechanism in children has been reported by Gomes et al. (2000). They showed that attention and active discrimination can enhance the MMN response in school-age children (8 to12 years of age). When an easy (1000 Hz standard, 1500 Hz deviant) or moderately difficult (1000 Hz vs. 1200 Hz) frequency deviant was presented, no change in amplitude was shown with attention. When a difficult (1000 Hz vs. 1050 Hz) frequency difference was used, MMN increased in amplitude with attention. For the adult subjects, however, attention did not increase MMN amplitude in any test condition. Gomes et al. (2000) suggested that in school-age children pre-attentive mechanisms may be unable to sufficiently process difficult discriminations. That is, as the listening environment becomes more complex, children need to actively attend to the stimuli in order to discriminate the sounds.

Alternatively, active discrimination of the auditory stream may be necessary to discriminate these subtly differing speech stimuli in children. The children and adults showed similar behavioral performance in this first experiment. Attention was required for the behavioral condition, but not for the electrophysiological condition. In an auditory environment the listener uses attention to improve the processing of the signal. For example, in noisy environments listeners are able to focus their attention on the signal or message presented by the speaker and ignore the competing environmental noise (i.e., the 'cocktail party' phenomenon; Moore, 1997). Listeners can both voluntarily and involuntarily use attention during auditory processing. It is important to determine how attention influences the auditory processing in different age-groups. Gomes et al. (2000) suggest that easy discriminations are probably automatically processed in children. Difficult discriminations, however, require focused attention by the child. Eventually the discrimination of difficult deviants becomes automatic due to both practice from discrimination with focused attention and from general auditory experience. The role of attention on auditory processing has been examined in adults using ERP measures and is still not completely understood. In the second experiment of this dissertation, the effect of attention on the brain's discriminative processes, as indexed by MMN, in school-age children and adults has been investigated.

6. Attention Effects on MMN

MMN is an index of an automatic discriminative brain response because it can be elicited while the subject's attention is directed elsewhere (e.g., reading a book). However, the effect attention has on the magnitude of this discriminative response has recently become a topic of great interest. Several studies with adults have compared MMN when elicited during an attend target deviant task (the deviant serves as the target), to when the stimuli are unattended (unattended non-target deviant; e.g., the subject attends to stimuli presented to one ear while the stimuli presented to the other ear are not actively attended to by the subject) or ignored (passive MMN; e.g., reading a book). Similar MMN amplitudes have been reported with and without attention (Alho, Sams, Paavilainen, Reinikainen, and Näätänen, 1989; Alho, Woods, Algazi, and Näätänen, 1992; Woods, Alho, and Algazi, 1992; Novak, Ritter, and Vaughan, 1992; Näätänen et al., 1993; Paavilainen, Tiitinen, Alho, and Näätänen, 1993; Alho and Sinervo, 1997; Alho et al., 1998; Kathmann, Frodl-Bauch, and Hegerl, 1999). Furthermore, magnetoencephalographic (MEG) measures showed similar generator sources of the MMNm for ignore and attend test conditions (Alho et al., 1998).

In contrast to the above findings, other experiments have shown an attenuation of the adult MMN amplitude in the absence of attention compared to the presence of attention (Woldorff et al., 1991; Näätänen et al., 1993; Trejo, Ryan-Jones, and Kramer, 1995; Woldorff, Hillyard, Gallen, Hampson, and Bloom, 1998). MEG recordings have also revealed suppressed dipolar field distributions of the unattend mismatch magnetic field (Woldorff et al., 1998). Other studies have reported an enhancement of MMN with attention in adults (Alho et al., 1992; Woods et al., 1992; Oades and Dittman-Balcar, 1995; Alain and Woods, 1997; Sussman, Ritter, and Vaughan, 1998b; Szymanski et al., 1999; Liebenthal et al., in preparation). At this time there is only one known study that has evaluated attention effects on MMN in children (Gomes et al., 2000). This study revealed an increase in MMN amplitude with attention in children in response to difficult frequency changes, but not to easy or moderately-difficult deviants. Similar increases in amplitude were not observed in adult subjects.

Several methodological factors differed across these studies making direct comparison difficult. In the attend MMN condition of several of the studies, researchers used the deviant as the target stimulus (e.g., Näätänen et al., 1993; Alho and Sinervo, 1997; Alain and Woods, 1997; Alho et al., 1998). This is problematic because of the possible overlap of the N2 and MMN components. The N2 component is elicited during active discrimination and is an index of a different brain mechanism than MMN. The overlap of the N2 and MMN makes it difficult to isolate the portion of the negative response associated with MMN. Thus, an enhancement of the negativity with attention may be attributed to the elicitation of the N2 and not to attentional influences. Furthermore, in several studies using binaurally presented stimuli the subjects were asked to selectively focus on the target deviant in one ear, while ignoring the non-target deviant in the other ear (e.g., Woldorff et al., 1991, 1998; Näätänen et al., 1993; Paavilainen et al., 1993). It is unclear how monaural discrimination relates to binaural processing. Furthermore, it may be difficult to compare findings across studies because some researchers compared the MMN obtained in response to an attended target deviant to the unattended non-target deviant MMN (e.g., Woldorff et al., 1991), while others compared the MMN to non-target deviants in a task requiring subjects to attend to the auditory modality to those in a task requiring subjects to ignore the auditory modality (e.g., Liebenthal et al., in preparation). More research needs to be undertaken to determine the affect of attention on MMN in adults, as well as, children.

7. Experiment 2

7.1 General Overview

The purpose of the present experiment was to examine the effect of attention on the brain's discriminative processes indexed by MMN in school-age children and adults and to determine whether a reliable MMN could be elicited to the speech contrast used in Experiment 1 by employing a simpler paradigm. Thus, in Experiment 2 a one deviant oddball paradigm was used. In the Attend condition, the task of the subject was to actively respond to an occasional target tone embedded within the stream of vowels. The dependent measure was the ERP response to the non-target vowel deviant. By using an infrequent target tone, we were able to focus the attention of the subjects to the auditory stream and eliminate any confounding effects of an N2 overlap with the MMN in the ERP response to the non-target vowel. In the passive test condition, the subjects ignored the stimuli and watched a silent video. The same oddball paradigm used in the Attend condition was presented, excluding the target tones. Similar to Gomes et al. (2000), we hypothesize that attention will enhance the MMN response of the children, but not of the adults because children are thought to be less efficient at automatic processing. We also hypothesize that we will observe a significant MMN to the deviant in the Passive condition because a simpler one deviant paradigm will be used.

Behavioral responses were also collected (i.e., identification, target discrimination, same/different discrimination), separately from the ERP recordings in the same subjects. The identification task and three deviant target discrimination tasks are identical to those used in Experiment 1. A one deviant target discrimination task was added to parallel the electrophysiological condition used in the present experiment. A same/different discrimination task was added to determine whether adults and children differ in performance in a task using the same SOA as in the electrophysiological section. We hypothesize that similar behavioral findings will be found across groups.

7.2 Methods

7.2.1 Subjects

Participants included two subject groups (child and adult). The children's ages ranged from 8;3 to 10;2 (mean=9;1, SD=0;8; n=9), with 3 males and 6 females. The adult's age ranged from 22;11 to 45;4 (mean=31;4, SD=7;9; n=9), with 3 males and 6 females. The same criterion for inclusion as in the first experiment was used. All participants were monolingual English speakers, except for one adult who learned Norwegian as an adult. The children had language standard scores of 90 or better and a nonverbal IQ standard score greater than 80 (see Table 4). A hearing screening was performed (500-4000 Hz at 20 dB HL) at the time of testing to rule out any hearing impairments[8].

7.2.2 Stimuli

The stimuli used in this study were from the same continuum created for Experiment 1. The standard and deviant stimulus choice, however, differed from Experiment 1. The standard stimulus 9[ɛ] was used with only one deviant (3[I]). The intent of Experiment 2 was to evaluate the effects of attention on MMN independent of the effects of a complex stimulus environment. These two stimuli were chosen because they fell across the phonetic category boundary and clear negativities were observed to these vowel sounds in the grand mean difference waveforms of both age groups tested in the first experiment (see Figure 5).

Stimulus 9 was chosen as the standard, as opposed to 3, based on a goodness rating conducted with 12 adult listeners (see Appendix A). While the listeners identified stimulus 9 and 3 equally well, they rated 9 as a better exemplar of its vowel class. We selected the stimulus with the higher "goodness" score as the standard because a recent investigation suggests that using a more prototypical exemplar of a phonemic category as the standard leads to a larger MMN (Shafer, Schwartz, and Kurtzberg, submitted). This more prototypical vowel may create a stronger memory trace because it has support from a representation in long-term memory (Shafer et al., submitted). Furthermore, the peak latency of the negativity to the deviant was found to be significantly more variable for the children in Experiment 1 when [I] served as the standard, than when [ɛ] was the standard. The children also showed greater variability compared to the adults in peak latency of the difference waveform when [I] was the standard, but not when [ɛ] served as the standard.

7.2.3 Procedures

Similar to Experiment 1, a familiarization test was provided prior to the behavioral and Attend oddball conditions to ensure that the subject understood the task. The behavioral and electrophysiological conditions were counterbalanced. Rewards (e.g., colored pencils, rubber balls) were provided to the children throughout testing as reinforcement.

Behavioral

Identification

Similar to Experiment 1, the children labeled stimulus 3, 5, 7, and 9. In the present experiment, the adults labeled the same stimuli as the children in this task to determine whether the adults and children have similar identification abilities under identical test conditions. In the first experiment, similar identification abilities were found across groups. However, it is possible that the nine-step continuum was a more demanding task for the adults in Experiment 1, and reduced their performance to the level of the children in the easier task. In order to remain consistent with Experiment 1, the adults also identified the entire nine-step continuum. This identification task was conducted after all of the behavioral tasks were completed (i.e., identification and discrimination).

As in the first experiment, each stimulus was presented fifteen times. Therefore, a total of 60 vowel sounds were presented in the four stimulus and 135 in the nine stimulus task. The SOA of the vowel sounds was set at 2 s. The task of the subject was to press one button when [I] was heard and another button for [ε]. Reaction times of the button presses were recorded for each subject.

Discrimination

A total of three discrimination tests were presented. The first task was the same oddball paradigm as used in Experiment 1 that contained three target deviants. Vowel sound 9[ε] served as the standard. Stimulus 3[I], 5[I], and 7[ε] served as the deviants. As in the first experiment, a total of twenty stimuli of each deviant were presented within 248 standards at an SOA of 2 s in two separate runs. Three adult participants were not tested with the three deviant discrimination task. These subjects participated in the first experiment, so their scores from the first experiment were used for the analyses in the present experiment. In the second task, a similar target discrimination task was used. However, only one deviant stimulus (stimulus 3) was presented along with the standard (stimulus 9). This two-stimulus condition was designed to match the oddball paradigm used in the electrophysiological conditions. The two-stimulus condition was presented once with thirty deviant stimuli embedded within 124 standards. Stimuli were presented at an SOA of 2 s. For both target discrimination tasks, the subject was asked to press a button when a change from the standard stimulus was perceived. Reaction times were recorded in both tasks for all subjects. Feedback (thumbs up for correct responses vs. a 'no' gesture for incorrect responses) was provided to responses of the child subjects. This helped keep the attention of the child on the task.

A same/different discrimination task was presented last. The same/different pairs consisted of the same stimuli used in the electrophysiological condition (e.g., 3-3, 3-9, 9-3, 9-9). The SOA between stimuli was 600 ms and the onset-onset ITI between pairs was 2 s. The 600 ms SOA is identical to that used in the ERP paradigm. This task was added to determine whether adults and children differ in discriminatory abilities in a task using the same SOA as in the ERP condition. A total of 22 different and 22 same pairs were presented. The task of the subject was to press a button when a different pair was perceived. The child subjects were rewarded with an M&M for correct responses.

Electrophysiological

Stimuli were presented in a similar oddball paradigm as used in the one target deviant discrimination task. Two different test conditions were presented: Passive and Attend. During the Passive condition (similar to Experiment 1) the subject was asked to ignore the stimuli presented and to watch T.V. (with the sound turned off; closed captions were provided for adult subjects). One adult chose to read a book. In the Attend condition the subjects were asked to actively respond by pressing a button to an occasional target tone embedded within the stream of vowels. A non-target deviant vowel was then used to assess the effect of attention on MMN without having the subject actively respond to its presence within the stream of standard vowels. This eliminated any confounding effects of an N2 overlapping with MMN. The child subjects were rewarded with M&M candy for correct responses.

There is evidence that suggests that MMN duration and area can be enhanced and MMN onset latency can decrease with learning (Tremblay et al., 1997). In order to avoid a possible confounding factor of the active discrimination used in the Attend condition influencing the Passive MMN, the Passive condition always preceded the Attend condition.

Recording Procedures

The identical electro-cap set-up and recording procedures were used as in Experiment 1. In the Passive test condition 500 stimuli were presented within each run at an SOA of 600 ms. The deviant occurred on 21% of the trials, which was the same probability as used in Experiment 1. Depending on the cooperation of the listener, subjects received three-to-four runs for a total of 1185-1580 standards and 315-420 deviants.

In the Attend MMN condition, the same test paradigm used in the Passive condition was presented. An additional 26 stimuli were embedded within the paradigm making a total of 526 stimuli per run. The additional 26 stimuli consisted of 13 tonal sounds that were pseudo-randomly interspersed and 13 standards that followed each tone. These 13 additional standards were not included in the averages of the standard. As in the Passive MMN condition, the subjects received three-to-four runs.

7.2.4 Analysis

Behavioral

As in the first experiment, the significance of the behavioral responses was tested using mixed ANOVAs. For the identification task, group (children and adults) x stimulus was examined. The dependent measure was the percentage of [I] responses. For the analysis of the responses to the 3 deviant discrimination task, the ANOVAs were calculated from Arc Sin transformed values. The data was transformed in order to ensure a more normal distribution. The false alarm responses (i.e., the responses to the standard) were then subtracted from the hit responses (i.e., the responses to the deviant). For the analysis of the responses to the 1 deviant discrimination task, t-tests of independent samples were calculated from Arc Sin transformed values. Tukey HSD and Tukey Unequal N HSD (when group was a factor) post-hoc tests were used to follow-up significant effects. Responses to the same/different discrimination task were transformed into A' measures, which corrects for biasing (i.e., false alarms; Grier, 1971). The corrected values were examined using a t-test for independent samples.

Mixed ANOVAs were also used to test the reaction time of the stimuli. Group x stimulus was examined for each behavioral task. For the identification task, the reaction times for only stimulus 3 and 5 for vowel sound [I] and for 7 and 9 for vowel sound [ɛ] were analyzed because only these stimuli had a sufficient number of responses to allow examination. For the target discrimination task, the reaction times to the standard stimulus were not included in the analyses. For the same/different task, the reaction times to same pairs of stimuli were not analyzed. Tukey HSD and Tukey Unequal N HSD (when group was a factor) post-hoc tests were used to follow-up significant effects.

Electrophysiological

Responses to the standard and deviant stimuli at frontal, central, and temporoparietal electrode sites were chosen for latency and amplitude measurements. The average amplitudes of the ERPs to the standard and deviant were calculated for the same seven 30 ms time periods (100-130, 130-160, 160-190, 190-220, 220-250, 250-280, 280-310 ms), as used in the first experiment. Within-group ANOVAs were conducted comparing stimulus by time to determine whether MMN was elicited in each test condition. These analyses were performed for eleven electrode sites situated over different brain regions (Fz, Cz, Pz, C3, C4, FC5, FC6, CP5, CP6, LM, RM). Within-group ANOVAs were also performed using the difference waveforms to determine whether hemispheric differences (FC5-Fz-FC6; C3-Cz-C4) were present. The ANOVAs were calculated separately for the Passive and Attend conditions. In order to determine whether MMN (if present) differed between the Passive and Attend conditions, within-group ANOVAs were conducted for the selected electrode sites that showed significant differences for the separate analyses of these conditions.

MMN was derived by subtracting the response to the standard from that of the deviant. The 30 ms average amplitudes of the subtraction waveforms for the seven time intervals served as the dependent measures. To determine whether MMN differed across groups, 2-way mixed ANOVAs were conducted with group as the between-group variable and time as the within-group variable. The dependent measure was the mean amplitudes of the seven 30 ms time intervals of the subtraction waveform. These analyses were conducted only for the sites that showed a significant MMN in the within-group calculations.

Tukey HSD and Tukey Unequal N HSD (when group was a factor) post-hoc tests were used to follow-up significant effects. The Greenhouse-Geisser adjusted univariate test was applied when time (which has greater than two levels) was a factor. Epsilon (ε) and corrected p values will be reported.

Scalp Current Density Maps

As in Experiment 1, the voltage grand mean difference waveforms were used to create the SCD maps. The maximal point, in the expected time frame of the MMN, in the

Laplacian estimations were used in creating the maps. The amplitude of the SCD maps was set at 0.5 $\mu V/cm^2$.

8. Results

8.1 Behavioral

8.1.1 Identification

Grand mean identification and reaction time values for both age groups can be seen in Figure 9 (adult values on top and child values on the bottom). A significant interaction of group by stimulus was seen ($F(3,48)=5.63$, $p=0.002$), although, post-hoc tests failed to reveal significant differences across groups for any particular stimulus. A significant main effect of stimulus was also found ($F(3,48)=370.26$, $p=0.000000$).

Post-hoc tests ($p<0.05$) of the main effect of stimulus indicated that when [I] was identified as the vowel, stimulus 3[I] significantly differed from 7[ε] and 9[ε], stimulus 5[I] differed from 7 and 9, and stimulus 7 differed from 9. In contrast, stimulus 3 and 5 did not significantly differ.

Reaction times were also examined. A significant main effect of stimulus ($F(3,48)=3.48$, $p=0.02$) was observed, however, post-hoc tests failed to reveal significance. The reaction time to stimulus 3 tended to be faster than the response time to stimulus 9.

Thus, the adults and children showed a similar identification pattern of the vowels using an identical four-stimulus labeling task. The finding of similar identification abilities across groups is consistent with the results found in Experiment 1. In addition, both age groups showed similar reaction times to the identification of the correctly labeled stimuli.

8.1.2 Target Discrimination

Three Deviant Target Discrimination

Grand mean three deviant target discrimination and reaction time values were calculated for the children and adults (see Figure 10 [left]; adult values on top and children values on the bottom). A main effect for stimulus was found (F(2,32)=93.66, p=0.000000). Post-hoc tests ($p<0.05$) showed that both groups discriminated the across-boundary deviants (stimulus 3[I] and 5[I]) significantly better than the within-boundary deviant (stimulus 7[ε]). No significant difference was seen between responses to 3 and 5. When reaction time was examined, a significant interaction of group by stimulus was found (F(2,32)=4.74, p=0.02). A significant main effect of stimulus (F(3,32)=18.04, p=0.000006) was also observed. Post-hoc tests ($p<0.05$) revealed that the adults were significantly faster at responding to deviant 3[I] and 5[I]. Both groups responded equally fast to deviant 7[ε]. Post-hoc tests ($p<0.05$) of the main effect revealed that both groups responded faster to stimulus 3 and 5 compared to stimulus 7.

In sum, similar three deviant target discrimination performance was observed across groups. Both age groups discriminated the across-category vowels better than the within-boundary vowel deviants. The adults responded significantly faster than the children to the across-category deviants. This was similar to the pattern of findings in Experiment 1.

One Deviant Target Discrimination

Grand mean one deviant target discrimination and reaction time values were calculated for the children and adults (see Figure 10 [right]; adult values on top and children values on the bottom). The t-test for independent samples revealed that the adults showed significantly better discriminatory performance compared to the children (t(1,16)=2.96, p=0.009). This slight difference is attributed to the percentage of false positive responses across groups (adults: 0.0%, children: 0.27%). Reaction time to the deviant was also examined and found to be similar across groups.

8.1.3 Same/Different Discrimination

Grand mean same/different discrimination scores and reaction times were calculated for the children and adults (see Figure 11; adult values on top and child values on the bottom). The t-test for independent samples showed a significant difference across groups in discrimination performance (t(1,16)=2.29, p=0.0001). This slight difference is attributed to the children showing more errors compared to the adults (adults=0%, children=5%). The adults were also significantly faster at responding to the different pairs compared to the children (t(1,16)=-2.82, p=0.01).

8.2 Electrophysiology

8.2.1 ERPs to the Standard and Deviant

The grand mean ERPs at C3 to the standard and deviant stimuli of both test conditions can be seen in Figure 12 (left; Passive on top, Attend on the bottom) for both the children (black) and adults (gray). As observed in Experiment 1, maturational differences in the morphology of the waveforms in response to the standard and deviant were observed. The adults showed the mature P1-N1-P2 component complex in both test conditions. The children showed a large positivity peaking between 100-150 ms ($P_{100-150}$) followed by a negativity peaking between 200-250 ms ($N_{200-250}$) in response to both the standard and deviant. This morphology has been found in children in other studies when stimuli are presented at fast rates of presentation (e.g., Čeponienė et al., 1998; Shafer et al., 2000).

8.2.2 Difference Waveforms

Figure 13 shows grand mean difference waveforms at central sites (C3, C4) for both the adults (gray) and children (black). The difference waveforms of the adults in the Passive and Attend conditions show two negative peaks. In both conditions, the first peak is likely to be N1 and the second negativity to be MMN.

The MMN of the children in the Passive condition was present, although embedded in slow negative activity that continued beyond the 500 ms latency window. In the Attend condition, a clear, robust MMN appeared to be elicited in the children, which was larger over the right hemisphere.

8.2.3 Within-Group Anova's Assessing Amplitude Across Time

As in Experiment 1, within-group ANOVAs were conducted comparing stimulus (standard/deviant) by time (100-130, 131-160, 161-190, 191-220, 221-250, 251-280, 281-310 ms) to determine whether MMN was elicited. These analyses were conducted for eleven electrode sites located over different brain regions (Fz, Cz, Pz, C3, C4, FC5, FC6, CP5, CP6, LM, RM). Only significant findings including stimulus (standard/deviant) will be reported.

Within-group ANOVAs using the difference waveforms were conducted to determine whether MMN (if present) differed between the Passive and Attend conditions for sites and times that showed a significant MMN for either the Passive or Attend conditions. Within-group ANOVAs were also conducted using the difference waveforms to determine whether hemispheric differences were present. The ANOVAs were calculated separately for the Passive and Attend conditions. In one analysis FC5-Fz-FC6 was examined and in another C3-Cz-C4 was tested. Only significant findings including stimulus (standard/deviant) will be reported.

Passive Condition

For the adults, a main effect of stimulus approached significance at Cz (F(1,8)=5.18, p=0.05). The response to the deviant tended to be more negative than the response to the standard at this electrode site. Otherwise, no significant interactions or main effects were found for the adults.

For the child listeners, a significant main effect of stimulus was found at Fz (F(1,8)=10.12, p=0.01), Cz (F(1,8)=10.62, p=0.01), Pz (F(1,8)=19.32, p=0.002), C3 (F(1,8)=8.33, p=0.02), C4 (F(1,8)=24.91, p=0.001), FC5 (F(1,8)=8.37, p=0.02), CP5 (F(1,8)=9.16, p=0.02), and CP6 (F(1,8)=6.72, p=0.03). No significant interactions were found. In sum, the main effects of stimulus suggest that the ERP to the deviant was more negative than the ERP to the standard at frontocentral, parietal, and centrolateral electrode sites. The magnitude of the difference between the ERPs to the standard and deviant stimuli did not significantly differ within the 100-310 ms time interval.

Attend Condition

A significant interaction of stimulus by time was found for the adults at Cz (F(6,48)=2.98, p=0.01), Pz (F(6,48)=2.58, p=0.03), C3 (F(6,48)=5.02, p=0.0005), C4 (F(6,48)=3.70, p=0.004), FC5 (F(6,48)=4.39, p=0.001), FC6 (F(6,48)=3.98, p=0.003), CP5 (F(6,48)=4.12, p=0.002), CP6 (F(6,48)=2.84, p=0.02), and RM (F(6,48)=3.20, p=0.01), with Fz (F(6,48)=2.29, p=0.05) approaching significance. Significant main effects of stimulus were found at Fz (F(1,8)=19.08, p=0.002), Cz (F(1,8)=6.74, p=0.03), C3 (F(1,8)=25.90, p=0.0009), C4 (F(1,8)=10.82, p=0.01), FC5 (F(1,8)=19.50, p=0.002), FC6 (F(1,8)=21.25, p=0.002), and CP5 (F(1,8)=9.27, p=0.02). Post-hoc tests of the interaction revealed that the response to the deviant was more negative than the response to the standard (p<0.05) at FC5 from 101-250 ms, at C3 from 101-130 and 161-250 ms, at FC6 from 101-130 and 191-250 ms, at RM from 251-310 ms, and at Cz, C4, and CP5 from 191-220 ms. Electrode sites Pz and CP6 failed to show significance.

Significant main effects of stimulus were found for the children at Fz (F(1,8)=9.86, p=0.01), Cz (F(1,8)=9.70, p=0.01), C4 (F(1,8)=13.05, p=0.007), FC6 (F(1,8)=6.75, p=0.03), and CP6 (F(1,8)=5.78, p=0.04).

In sum, for the adults the ERP to the deviant was more negative than the ERP to the standard at frontocentral and centrolateral electrode sites. Early and late time intervals were found to be significant in the interaction. The early significant time frames (e.g., C3 at 101-130 ms) are associated with the first peak, which is an enhanced N1 (see Figure 13). The later significant time intervals (e.g., C3 at 161-250 ms) are associated with the second peak, which we suggest is MMN. The significant main effects for the children suggest that the ERP to the deviant was more negative than the ERP to the standard at frontocentral and right hemispheric lateral sites. However, the magnitude of the difference between the ERPs to the standard and deviant stimuli did not significantly differ within the 100-310 ms time interval.

Passive vs. Attend

The following electrode sites and time intervals were not examined because they did not satisfy the requirements of homogeneity of variance ($F(9,9)=3.18$, $p<0.05$). For the adults: Fz, Pz, and FC5 (251-280), Cz, C4 (221-280), FC6 (191-280), and CP6 (221-250). For the children: C3 (281-310), Pz (101-130), CP5 (221-250), and LM (101-130, 191-220).

A significant main effect of condition (Passive vs. Attend) was found for the adults only at FC5 ($F(1,8)=5.74$, $p=0.04$). An increase in MMN amplitude was observed in the Attend condition. A main effect was found for the children only at CP5 ($F(1,8)=8.10$, $p=0.02$). A decrease in MMN amplitude was seen in the Attend condition. No additional significant main effects or interactions were found for either the adults or children.

Hemispheric Differences

Passive Condition

No significant interactions or main effects including hemisphere were found for either the children or the adults. This suggests that MMN was uniformly distributed across left and right hemispheric electrode sites.

Attend Condition

A significant main effect for electrode was found for the adults (F(2,16)=4.37, p=0.04, ε =0.88) and children (F(2,16)=4.16, p=0.04, ε=0.90) at C3-Cz-C4. No significant interactions were found for either group.

Post-hoc tests ($p<0.05$) of the main effect of electrode (C3-Cz-C4) for the adults revealed that the MMN response over the left hemisphere (C3) was significantly larger than the MMN elicited at midline (Cz). For the children the MMN response over the right hemisphere (C4) was larger in magnitude compared to the MMN response over the left (C3). Thus, MMN amplitude differences were observed for both groups at central electrode sites, but not at frontolateral electrode sites (FC5-Fz-FC6).

8.2.4 Between-Group ANOVAs Assessing Amplitude Across Time

As in Experiment 1, to determine whether MMN was elicited and differed across groups, 2-way mixed ANOVAs examining MMN amplitude were calculated separately for the Passive and Attend conditions comparing group (child/adult) by time (seven time intervals). Only the time intervals and electrode sites that were found to be significant for the within-group ANOVAs, and were not found to be significantly variable across group, will be examined.

Passive Condition

The following electrode sites and time intervals were examined because they satisfied the requirements of homogeneity of variance: Fz (131-310), Cz (101-130, 191-310), Pz (101-130, 191-310), C3 (251-280), C4 (101-130, 161-310), FC5 (101-310), CP5 (131-160, 251-310), and CP6 (101-130, 161-310).

A significant main effect of group was found only at CP5 (F(1,16)=5.09, p=0.04). The children showed a greater negative deflection in the difference waveform compared to the adults (Children: mean=-0.87, SD=1.01; Adults: mean=-0.07, SD=0.77). No additional significant interactions or main effects were observed. In sum, the MMN for the adults and children differed at only one left hemispheric electrode site.

Attend Condition

The following electrode sites and time intervals were examined because they satisfied the requirements of homogeneity of variance: Fz (221-250, 281-310), Cz (161-220, 251-310), Pz (251-310), C3 (221-310), C4 (161-190, 281-310), FC5 (281-310), FC6 (281-310), CP5 (221-310), CP6 (161-190), and RM (101-250).

The main effect of group was significant at Cz (F(1,16)=5.14, p=0.04), C4 (F(1,16)=10.46, p=0.005), and FC6 (F(1,16)=7.17, p=0.02). The children showed a greater negative deflection in the difference waveform compared to the adults (Children: Cz: mean=-1.03, SD=1.26, C4: mean=-1.24, SD=1.10, FC6: mean=-1.07, SD=1.07; Adults: Cz: mean=-0.31, SD=0.91, C4: mean=-0.16, SD=0.88, FC6: mean=0.09, SD=0.74). The main effect of time was significant at Cz (F(3,48)=4.33, p=0.03, ε=0.52). In both groups, time interval 191-220 ms was significantly more negative than time period 281-310 ms. In sum, the group comparisons revealed that the MMN was significantly larger over central and right hemispheric sites for the children compared to the adults. No difference was observed for the left hemispheric sites.

8.2.5 Scalp Current Density Maps

Figure 14 shows the SCD maps of the negativity in the grand mean waveforms for the adults (left) and children (right) for the Passive (top) and Attend (bottom) conditions.

The negative focus (or inward current flow) is illustrated by white contours and the black contours represent the positivity (or outward current flow) of the waveform. See Table 5 for a listing of the peak latencies used to create the grand mean and individual SCD maps.

The adults showed bilateral, frontocentral foci in both test conditions. In the Passive condition the amplitude of the negative foci was comparable across both hemispheres. In the Attend condition, stronger activation is seen over the left hemisphere. This is consistent with the significant increase in MMN amplitude found at FC5 in the Attend compared to the Passive condition. The right focus was similar across the Passive and Attend conditions.

The children showed bilateral central foci, with greater amplitude over the right hemisphere, in both test conditions. Furthermore, the foci of the children had greater amplitude (denser contour lines) compared to the foci of the adults. Lastly, the shape and distribution of the foci of the children was similar to that of the adults in the Passive condition. However, the distribution of the negative and positive foci differed across groups in the Attend condition. In the adults, the positivity is largest over the mastoids sites, whereas in the children it is largest more posteroinferior sites (O1, T6). This different distribution may be attributed to a different orientation of the neural source or to differential contribution of the activity measured at the scalp by the underlying sources.

Individual SCD maps were also examined in the present experiment to determine whether the topographical response patterns of the children were similar to those of the adults. In Experiment 1 the children's topographies were less uniform compared to the adults. Furthermore, in this experiment no significant MMN was found in the adults in the Passive condition. However, a negativity can be seen in the grand mean difference waveforms of both groups. Distinct negative foci can also be seen in the grand mean SCD maps across conditions in the children and adults. Taken together these findings suggest that MMN was elicited in both groups in the Passive condition. It may be the case that a few subjects who do show an MMN are dominating the response in the grand means. Thus, the SCD maps of the grand mean may not reflect the majority of the individuals. For this reason we examined SCD maps for each subject. Similar to Experiment 1, a time window of +/- 15 ms around the peak latency of the grand mean SCD maps was used (Passive: adults=224 ms [209-239 ms], children=213 ms [198-228 ms]; Attend: adults=205 ms[190-220 ms], children=220 ms [205-235 ms]).

Figure 15 (left) shows the SCD maps for each adult subject over the left and right hemispheres for the Passive condition. Seven of the nine adults (subjects 1-5) showed either a similar left hemispheric focal pattern over superior sites compared to the grand mean SCD maps or some negative activity over these sites (6, 7). The left hemispheric topography of the remaining subjects was either more posterior (8) or lateral (9) compared to the grand mean. Eight of the nine adults (1-4, 6, 9) showed either a similar right hemispheric response over superior sites compared to the grand mean or some negative activity over these areas (7, 8). Subject 5 showed negative activity at right inferior rather than superior electrode sites.

In the child group, six of the nine children (1-4; see Figure 15, right) showed similar left hemispheric superior foci compared to the grand mean SCD maps of the Passive condition or some negative activity over these regions (5, 6). The left hemispheric topography of the remaining subjects was either more lateroinferior (7) or superior-posterior (8) compared to the grand mean. Subject 9 showed no distinct negative focus over superior sites in the left hemisphere. Seven of the nine children (1-4, 6-8) showed similar right hemispheric superior foci compared to the grand mean. Subject 5, however, showed a right hemispheric negative focus that was more anterior compared to the grand mean, where as the focus of subject 9 was found over posterior parietal scalp regions.

Figure 16 shows the individual SCD maps when the subjects were asked to actively discriminate the stimuli (Attend condition). In general, the foci appear to be somewhat larger in amplitude in the Attend than the Passive condition (represented by denser contour lines). Seven of the adults (1-6, 9) showed similar left hemispheric superior foci to the grand mean SCD maps, with one additional subject showing some negative activity over this region (7). Subject 8 showed negative activity over the left hemisphere that was situated over anterior and posterior electrode sites. The right hemispheric superior foci of five of the adults (1, 3-5, 9) were similar to the grand mean. Two subjects showed some negative activity over these right hemispheric regions (2, 6). The response of the remaining two subjects (7, 8) showed negative activity that was more posterior than that found for the grand mean.

Four of the nine children (2, 5, 6, 8) were found to have similar lateroanterior focal patterns over the left hemisphere compared to the grand mean SCD maps in the Attend condition. Two children showed some negative activity over this left hemispheric region (1, 4). For the remaining children, the left hemispheric response was either more temporolateral (7) or superior-posterior (9) compared to the grand mean. No distinct left hemispheric focus was shown for subject 3. Eight of the nine children showed over the right hemisphere either a similar superior central focus (1, 2, 5, 6) to the grand mean SCD maps or some negative activity (3, 7-9). Subject 4 showed more lateroanterior negative activity compared to the grand mean.

Summary of Findings

In sum, attention to the auditory stream appeared to slightly enhance the amplitude of the MMN in the adults. This is illustrated by the denser contour lines, particularly over the left hemisphere. In addition, an increased number of the adult participants were found to have similar topographical patterns to the grand mean SCD maps over the left hemisphere in the Attend condition (n=7) compared to their responses in the Passive condition (n=5). This is consistent with the significant increase in MMN amplitude at FC5 when the adults actively discriminated the stimuli. Active discrimination did not appear to enhance the detectability of the MMN in the children, since fewer children showed topographical patterns similar to the grand mean in the Attend condition. However, the MMNs that were elicited by the children with attention appeared to be less variable over the right hemisphere compared to their pattern of response in the Passive condition. Appendix D displays the SCD maps of the children in the Passive and Attend conditions. As the children attended to the auditory stream, an increase in negative activity can be found over the right hemisphere, with all of the children showing right frontocentral negative activity.

9. Discussion

The behavioral data revealed similar category boundaries and pattern of identification across groups. Similar discrimination abilities were found across groups on the three deviant target discrimination task. The adults, however, were significantly better in discriminating the deviant in the one target discrimination task than the children. This slight difference is attributed to the percentage of false positive responses across groups (adults: 0.0%, children: 0.27%). The adults were also significantly better at discriminating the different pair in the same/different discrimination task. This slight difference is attributed to the greater error rate (i.e., false positive responses to the same pair) of the children compared to the adults (adults: 0.0%, children: 4.55%). Reaction times were similar across groups in the identification and one target discrimination tasks. In the three deviant and same/different discrimination tasks, the children responded significantly slower than the adults. These findings are consistent with Experiment 1, in which several behavioral tasks showed similar response performance for the children and adults. In the tasks in which the groups differed, the adults showed better behavioral performance.

The neurophysiological data failed to reveal a significant MMN in the adults in the Passive condition. This finding was surprising considering a negative response can be seen in the grand mean difference waveforms at the expected latency of the MMN (see Figure 13). In the Passive condition, the difference waveforms of the adults show two negative peaks. Two negative peaks can also be seen in the difference waveforms in the Attend condition for the adults (which was found to be significant). The first peak is likely to be N1 and the second negativity to be MMN. An alternate explanation of this complex, however, is that the first component is MMN and the second negativity is N2. This possibility is unlikely because inversion of polarity at the mastoids was present over the second peak. The N2 component does not invert in polarity below the Sylvian fissure (Picton et al., 2000). Furthermore, two peaks were elicited in the Passive condition. N2 is only elicited with active discrimination of the stimuli. The first peak was also elicited at approximately 100 ms, which is in the time frame of the N1 component. Thus, it can be concluded that the double peak is an enhanced N1 followed by MMN. However, this passively elicited MMN was not statistically significant in the within-group ANOVAs in the adults.

A possible explanation to account for the absence of a significant MMN in the adults in the Passive condition is that the probability of the deviant was too great to elicit a robust MMN. In the present experiment, the deviant occurred on 21% of the trials. As the probability of the deviant stimulus increases, the amplitude of the MMN decreases (Javitt, Grochowski, Shelley, and Ritter, 1998). It is unknown at this time whether the probability of the deviant affects children differently than adults. By increasing the probability of the deviant, the interdeviant time interval is reduced and fewer standards are presented between deviants. In the present study, it was often the case that the deviants were separated by as few as three to four standards. Due to the efficiency of the adults MMN mechanism, it may be the case that the adults created two memory traces, one for the standard stimulus and one for the deviant (Sabri and Campbell, 2001). Thus, MMN amplitude would be reduced due to the refractoriness of the MMN mechanism. However, the children's discriminative processes are not as efficient as an adults'. Thus, due to inefficient pre-attentive processing and limited memory capacity, it is likely that a single memory trace was created only to the standard stimuli. When the deviant was then presented, the processes underlying MMN successfully discriminated the deviant stimulus from the standard.

It is also possible that the differences observed across groups are attributed to the different resources used to elicit MMN. Due to the efficiency of the adult's discriminative processes it is possible that neuronal populations responding to phonetic properties were elicited. If so, then the same neuronal populations could have been elicited to both the standard and deviant stimuli since the vowels were phonetically-similar, causing the neurons to be refractory. However, due to the inefficiency of the child's MMN mechanism, they may rely on both phonetic and acoustic neurons in order to discriminate the stimuli. Thus, it is likely that different neuronal populations would be elicited to both the standard and deviant stimuli. The obligatory responses of the children were much larger than the adults suggesting that greater numbers of neurons were being elicited. Source analysis using an equivalent current dipole method (e.g., BESA) would be necessary to model potential sources of this activation.

Alternatively, it may be the case that since the standard is frequently presented, the neurons responding to the standard stimulus enter a state of refractoriness causing the amplitude of the response to the stimulus to decrease. In children, the neurons may enter a state of refractoriness sooner compared to adults. Studies that have examined the effect of rate of presentation on ERPs have shown greater refractoriness for children than adults (Čeponienė et al., 1998; Morr et al., in preparation). Thus, fewer standards are needed to reach an asymptote of refractoriness. Furthermore, the MMN response is embedded in the response to the deviant stimulus. In order to derive the MMN response, the ERP to the standard is subtracted from the ERP to the deviant. If the response to the standard is smaller for the children due to greater refractoriness, then the subtraction would yield a larger negativity in the difference waveform compared to the adults, whose ERPs to the standard and deviant may be more comparable in amplitude. Thus, it is possible that the amplitude of the subtraction waveform may have been larger in the children than adults due to the smaller ERP amplitude to the standard (associated with the greater refractoriness) resulting in the significant main effects for the children, but not for the adults. Further research is needed to determine the degree of refractoriness across different ages and how refractoriness is affected by different test conditions and stimulus types.

In the Passive condition for the children, the ERP to the deviant was significantly more negative than the ERP to the standard at frontocentral, parietal, and centrolateral electrode sites. This difference extended from 100-310 ms, with no significant peak within the interval. The MMN of the children was embedded in slow negative activity that continued beyond the 500 ms latency window. It is unclear at this time to what this negative activity can be attributed. It is possibly a correlate of the late discriminative negativity, which has been reported to follow the MMN in children (Cheour, Korpilahti, Martynova, and Lang, 2001). Others have suggested that a later negativity following MMN may be associated with "sensitization processes" after a stimulus change (for review see Alho, 1995). This later activity may serve as an automatic preparatory process for the detection of additional changes in stimuli. Further research is needed to determine this later negativity's role in auditory processing.

In the Attend condition, the ERP to the deviant was significantly more negative than the ERP to the standard at frontocentral and centrolateral electrode sites in the adults. Two significant negative peaks were observed. The first negative peak (e.g., C3 101-130 ms) may reflect an enhanced N1 (see Figure 13). The second negative peak (e.g., C3 at 161-250 ms) is MMN. The ERP to the deviant was significantly more negative than the ERP to the standard for the children at frontocentral and right hemispheric lateral sites. As in the Passive condition, this difference extended from 100-310 ms, with no significant peak within the interval.

In the present experiment, it was hypothesized that attention would enhance the MMN response of the children, but not of the adults. However, comparison of the Passive MMN to that elicited in the Attend condition revealed that attention to the auditory stream significantly enhanced the amplitude of the MMN in the adults at FC5. For the children the MMN amplitude at CP5 was found to decrease with attention. MMN amplitude has been found to increase in adults to difficult discriminations (see Attention Effects on MMN section). Thus, this finding is consistent with the adult literature. However, the absence of a significant increase in MMN amplitude with attention in the children was unexpected.

The absence of predicted significant differences across test conditions for the children may be attributed to the variability of the responses. In the first experiment, the majority of the electrodes sites and time intervals examined revealed that the children were more variable in the amplitude and latency of the most negative interval in the time frame of the MMN compared to the adults. In the present experiment, the children were also found to have significantly greater variability in the amplitude of the subtraction waveform than the adults, within the expected latency of the MMN. This increased variability for the children compared to the adults was observed more for the ERPs elicited in the Attend condition compared to their responses in the Passive condition (See Appendix C for a summary of the F-value's). Thus, variability in the amplitude and latency of the negativity of the children contributed to the absence of significant increases in MMN amplitude with attention.

No significant hemispheric differences were found for either group, except in the Attend condition. MMN amplitude differences were observed for both groups at central electrode sites, but not at frontal electrode sites. For the adults, results revealed that the MMN response over the left hemisphere (C3) was significantly larger in magnitude than the MMN elicited at midline (Cz). A greater left hemispheric amplitude to speech sounds is consistent with a number of papers (e.g., Näätänen et al., 1997). For the children, the MMN response over the right hemisphere (C4) was significantly larger compared to the MMN response over the left (C3). This finding suggests that children may rely on different neural sources for processing speech sounds compared to adults.

As in the first experiment, SCD maps were created to examine topographical response patterns across groups. Individual maps were also examined to determine whether the response patterns of the children were similar to that of the adults. The grand mean SCD maps revealed bilateral frontocentral foci in the adults in both test conditions. In the Passive condition, the amplitude of the negative foci was comparable across hemispheres. In the Attend condition, the amplitude of the negative foci increased over the left hemisphere. This is consistent with the significant increase in MMN amplitude found at FC5 across test conditions. In addition, more adults showed similar topographical patterns to the grand mean SCD maps over the left hemisphere in the Attend condition (n=7) compared to their responses in the Passive condition (n=5). The left hemispheric dominance is also consistent with the findings of Experiment 1 and other ERP studies examining brain responses to speech sounds (e.g., Näätänen et al., 1997).

Bilateral central negative foci were found in the children, with greater amplitude over the right hemisphere in both test conditions. A right dominant scalp distribution has been observed by other researchers, although, generally in response to tonal changes (for review see Picton et al., 2000). Variability in scalp distribution has been previously observed in response to speech sounds in adults (Maiste, Wiens, Hunt, Scherg, and Picton, 1995). It may be the case that the right hemispheric dominance of the children in the present experiment is attributed to the variability of the MMN response in the children tested in the present experiment. Furthermore, MMN is generated from a number of cortical regions that may mature at different rates among different children (Martin et al., 2001). Thus, the different topography may reflect differential refractoriness of these regions due to immaturity. Few studies, however, have been conducted examining scalp distribution of the MMN in children. More research is needed examining whether the topography of the MMN changes with age and whether it is influenced by context factors or stimuli. The foci of the children were also greater in amplitude compared to the adults. This is consistent with the significant between-group differences in which the children showed a greater negative deflection in the difference waveform compared to the adults. The shape and distribution of the negative and positive foci was similar across groups in the Passive condition. However, the distribution of the foci differed across groups in the Attend condition. This difference in distribution may be attributed to a different orientation of the neural mechanism.

Active discrimination did not appear to enhance the detectability of the MMN in the children as it did for the adults. However, the MMN responses over the right hemisphere appeared to be less variable in the Attend compared to the Passive condition (see Appendix D). In the Attend condition, an increase in negative amplitude was seen over the right hemisphere, with all of the children showing right frontocentral negative activity. This pattern in the SCD maps was confirmed by statistical tests in which MMN was found to be significantly larger at C4 compared to C3. This difference in MMN amplitude across hemispheres was not found in the Passive condition.

In the present experiment, the statistical analyses and inspection of the SCD maps both lead to the conclusion that MMN was elicited to the speech stimuli in the Passive and Attend conditions. For adults, attention to the auditory modality appeared to slightly enhance the amplitude of the MMN over the left hemisphere (i.e., at FC5). For the children, attention to the auditory stream appeared to improve the detectability of the MMN over the right hemisphere in the SCD maps. However, no significant difference in MMN amplitude was found for the children across test conditions, as observed for the adults. Although the effect of attention on MMN was slight in the present experiment, it is still consistent with the literature that suggests that attention to the auditory stream can enhance MMN amplitude. Furthermore, similar to Experiment 1, the observations of topographical differences and greater variability in amplitude and latency for children than adults supports the argument that MMN continues to mature beyond the school-age years. Lastly, under certain test conditions MMN does not appear to correlate with behavioral performance. In the present experiment, the behavioral performance of both groups on the majority of the behavioral tasks was found to be similar. Yet, several differences were found in the ERPs across groups. In particular, differences in topography and lateralization were found.

10. General Discussion

The present dissertation was undertaken to provide more information about the development of the brain's discriminative processes as indexed by MMN, how these processes relate to behavioral findings, and the affect of attention on the discriminative processes. In Experiment 1, we hypothesized that children and adults would show similar identification and discrimination abilities. Similar categorical perception was observed across groups. We also observed similar discrimination performance for the children and adults when the vowel [ε] served as the standard. However, when [I] served as the standard, the adults showed slightly better discrimination. Reaction time was similar across groups in the identification task, but significantly slower for the children in the discrimination task.

We also predicted that the children would show longer MMN latencies compared to the adults. However, no significant MMN was found for the children in either test condition. Nevertheless, the findings are consistent with other studies (e.g., Shafer et al., 2000) in that differences in the ERPs were found for the children and adults. These differences suggest that the neural processing of these vowel stimuli is immature in children. In particular, SCD maps revealed differences in the topographical patterns for the children and adults. The majority of the individual SCD maps from the adults showed a similar scalp topography of the negative activity to the grand mean. The topography of the negativity of the children, however, was less uniform than for the adults. The children's topographical response patterns were also more uniform when [I] served as the standard stimulus than when [ε] served as the standard. The children also showed significantly greater variability than the adults in the amplitude of the difference waveform in the latency range of the MMN. This variability may have led to the absence of a significant negativity in the time interval of the MMN.

The evidence supporting developmental differences in MMN is inconsistent at this time. The results of Experiment 1 support the claim that MMN is not mature until beyond the school-age years (e.g., Morr et al., 2002; Shafer et al., 2000). This experiment also provides further evidence that under certain test conditions behavioral performance is not directly related to the processes indexed by MMN.

Experiment 2 was conducted to follow-up the question of whether the differences observed between the behavioral and neurophysiological (i.e., MMN) findings in Experiment 1 were associated with the absence of attention during the electrophysiological recordings and to determine whether simplifying the paradigm by using one deviant would elicit a clear MMN. Similar to Experiment 1, we hypothesized similar behavioral performance across groups. Our predictions were supported by the similar identification performance across groups. Discrimination abilities were also similar for the children and adults for the three deviant target discrimination test. In the one target discrimination task, the adults were significantly better than the children in discriminating the deviant, although, this slight difference is attributed to the percentage of false positive responses across groups (adults: 0.0%, children: 0.27%). In the same/different task, the adults showed significantly better discrimination of the different pair compared to the children. This slight difference is also attributed to a greater error of the children compared to the adults (adults: 0.0%, children: 4.55%). Reaction times were similar across groups in the identification and one target discrimination tasks. In the three deviant and same/different discrimination tasks, the children responded significantly slower than the adults. These findings are consistent with Experiment 1, in which several behavioral tasks showed similar performance across groups. In the tasks in which the groups differed, the adults showed better behavioral performance.

Differences in the electrophysiological data and SCD maps were observed across groups. This is consistent with Experiment 1 in which differences in the ERPs and topography were seen between the children and adults. In the second experiment, we hypothesized that simplifying the paradigm by using one target deviant would enable us to elicit a passive MMN in the children. A negativity was, in fact, found for the children at frontocentral, parietal, and centrolateral electrode sites. However, no MMN was found for the adults. Thus, a different effect was found for the adults by simplifying the paradigm in this fashion. This difference may be attributed to the refractoriness of the MMN generator in the adults. Since a large deviance probability was used, as few as three to four standards were often presented between deviants. It may be the case that due to the efficiency of the adult's discriminative mechanisms, two memory traces were created (one to the standard stimulus and one to the deviant; Sabri and Campbell, 2001). However, due to inefficient pre-attentive processing or limited memory capacity of the children it is likely that only one memory trace was created to the standard stimuli. Thus, a clear MMN was elicited to the infrequent deviant stimulus.

It is also possible that the differences observed across groups may be attributed to the neuronal resources activated. It may be the case that in the adults, phonetic neurons were elicited to discriminate the vowels. Due to the phonetic-similarity of the vowels similar neuronal populations would have been elicited to both the standard and deviant stimuli, which would then cause the neurons to be refractory. Due to the inefficiency of the child's discriminative processes, both phonetic and acoustic neurons would be activated. Thus, it is likely that different neuronal populations would be activated to both the standard and deviant stimuli. Larger obligatory components were found in the children compared to the adults suggesting that greater numbers of neurons were being activated.

Alternatively, this difference may be attributed to a greater neuronal refractoriness for the children compared to the adults when using a large deviance probability. As deviance probability increases, the number of standards between each successive deviant decreases. Because the standard stimulus is frequently presented, the neuronal populations responding to the standard enters a state of refractoriness causing the amplitude of the ERP to decrease. In children, neurons may enter a state of refractoriness sooner than adults. Thus, in children fewer standards are needed to reach an asymptote of refractoriness. In order to derive the MMN, the ERP from the standard is subtracted from the ERP to the deviant. If the ERP to the standard stimulus is smaller for children due to greater refractoriness, then the subtraction would yield a larger negativity in the difference waveform compared to adults, whose ERPs to the standard an deviant would be more comparable in amplitude. Greater neuronal refractoriness for children than adults has been found in studies examining rate of presentation (Čeponienė et al., 1998; Morr et al., in preparation).

For the second experiment, we had also predicted that attention to the auditory modality would enhance the MMN in the children, but not in the adults. The findings of this experiment, however, do not confirm this prediction. Active discrimination significantly enhanced the amplitude of the MMN only for the adults over the left hemisphere at FC5. For the children, attention to the auditory modality did not statistically enhance the MMN. However, SCD topography appeared to indicate a more uniform response over the right hemisphere for the children. This observation is consistent with a significantly larger MMN amplitude at C4 compared to the MMN elicited at C3 in the Attend condition. Variability was also examined in the second experiment. The children showed significantly greater variability in the amplitude of the difference waveform in the latency range of the MMN, particularly in the Attend condition. This large variability may have led to the absence of significant differences across test conditions in the time interval of the MMN.

The effect of attention on MMN was slight in the second experiment. Nevertheless, the findings observed are still consistent with the literature that suggests that attention to the auditory stream can modify MMN amplitude. The data of the present experiment is also consistent with Experiment 1 supporting the claim that MMN is not mature by school-age and that under certain test conditions behavioral and electrophysiological responses are not related.

10.1 MMN as a Clinical Tool

To date, the auditory brainstem response (ABR) is the most widespread electrophysiological method used in the clinical setting to evaluate functional brain activity of infants and children. The ABR can be used to assess hearing sensitivity and the functional integrity of the VIIIth nerve and brainstem. However, using ABR limits the assessment to the peripheral and brainstem portions of the auditory pathway. It has been suggested that the combined use of ABR and cortical auditory evoked potentials (CAEP) would provide a more complete assessment of the auditory pathway (Stapells and Kurtzberg, 1991). CAEPs are brain potentials that index processing from the supratemporal auditory cortex (Sams, Kaukoranta, Hämäläinen, and Näätänen, 1991) and can be elicited to complex stimuli (e.g., speech sounds). CAEPs, however, can only be used to analyze the physical features of a single stimulus. For this reason, there has been a great deal of interest in determining whether MMN can be used as an objective measure to evaluate the neural mechanisms involved in the processing and discrimination of fine-grained acoustic/phonetic differences of auditory stimuli by infants and children.

However, before MMN can be considered clinically useful many questions need to be addressed. The data from both experiments of the present dissertation corroborates the claim that MMN continues to mature during the school-age years (e.g., Shafer et al., 2000). To date, however, there are only a few studies that have compared MMN between adults and children (see MMN in Children section) and even fewer that have tested infants (e.g., Morr et al., 2002; Cheour-Luhtanen et al., 1996). By examining the maturation of MMN we can make inferences concerning the time-course of the development of auditory sensory memory and discriminative abilities. In addition, if MMN is to be considered useful as an objective measure, any changes of the MMN across age need to be determined. Presently, only one known study has examined the maturation of MMN across age in response to tones (Shafer et al., 2000). Longitudinal and/or cross-sectional studies examining MMN to speech stimuli, however, need to be conducted.

This dissertation has also shown that under certain test conditions the MMN elicited in children can be significantly more variable than the MMN of adults, making identification more difficult. Other studies that have examined MMN in children and adults in response to speech sounds, and found no difference or larger MMNs in the children, used synthesized stimuli (see MMN in Children section). Maiste and colleagues (1995) used synthesized CV syllables that were based on naturally-produced speech stimuli. They reported variability of the scalp distributions of the adult MMN to these sounds. Thus, the differences in findings with the children in this study and the studies by other researchers (e.g., Kraus, McGee, Carrell et al., 1993; Kraus, McGee, Micco et al. 1993) may be due to differences in stimulus properties. More research needs to be conducted examining the relationship between MMN and stimulus properties.

The use of subjective examination of the ABR (i.e., comparing the response of the patient to normative reference values, such as interpeak latency, peak-to-peak amplitude, waveform morphology, and peak presence) is consistently practiced in the clinical setting. However, the results of the present dissertation suggest that subjective examination is unreliable because of the variability in the responses of the children. Objective measures for identifying MMN have been proposed (for review see Sinkkonen and Tervaniemi, 2000). Sinkkonen and Tervaniemi (2000) suggest that perhaps it may be more useful to identify MMN responses as atypical when compared to normative data, as opposed to identifying MMN as present vs. absent. One criteria used in ABR examination is to determine whether the patient's responses differ from the normative data used as reference. In the present dissertation, in some cases we observed a dominant topographical pattern for the two groups (e.g., the children's right hemispheric responses were more uniform in the Attend than the Passive condition). However, a larger number of participants need to be examined to identify the variation in topography in typically-developing subjects. Thus, to date there is no consensus on which method of MMN identification is best.

In sum, the clinical use of MMN at this time is limited at best. Little is known about the maturational time-course of MMN to speech and how MMN relates to auditory processing. In addition, MMN is not reliably elicited in individual subjects who have been shown to behaviorally discriminate these same sounds. Furthermore, results of both experiments have shown essentially similar behavioral perceptual abilities for the children and adults to the vowels used in the present dissertation, yet different neurophysiological responses. Future studies will be needed to determine how MMN is related to auditory processing and discrimination and why behavioral and MMN responses do not always correspond.

Using an Attend MMN Paradigm in the Clinical Setting

In Experiment 2, active discrimination of the auditory stream slightly enhanced MMN amplitude in the adults. Attention did not appear to enhance MMN amplitude in the children. However, the MMN of the children appeared to be less variable over the right hemisphere compared to their pattern of response in the Passive condition. Attention to the auditory modality appeared to increase the negative activity found over the right hemisphere, with all of the children showing right frontocentral negative activity (see Appendix D).

These results indicate that an attention task is inappropriate for the clinical setting at this time because it does not substantially improve the detectability of the MMN. Gomes et al. (2000) found a significant increase in MMN amplitude with attention in children in response to difficult frequency changes, but not to easy or moderately-difficult deviants. Similar increases in MMN amplitude were not observed in adult subjects. Thus, it appears that stimulus properties play a part in the effect of attention on the MMN. Further research is needed to determine for what stimulus properties attention is necessary for discrimination.

Using SCD Mapping in the Clinical Setting

In the present dissertation SCD mapping was used to illustrate topographical differences across groups, across deviant types, across test conditions, and across individual subjects. It has been argued that MMN identification may be difficult in individual subjects. Although, we often observed a consistent topographical response pattern in a single test condition, a dominant pattern was not seen across all of the test conditions in the present dissertation. Under certain test conditions the combined use of examining ERP waveforms and SCD maps may prove useful. If atypical processing can be shown in an individual using two different measures it would increase the reliability of the diagnosis and reduce the false negative rates.

Furthermore, SCD maps may be more sensitive than the standard statistical methods used in the ERP literature. These standard methods (ANOVAs) treat each electrode site as an independent measure. In contrast, SCD analyses utilize information from all of the electrode sites. Thus, the maps show patterns that cannot be observed by examining individual sites. For example, the individual SCD maps in Experiment 1 suggest that MMN was elicited in the children as well as adults. Yet, no significant MMN was found for the children. In Experiment 2, the SCD maps of the individual children varied less in topography in the Attend than in the Passive condition. However, the within-group ANOVAs did not reveal a significant increase in MMN amplitude with attention. It will be important in the future to develop statistical methods that can make use of all of the information. Future research will need to be conducted to examine the clinical value of SCD mapping.

10.2 Is MMN an index of acoustic or phonetic processing?

In Experiment 1, two across-boundary and one within-boundary deviant were presented in each test condition. The intent for using a paradigm with deviants that were across and within-phonetic-category boundary from the standard was to examine whether MMN indexed a discriminative process affected by phonetic properties. Significant MMN responses were observed in the adults at frontal, lateral, and parietal sites to the extreme stimuli presented (standard=9, deviant=3; standard=3, deviant=9) and to the intermediate across-boundary vowel in Condition 2 (standard=3, deviant=7). No significant within-category MMN was found.

The absence of an MMN to the within boundary contrasts supports the hypothesis that the discriminative processes indexed by MMN is influenced by phonetic properties. Further evidence to support the claim that phonetic properties affect automatic brain discrimination is the research that has shown larger or earlier MMN responses to native phonemic distinctions compared to non-native phonemes (e.g., Shafer et al., submitted; Winkler et al., 1999; Näätänen et al., 1997). While the pattern of the results observed in Condition 2 (standard=3) is consistent with a phonetic influence, the failure to elicit an MMN in Condition 1 (standard=9) to deviant stimulus 5 (across boundary) in the adults does not support this hypothesis. Behaviorally, adults easily discriminated stimulus 5 from 9. Thus, a robust MMN comparable to that elicited to stimulus contrast 3 vs. 9 should have been observed. Furthermore, a significant MMN was not observed in the children despite having similar behavioral identification and discrimination abilities to the adults. These findings suggest that MMN does not reflect phonetic differences between stimuli in a straightforward manner.

It may be the case that the absent MMN response of the adults to the within-boundary contrast pairs suggests that MMN is not sensitive to very small changes between standard and deviant stimuli. Other researchers, however, have reported an MMN response to synthetically-produced, within-category stimulus contrasts in adults (Sharma and Dorman, 1998; Sharma et al., 1993; Dalebout and Stack, 1999) and children (Kraus, McGee, Micco et al. 1993). Sharma and Dorman (1998) elicited MMN in response to a within-phonetic-category vowel difference that subjects were shown to behaviorally discriminate. Sharma et al. (1993) elicited MMN to a within-boundary CV deviant that was similar in latency, amplitude, and area to MMN elicited to an across-boundary deviant of the same acoustic differences, suggesting that MMN reflects the processing of acoustic parameters. In the study conducted by Dalebout and Stack (1999), the subjects could not behaviorally discriminate the CV within-category stimuli, yet MMN was still elicited. Kraus, McGee, Micco et al. (1993) reported significantly larger MMN magnitudes in children compared to adults to a within-category CV contrast. This difference in MMN amplitude across groups is likely attributed to maturational differences in the ERPs. Results on a discrimination task revealed chance performance for the children (53.2%) and slightly better performance for the adults (64.6 %). The finding of a robust MMN in both groups is interesting since both the children and adults performed at or near chance levels on the behavioral task. Furthermore, the adults appeared to behaviorally discriminate the speech sounds slightly better than the children, yet their MMNs were found to be significantly smaller. These findings are more consistent with the claim that MMN reflects acoustic processing.

Thus, the failure to observe a clear MMN to the within-category contrast in either group in this dissertation may be associated with the nature of the stimuli. The former studies used synthetically-produced speech sounds. The stimuli used in the current study maintained some of the natural acoustic information of natural speech sounds. Similar to this dissertation, preliminary data from our lab reveals that no clear MMN was elicited in children to CV syllables /da/ vs. /ba/. Instead, a late negativity was observed in the child listeners. Small MMN responses were found for the adults (Maul et al., 2001). These CV stimuli were created in the same manner as the vowels used in this dissertation.

Maiste and colleagues (1995) also presented CV syllables that were derived from naturally-produced speech. Similar to our first experiment, they found asymmetries of the MMN that varied depending on the direction of the stimuli presented (/ba/ standard vs. /da/ deviant; /da/ standard vs. /ba/ deviant). One argument offered by Maiste et al. (1995) to account for the asymmetry in MMN amplitude is that it was due to the frequency components of the stimuli (i.e., the presence of certain frequencies within the deviant that were not present in the standard due to the information in the formant frequency transitions). However, in the present study the response asymmetry cannot be explained by a stimulus asymmetry because the vowels used were steady-state and the standard and deviant stimuli differed in all of the conditions presented.

An alternate hypothesis is that the asymmetry may be related to whether the standard was a good exemplar of its vowel class. Maiste et al. (1995) suggested that if the standard stimulus was situated too close to the categorical boundary, a clear memory template of the standard may not be created. According to a Goodness Rating we conducted vowel sound 9[ε] was considered a better exemplar of its vowel class compared to 3[I], even though the adult listeners identified the vowels equally well. However, no MMN was elicited in the adults when 5[I] was the deviant and 9[ε] was the standard, but an MMN was elicited when 7[ε] served as the deviant and 3[I] as the standard. It is possible that the Goodness Rating was biased by a greater number of vowels identified as [I]. Of the nine stimuli from the continuum, six were identified as vowel sound [I]. Therefore, when [ε] was presented to the subject, among a larger number of [I] vowels, it may have been perceived as a clearer exemplar of its vowel class. It is important to note, however, that vowel stimulus 9 was not situated near the category boundary and was clearly identified (98%) as an [ε].

In sum, there does not appear to be any clear evidence from this experiment supporting the claim that MMN reflects discriminative processes influenced by phonetic properties. There is, however, convincing evidence of the influence of phonemic processes on MMN latency and amplitude (e.g., Shafer et al., submitted; Winkler et al., 1999; Näätänen et al., 1997). Thus, the failure to see an effect of phonetic factors in the current study indicates that further research is needed to understand how different stimulus properties affect the brain's discriminative response as indexed by MMN. Whether the 'naturalness' of the stimuli used in the present dissertation contributed to the differences observed is only speculative. Future studies need to be conducted directly comparing MMN to purely synthetic vs. more natural-sounding speech stimuli.

Research has also shown that the orientation of the generators of the discriminative processes indexed by MMN differs according to acoustic properties being discriminated, such as intensity, frequency, and duration (for review see Alho, 1995). Therefore, one population of neurons is not responsible for MMN elicitation. Thus, under different test conditions using various stimuli (i.e., tones vs. speech; simple vs. complex; synthetic vs. naturally-produced speech sounds), different neuronal populations are activated and can be contributing to the MMN response. Further research is needed to determine how the various neuronal populations contribute to the MMN response.

10.3 What accounts for the dissociation between the behavioral and neurophysiological findings?

The behavioral data were found to be similar on the identification tasks for both experiments and on several of the discrimination tasks for the children and adults, yet neurophysiologically their responses differed. As reviewed in the Discussion section of Experiment 1, two factors differed between the behavioral and electrophysiological conditions: attention and rate of presentation. During the behavioral task, the subject was asked to attend to the stimuli and make a decision. However, in the ERP condition the subject's attention was directed away from the auditory stimuli. Therefore, attention may have contributed to the differences observed across test conditions. One purpose of the second experiment was to examine attention effects on MMN.

Studies have shown an enhancement of MMN amplitude to difficult discriminations in adults (see Attention Effects on MMN section). The stimuli presented in this dissertation can be considered difficult to discriminate because they are acoustically similar in frequency. Research has also shown differential effects of attention on MMN amplitude with age. MMN amplitude was found to increase for children with active discrimination of difficult frequency discriminations, but not for adults (Gomes et al., 2000). Thus, one of our hypotheses was that MMN amplitude would increase with attention to the auditory modality, with greater amplitude increases for the children than the adults.

However, our hypothesis was not supported by the findings reported in the second experiment. Instead, we found that attention to the auditory stream only slightly enhanced MMN in the adults over the left hemisphere at FC5. For the children, attention to the stimuli appeared to increase the amplitude of the MMN over the right hemisphere. However, this increase can only be seen in the SCD maps and was not found in the statistical analyses.

The absence of an increase in MMN amplitude for the children and the enhancement of the MMN in the adults may be attributed to the deviance probability used in Experiment 2. No significant negativity was found for the adults in the Passive condition, yet MMN was elicited in the Attend condition. For the children, a negativity was elicited in both test conditions. It may be the case that the absence of a significant MMN in the adults in the Passive condition can be attributed to the large deviance probability, which prevented the elicitation of a robust MMN. The probability of the deviant used in Experiment 2 was 21%. As the probability of the deviant stimulus increases, the MMN amplitude decreases (Javitt et al., 1998). It is unknown at this time whether deviance probability affects MMN amplitude differently in children compared to adults. Further research is needed to examine this issue.

The effect of rate of presentation on MMN has not been addressed in this dissertation. An SOA of 2 s was used for the behavioral tasks in order to allow the subject adequate time to respond before the presentation of the next stimulus. In the electrophysiological paradigm, a long SOA was not needed and therefore 600 ms was used in order to reduce the test time for the ERP session. Research has shown that rate of presentation affects the MMN differently for adults and children (Gomes et al., 1999; Morr et al., in preparation). In the present experiments, the relatively rapid SOA of 600 ms may have been too fast to allow the child sufficient processing of the difficult speech stimuli. The brain of the child may have needed more time to recover between stimulus presentations. A study needs to be conducted in which both the behavioral and electrophysiological conditions use the same SOA to determine whether the differences in findings are related to rate of presentation.

In sum, the relationship between behavioral and electrophysiological responses could not be completely determined from the results of this dissertation. Gomes et al. (2000) suggested that the child's pre-attentive mechanisms may be unable to sufficiently process difficult discriminations. In complex listening environments, a child will need to actively attend to stimuli in order to discriminate the sounds. Therefore, it may be the case that behavioral and MMN findings are not directly related, at least in childhood, and differences across groups may be attributed to immature pre-attentive mechanisms. However, adult studies have also shown a dissociation between behavioral and MMN findings (see MMN Association with Behavioral Findings section). Additional research is needed to determine the relationship between the brain's discriminative responses as indexed by MMN and behavioral responses.

11. Conclusions

Currently, little is known about the maturation of the brain's discriminative responses as indexed by MMN. In addition, the relationship between behavioral discrimination and the MMN response remains unclear. The results of the present dissertation supports the claim that the brain's discriminative responses, as indexed by MMN, continues to mature during the school-age years and that under certain test conditions MMN and behavioral performance are not directly related. In Experiment 2, attention to the auditory stream was also observed to slightly modify MMN amplitude. This finding suggests that attention-related mechanisms can alter the discriminative processes indexed by MMN. However, the effect was different for the children compared to the adults. MMN amplitude was also found to be significantly more variable for the children compared to adults in both experiments. Thus, the clinical usefulness of MMN at this time is limited at best. However, the possibility of an objective brain component that is elicited to discriminatory changes that indexes auditory memory is worthy of extensive investigation. Future studies will need to be conducted to address the questions raised in this dissertation.

Table 1. Standard scores for the child subjects from Experiment 1 on the CELF receptive (R) and expressive (E) language tests and their nonverbal skills (TONI).

Subject	CELF-R	CELF-E	TONI
1	116	-----	111*
2	116	104	103
3	125	118	105
4	92	102	102
5	114	118	121
6	94	102	89
7	120	110	95
8	114	108	103
9	96	102	100
10	104	94	130

Note. The expressive language of Subject 1 was not examined using the CELF-E. Instead, the the CELF formulated sentences test was used. The score of Subject 1 was found to be in the 75th percentile, which is considered a high average score. The asterisk indicates that the non-verbal skills of Subject 1 were examined using the Stanford Binet test rather than the TONI.

Table 2. Re-synthesized edited natural vowel sounds [I]- [ε]. F1 increased by 25 Hz steps, while F2 decreased by 30 Hz steps. Formants 3 and 4 were kept constant throughout the nine-step continuum. Stimuli 3, 5, 7, and 9 were chosen for testing in order to examine across- and within-phonemic category.

	1	2	**3**	4	**5**	6	**7**	8	**9**
	I	I	I	I	I	I	ε	ε	ε
F1 +25 Hz			500		550		600		650
F2 -30 Hz			2160		2100		2040		1980
F3			2714		2714		2714		2714
F4			3175		3175		3175		3175

Table 3. Peak latencies for the grand mean and individual SCD maps of Experiment 1. Subject age is also indicated.

Adults				Children			
Cond 1: Standard=9[ε], Deviant=3[I]							
Grand Mean PL=176 ms				Grand mean PL=218 ms			
Cond 2: Standard=3[I], Deviant=9[ε]							
Grand Mean PL=175 ms				Grand mean PL=210 ms			
Subject	Age	Cond 1: PL	Cond 2: PL	Subject	Age	Cond 1: PL	Cond 2: PL
1	31;2	176	176	1	9;11	220	210
2	26;4	191	185	2	8;8	220	210
3	27;2	177	168	3	9;10	233	216
4	36;6	172	167	4	9;8	208	214
5	31;7	173	164	5	10;3	214	216
6	22;10	166	166	6	9;0	216	214
7	26;5	175	170	7	8;9	206	216
8	30;11	181	186	8	10;0	210	223
9	29.9	162	183	9	9;10	216	225
10	------	-----	-----	10	10;5	231	225

Note. The most negative peak was chosen in the interval. Cond=Condition, PL=Peak Latency

Table 4. Standard scores of the child subject's from Experiment 2 on the CELF receptive (R) and expressive (E) language tests and their nonverbal skills (TONI).

Subject	CELF-R	CELF-E	TONI
1	100	92	103
2	104	135	105
3	131	110	104
4	114	125	123
5	120	116	140
6	104	100	93
7	98	98	108
8	114	116	135
9	106	96	100

Table 5. Peak latencies for the grand mean and individual SCD maps of Experiment 2. Subject age is also indicated.

Adults	Children
Passive Condition	
Grand Mean PL=224 ms	Grand mean PL=213 ms
Attend Condition	
Grand Mean PL=205 ms	Grand mean PL=220 ms

Subject	Age	Passive: PL	Attend: PL	Subject	Age	Passive: PL	Attend: PL
1	28;9	217	205	1	8;10	210	235
2	26;0	216	195	2	8;8	204	217
3	22;11	235	197	3	8;11	198	220
4	29;1	209	203	4	8;3	208	220
5	30;3	237	220	5	8;9	228	210
6	44;6	233	218	6	10;0	228	220
7	45;4	218	203	7	9;9	198	225
8	27;8	238	208	8	10;2	210	205
9	31;4	209	195	9	9;2	202	207

Note. The most negative peak was chosen in the interval. PL=Peak Latency

Figure Legends

Figure 1. Superset of the International 10-20 electrode system.

Figure 2. Mean and standard deviations (illustrated by the error bars) of the adults (top) and children (bottom) from the identification task for Experiment 1. The identification scores and reaction times for [I] is on the left and for [ɛ] is on the right. The black bars represent the response of the subject group, while the gray line represents the reaction time.

Figure 3. Mean and standard deviations (illustrated by the error bars) of the adults (top) and children (bottom) from the target discrimination task for Experiment 1. The discrimination scores and reaction times for when [ɛ] served as the standard stimulus is on the left and for when [I] served as the standard is on the right. The black bars represent the response of the subject group, while the gray line represents the reaction time.

Figure 4. The grand mean ERPs to the standard and deviant stimuli at C3 for Conditions 1 (standard=9[ɛ]; left) and 2 (standard=3[I]; right) for Experiment 1. The ERP waveforms elicited to the greatest acoustical difference are on top (i.e., 9 vs. 3) progressing to the within-category stimulus comparison on the bottom (i.e., 9 vs. 7 and 3 vs. 5). The children are illustrated in black and the adults in gray.

Figure 5. The grand mean difference waveforms at C3 for Conditions 1 (standard=9[ɛ]; left) and 2 (standard=3[I]; right) for Experiment 1. The tiled difference waveforms are consistent with the ERPs illustrated in Figure 4. The difference waveforms to the greatest acoustical difference are on top (i.e., 9 vs. 3) progressing to the within-category stimulus comparison on the bottom (i.e., 9 vs. 7 and 3 vs. 5). The children are illustrated in black

and the adults in gray. The suspected MMN is the negative peak falling between 100-250 ms.

Figure 6. SCD maps of the grand mean difference waveforms for both test conditions and for the across-category deviant types of the adults (left) and children (right) in Experiment 1. The white speckled fill represents the negativity or inward current flow. The black unfilled contours illustrate the positivity or outward current flow. The amplitude of the SCD maps was set at 0.5 μV/cm^2.

Figure 7. SCD maps of the difference waveforms of the adults (left) and children (right) for Condition 1 when 9[ε] served as the standard and 3[I] as the deviant for Experiment 1. The white speckled fill represents the negativity or inward current flow. The black unfilled contours illustrate the positivity or outward current flow. The amplitude of the SCD maps was set at 0.5 μV/cm^2.

Figure 8. SCD maps of the difference waveforms of the adults (left) and children (right) for Condition 2 when 3[I] served as the standard and 9[ε] as the deviant for Experiment 1. The white speckled fill represents the negativity or inward current flow. The black unfilled contours illustrate the positivity or outward current flow. The amplitude of the SCD maps was set at 0.5 μV/cm^2.

Figure 9. Mean and standard deviations (illustrated by the error bars) of the adults (top) and children (bottom) from the identification task for Experiment 2. The identification scores and reaction times for [I] is on the left and for [ε] is on the right. The black bars represent the response of the subject group, while the gray line represents the reaction time.

Figure 10. Mean and standard deviations (illustrated by the error bars) of the adults (top) and children (bottom) from the target discrimination task for Experiment 2. The discrimination scores and reaction times for the three target discrimination is on the left and for the one target discrimination is on the right. The black bars represent the response of the subject group, while the gray line represents the reaction time.

Figure 11. Mean and standard deviations (illustrated by the error bars) of the adults (top) and children (bottom) from the same/different discrimination task for Experiment 2. The response to the different pair is on the left of the figure, the false positive responses to the same pair is in the middle, and the percentage of missed different pairs is on the right. The black bars represent the response of the subject group, while the gray line represents the reaction time.

Figure 12. The grand mean ERPs to the standard and deviant stimuli (left) at C3 for the Passive (top) and Attend (bottom) conditions for Experiment 2. The children are illustrated in black and the adults in gray.

Figure 13. Grand mean difference waveforms from central electrode sites (C3, C4) for the adults (left) and children (right) in Experiment 2. The difference waveforms from the Passive condition are illustrated by the dotted line and the responses from the Attend condition by the solid lines.

Figure 14. SCD maps of the grand mean difference waveforms for the Passive (top) and Attend (bottom) conditions of the adults (left) and children (right) in Experiment 2. The white speckled fill represents the negativity or inward current flow. The black unfilled contours illustrate the positivity or outward current flow. The amplitude of the SCD maps was set at 0.5 $\mu V/cm^2$.

Figure 15. SCD maps of the difference waveforms of the adults (left) and children (right) for the Passive condition for Experiment 2. The white speckled fill represents the negativity or inward current flow. The black unfilled contours illustrate the positivity or outward current flow. The amplitude of the SCD maps was set at 0.5 $\mu V/cm^2$.

Figure 16. SCD maps of the difference waveforms of the adults (left) and children (right) for the Attend condition for Experiment 2. The white speckled fill represents the negativity or inward current flow. The black unfilled contours illustrate the positivity or outward current flow. The amplitude of the SCD maps was set at 0.5 $\mu V/cm^2$.

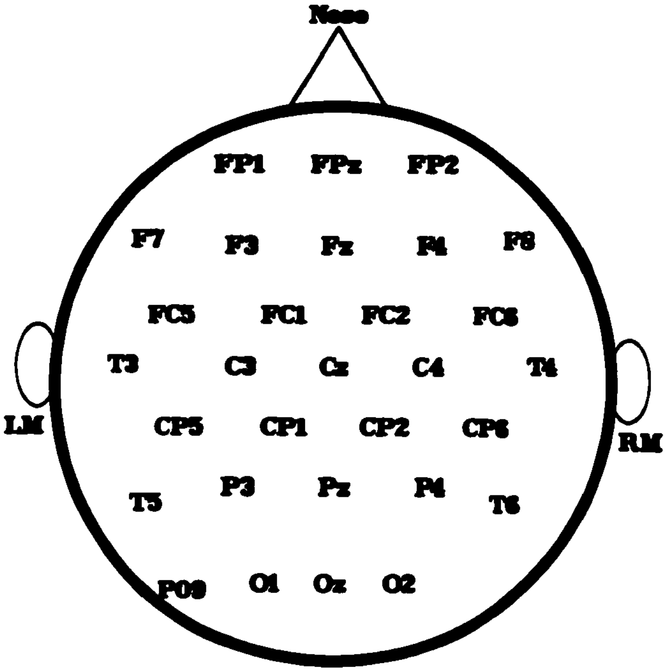
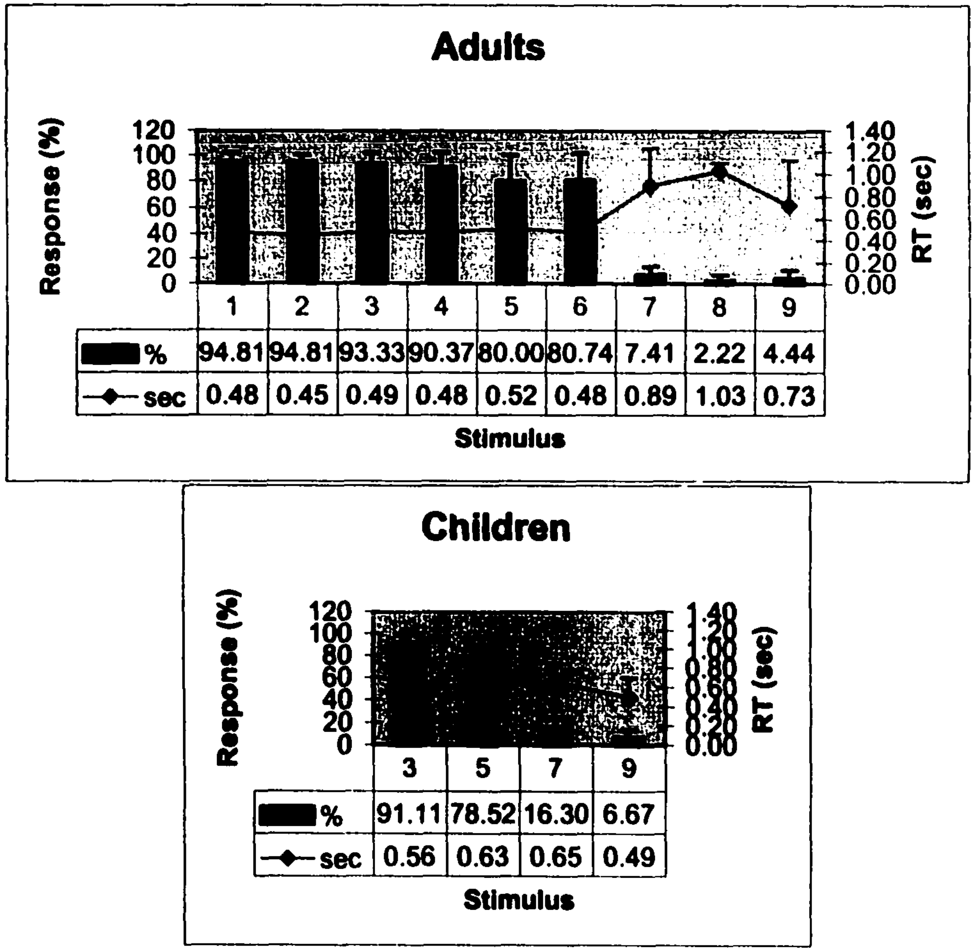

Nose
FP1
FPz
FP2
F7
F3
Fz
F4
F8
FC5
FC1
FC2
FC6
T3
C3
Cz
C4
T4
LM
RM
CP5
CP1
CP2
CP6
T5
P3
Pz
P4
T6
PO9
O1
Oz
O2

Figure 1

Identification of Vowel Stimulus /I/



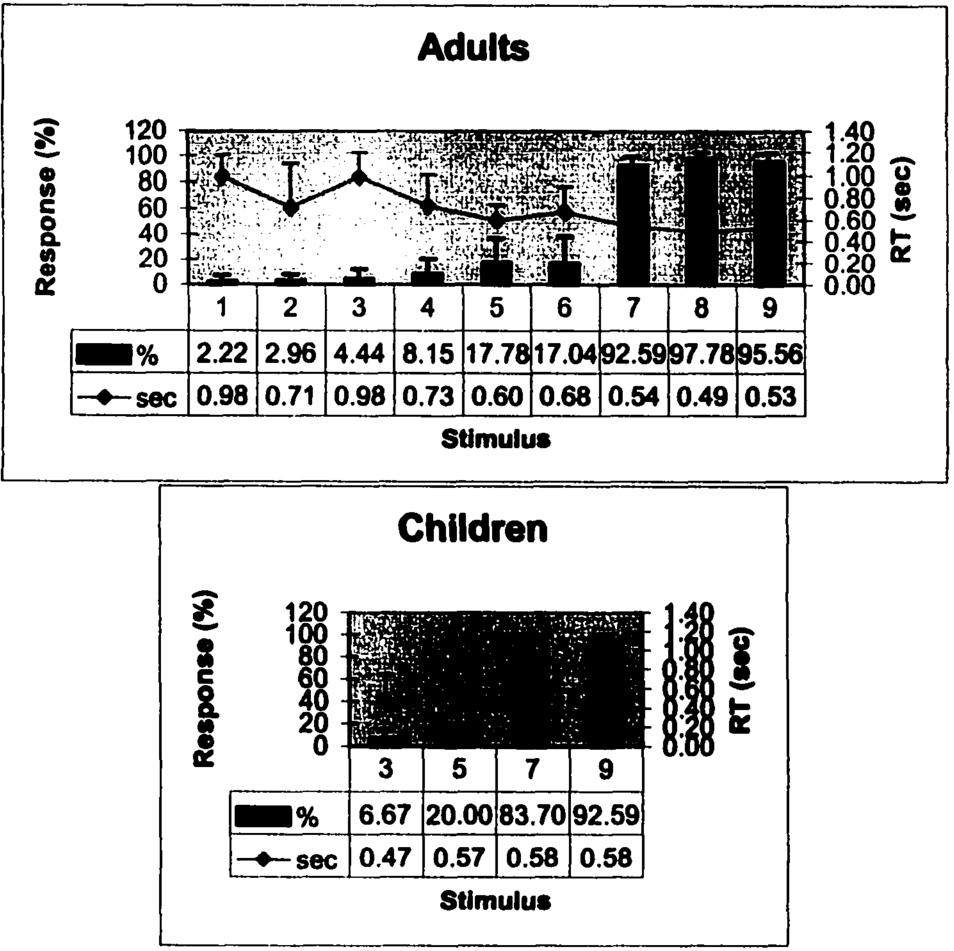
Adults

	1	2	3	4	5	6	7	8	9
■ %	94.81	94.81	93.33	90.37	80.00	80.74	7.41	2.22	4.44
—◆— sec	0.48	0.45	0.49	0.48	0.52	0.48	0.89	1.03	0.73

Children

	3	5	7	9
■ %	91.11	78.52	16.30	6.67
—◆— sec	0.56	0.63	0.65	0.49

Identification of Vowel Stimulus /ε/



Adults

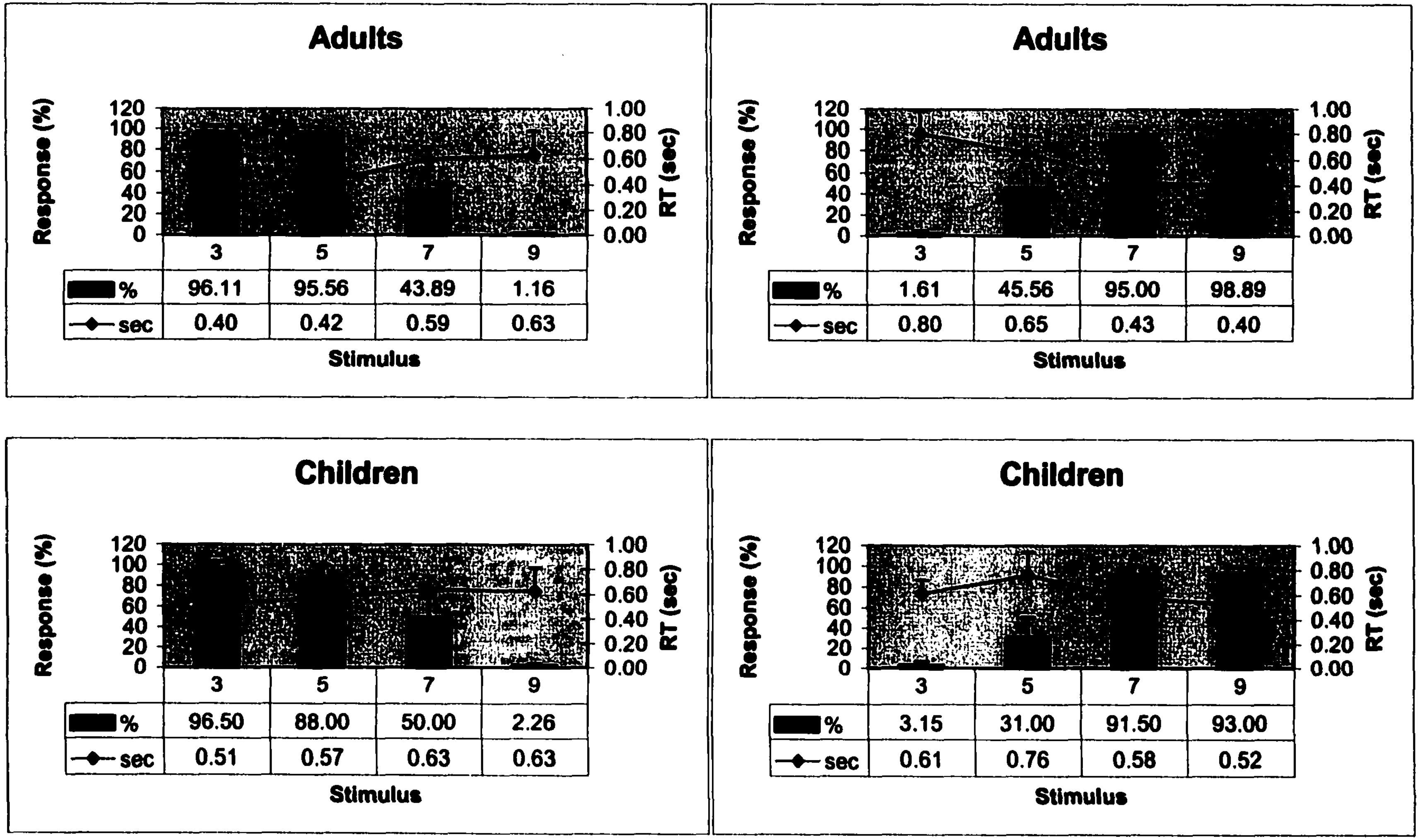
	1	2	3	4	5	6	7	8	9
■ %	2.22	2.96	4.44	8.15	17.78	17.04	92.59	97.78	95.56
—◆— sec	0.98	0.71	0.98	0.73	0.60	0.68	0.54	0.49	0.53

Children

	3	5	7	9
■ %	6.67	20.00	83.70	92.59
—◆— sec	0.47	0.57	0.58	0.58

Figure 2

Target Discrimination to Standard Stimulus 9/ε/ Target Discrimination to Standard Stimulus 3/I/



Adults (Standard Stimulus 9/ε/)

Stimulus	3	5	7	9
■ %	96.11	95.56	43.89	1.16
—◆— sec	0.40	0.42	0.59	0.63

Adults (Standard Stimulus 3/I/)

Stimulus	3	5	7	9
■ %	1.61	45.56	95.00	98.89
—◆— sec	0.80	0.65	0.43	0.40

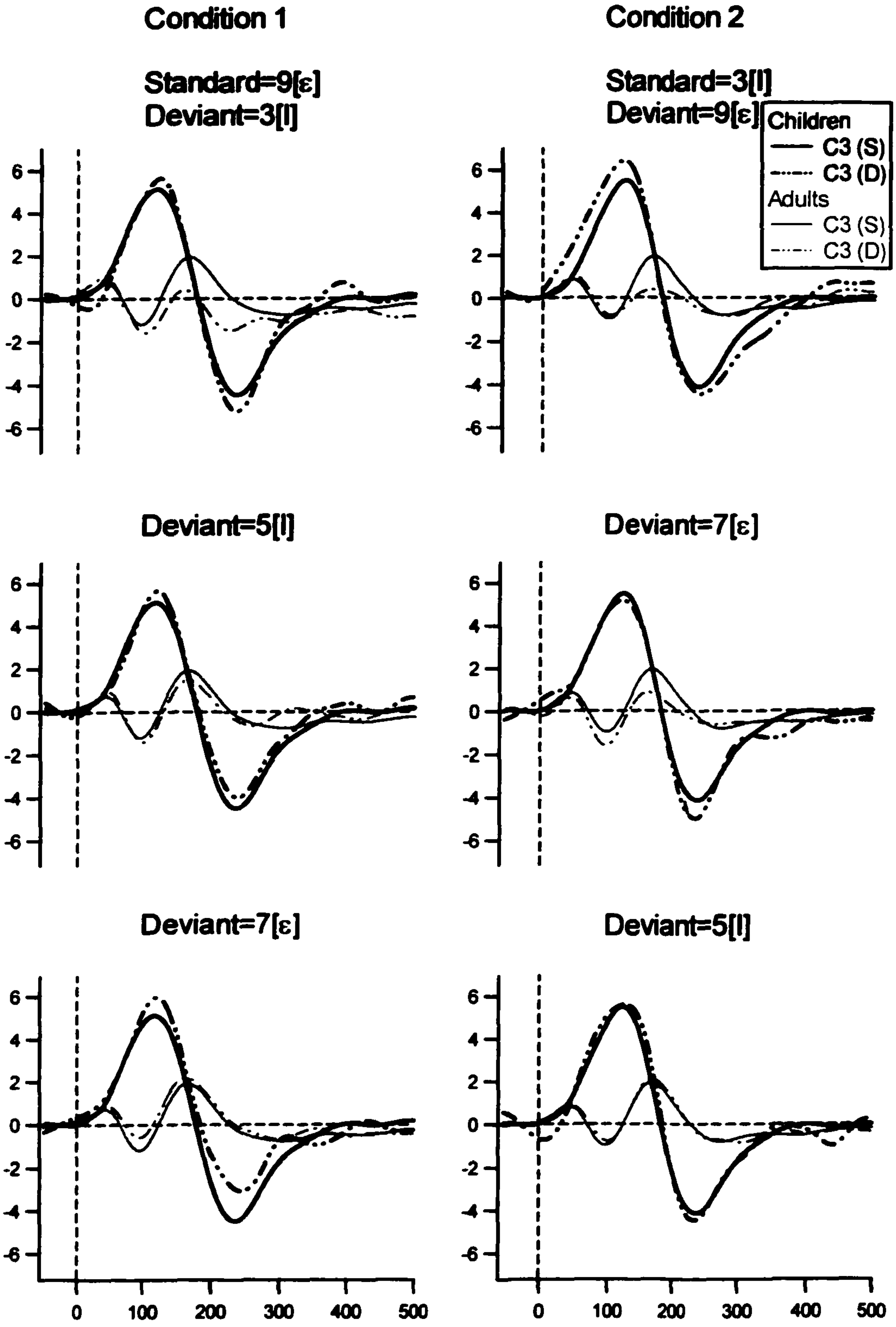
Children (Standard Stimulus 9/ε/)

Stimulus	3	5	7	9
■ %	96.50	88.00	50.00	2.26
—◆— sec	0.51	0.57	0.63	0.63

Children (Standard Stimulus 3/I/)

Stimulus	3	5	7	9
■ %	3.15	31.00	91.50	93.00
—◆— sec	0.61	0.76	0.58	0.52

Figure 3



Condition 1

Standard=9[ε]
Deviant=3[ɪ]

Condition 2

Standard=3[ɪ]
Deviant=9[ε]

Deviant=5[ɪ]

Deviant=7[ε]

Deviant=7[ε]

Deviant=5[ɪ]

Figure 4

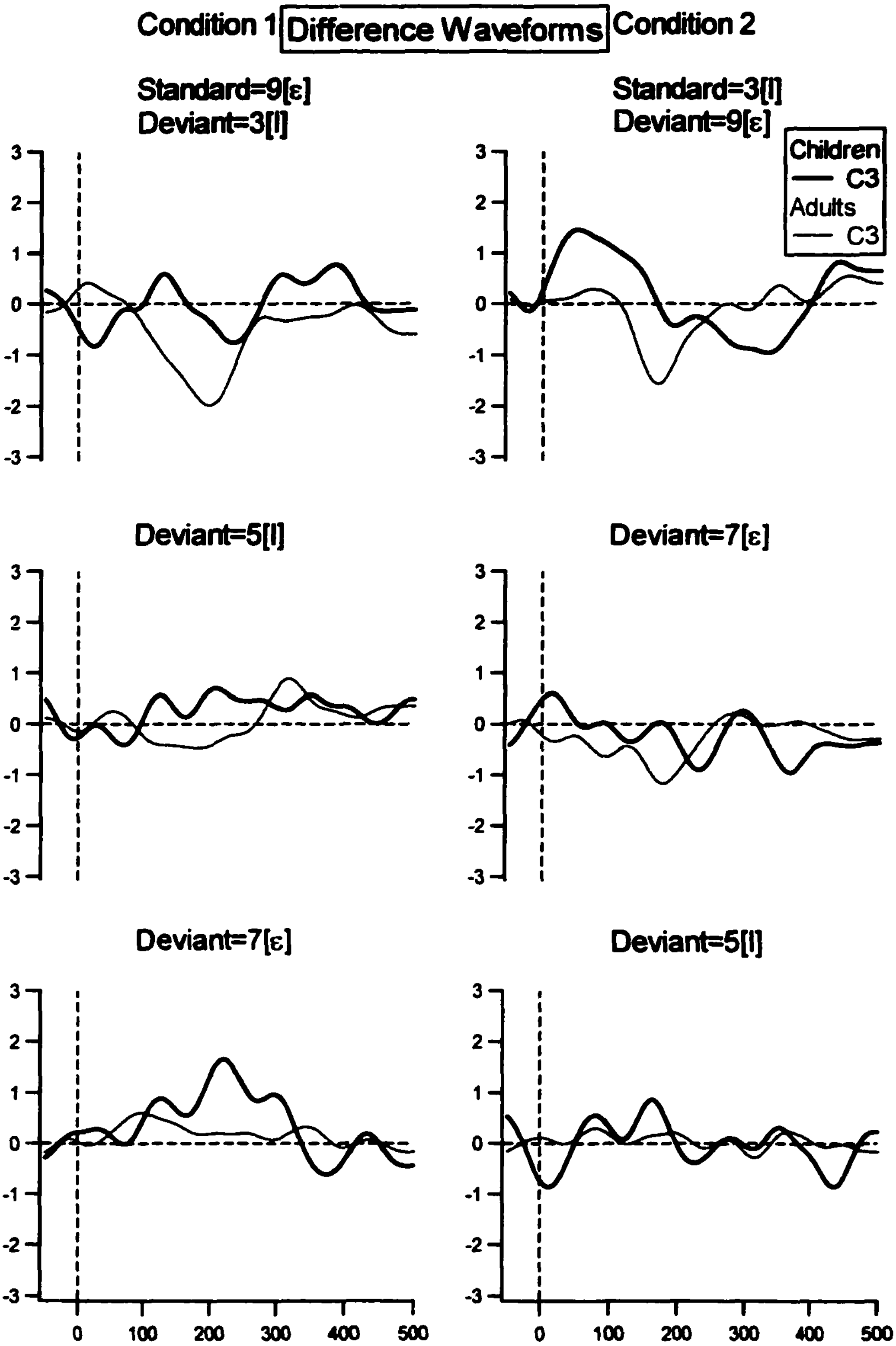
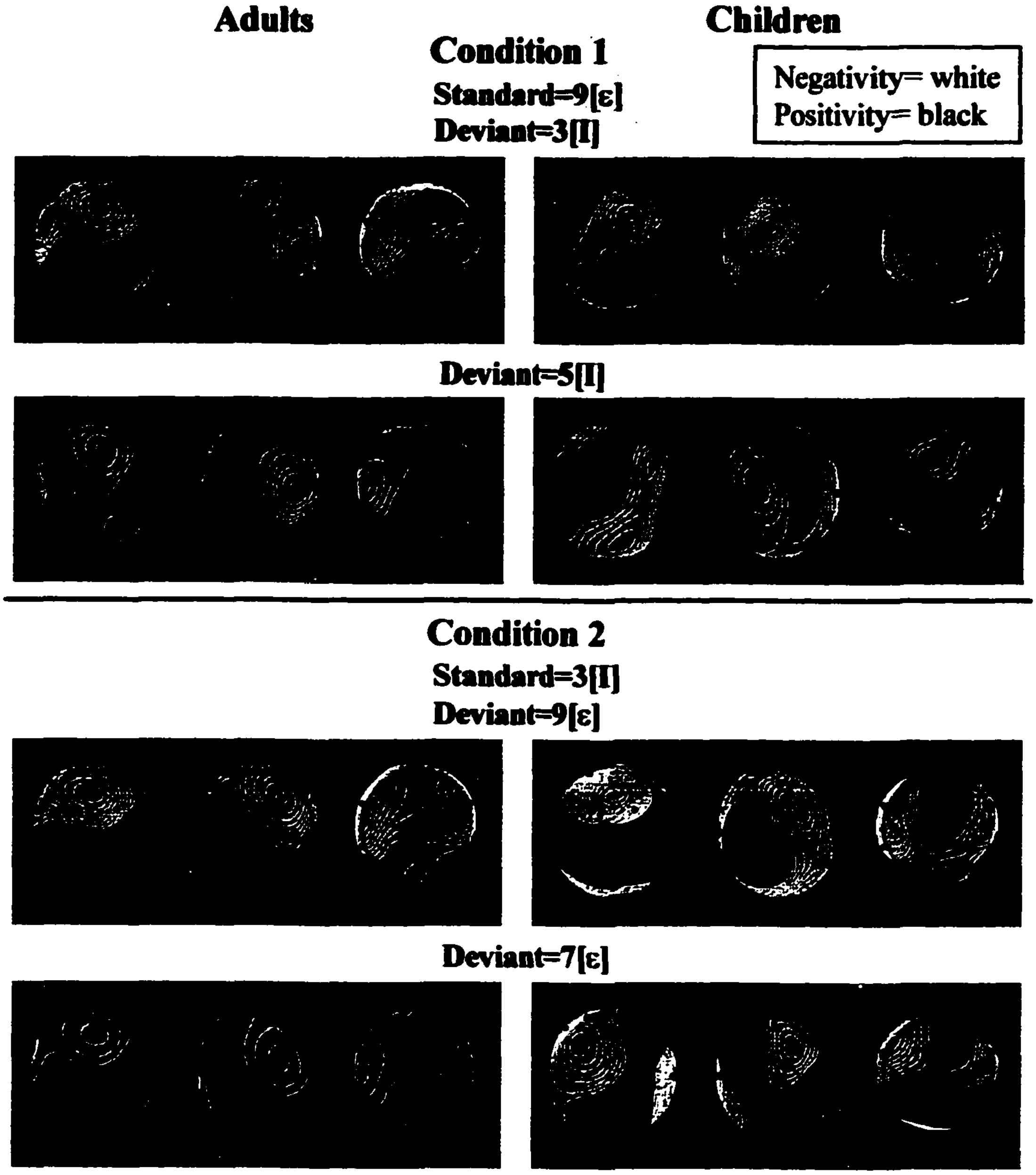

Condition 1
Difference Waveforms
Condition 2
Standard=9[ε]
Deviant=3[I]
Standard=3[I]
Deviant=9[ε]
Children
— C3
Adults
— C3
Deviant=5[I]
Deviant=7[ε]
Deviant=7[ε]
Deviant=5[I]
3
2
1
0
-1
-2
-3
0
100
200
300
400
500

Figure 5



Adults

Children

Condition 1

Standard=9[ε]

Deviant=3[I]

Negativity= white

Positivity= black

Deviant=5[I]

Condition 2

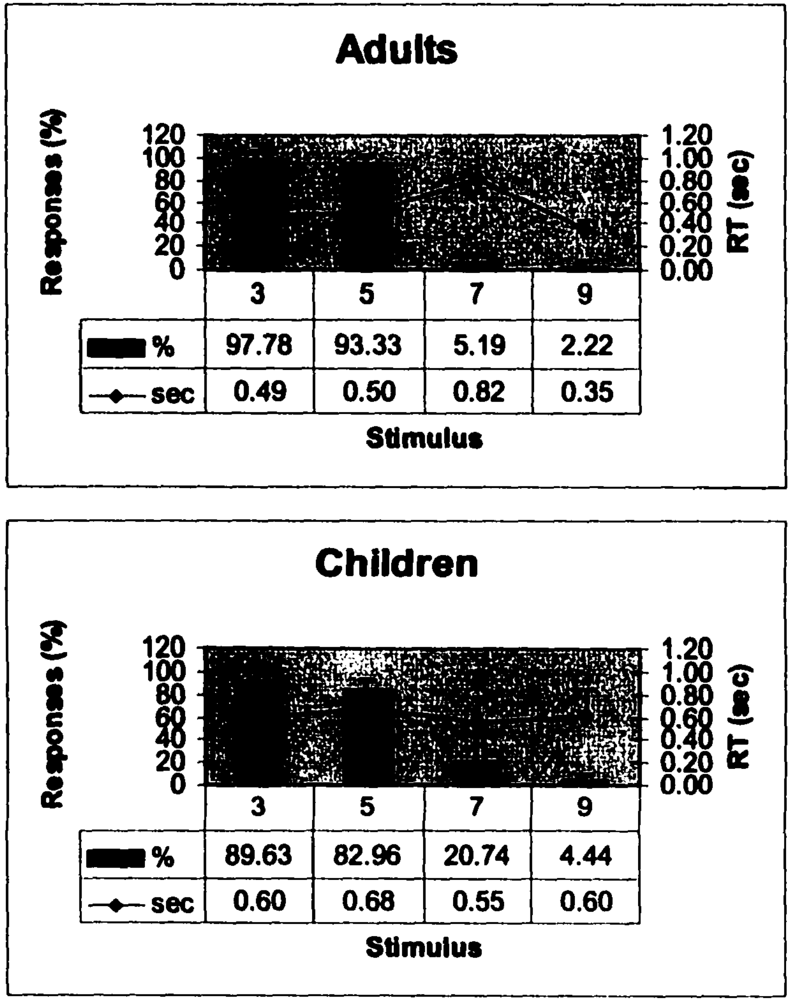
Standard=3[I]

Deviant=9[ε]

Deviant=7[ε]

Figure 6

Identification of Vowel Stimulus /I/



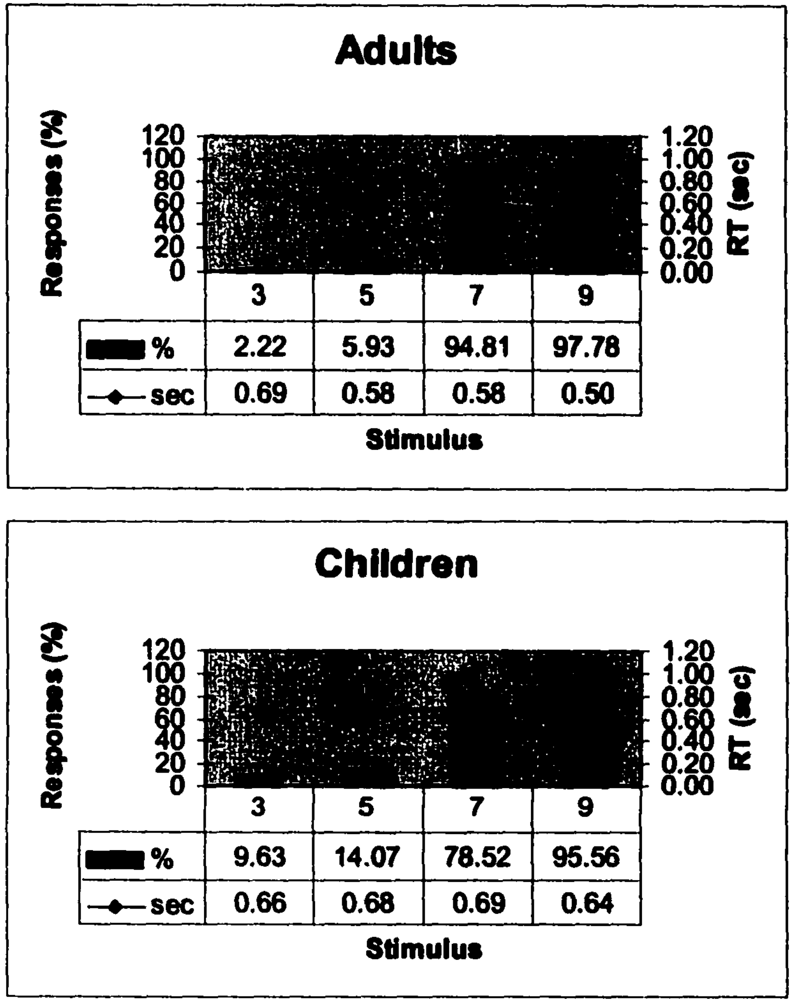
Adults

Stimulus	3	5	7	9
■ %	97.78	93.33	5.19	2.22
—◆— sec	0.49	0.50	0.82	0.35

Children

Stimulus	3	5	7	9
■ %	89.63	82.96	20.74	4.44
—◆— sec	0.60	0.68	0.55	0.60

Identification of Vowel Stimulus /ε/



Adults

Stimulus	3	5	7	9
■ %	2.22	5.93	94.81	97.78
—◆— sec	0.69	0.58	0.58	0.50

Children

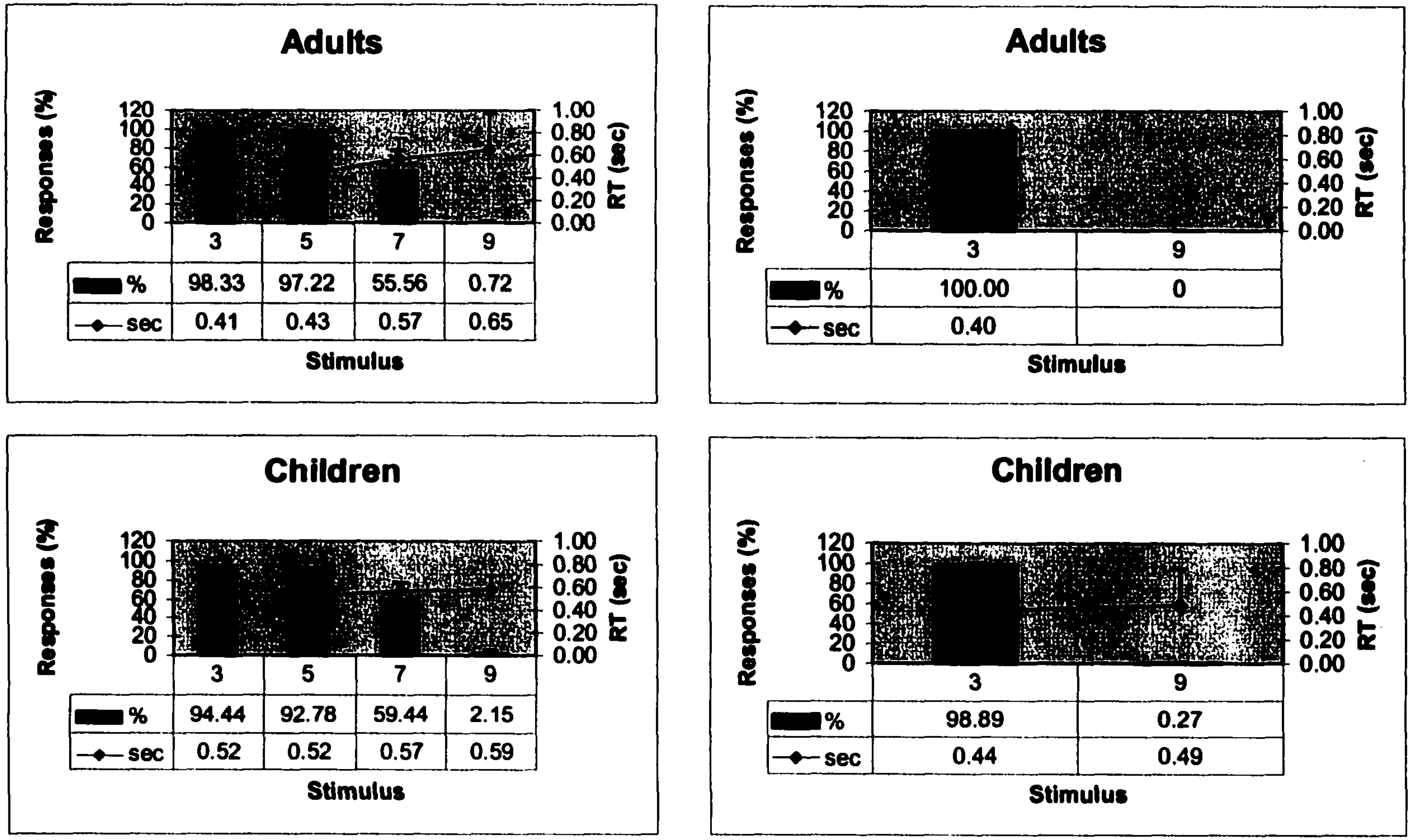
Stimulus	3	5	7	9
■ %	9.63	14.07	78.52	95.56
—◆— sec	0.66	0.68	0.69	0.64

Figure 9

Target Discrimination to Standard Stimulus 9/ɛ/

3 Deviants

1 Deviant



3 Deviants — Adults

Stimulus	3	5	7	9
■ %	98.33	97.22	55.56	0.72
—◆— sec	0.41	0.43	0.57	0.65

1 Deviant — Adults

Stimulus	3	9
■ %	100.00	0
—◆— sec	0.40	

3 Deviants — Children

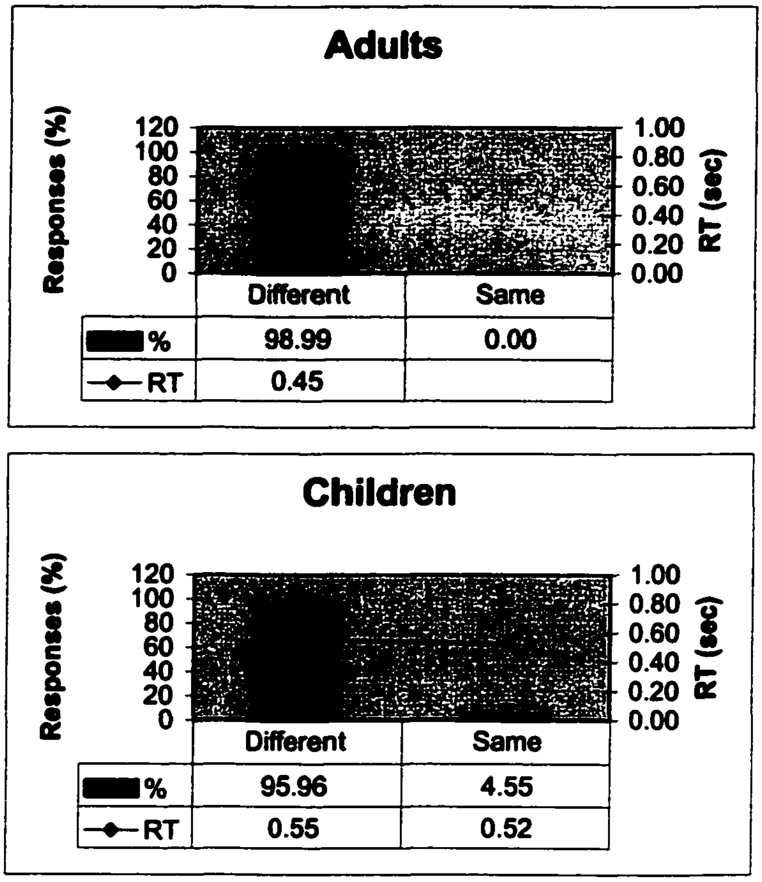
Stimulus	3	5	7	9
■ %	94.44	92.78	59.44	2.15
—◆— sec	0.52	0.52	0.57	0.59

1 Deviant — Children

Stimulus	3	9
■ %	98.89	0.27
—◆— sec	0.44	0.49

Figure 10

Same/Different Discrimination



Adults

	Different	Same
■ %	98.99	0.00
—◆— RT	0.45	

Children

	Different	Same
■ %	95.96	4.55
—◆— RT	0.55	0.52

Figure 11

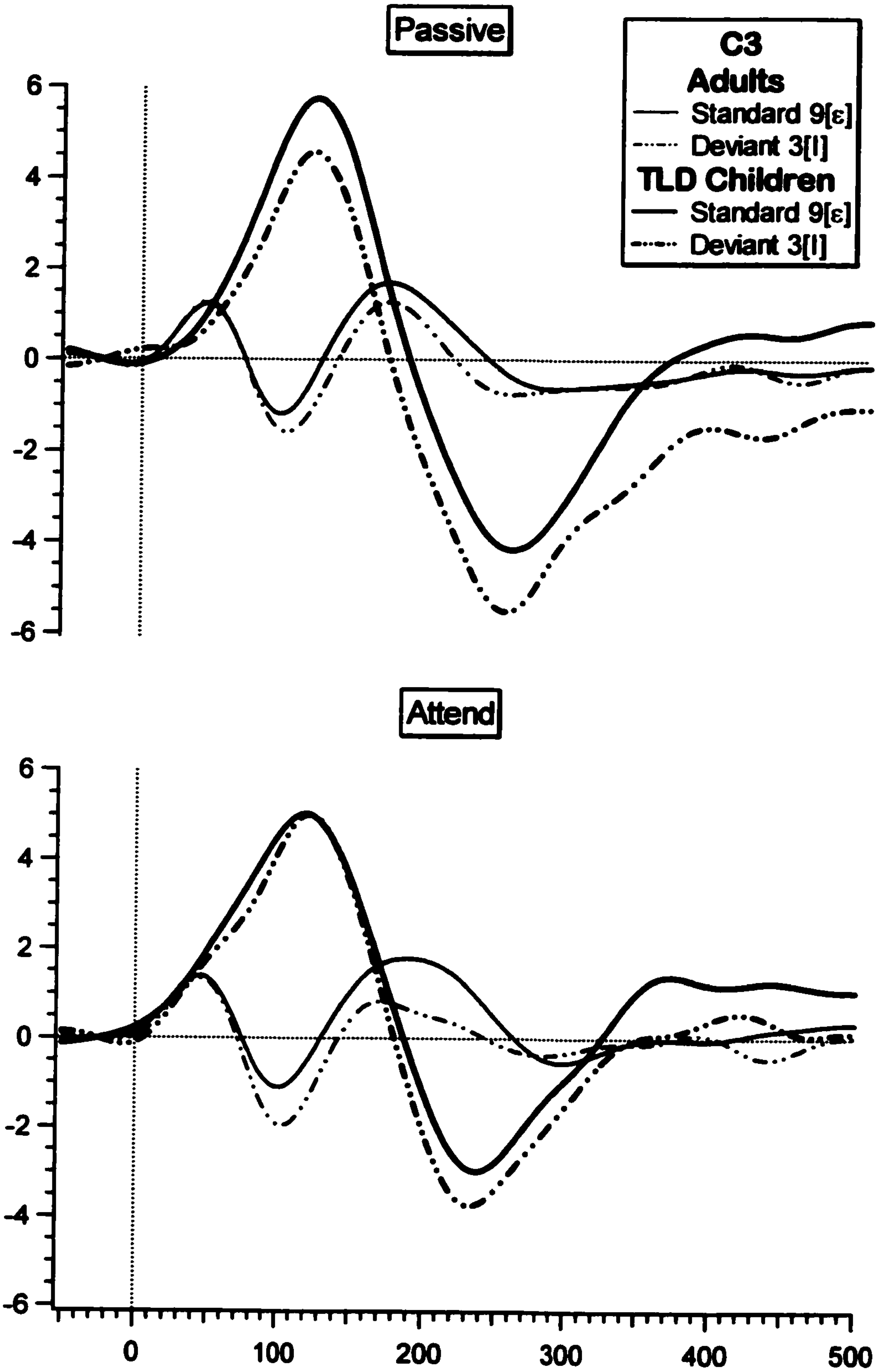

Passive
C3
Adults
Standard 9[ε]
Deviant 3[I]
TLD Children
Standard 9[ε]
Deviant 3[I]
6
4
2
0
-2
-4
-6
Attend
6
4
2
0
-2
-4
-6
0
100
200
300
400
500

Figure 12

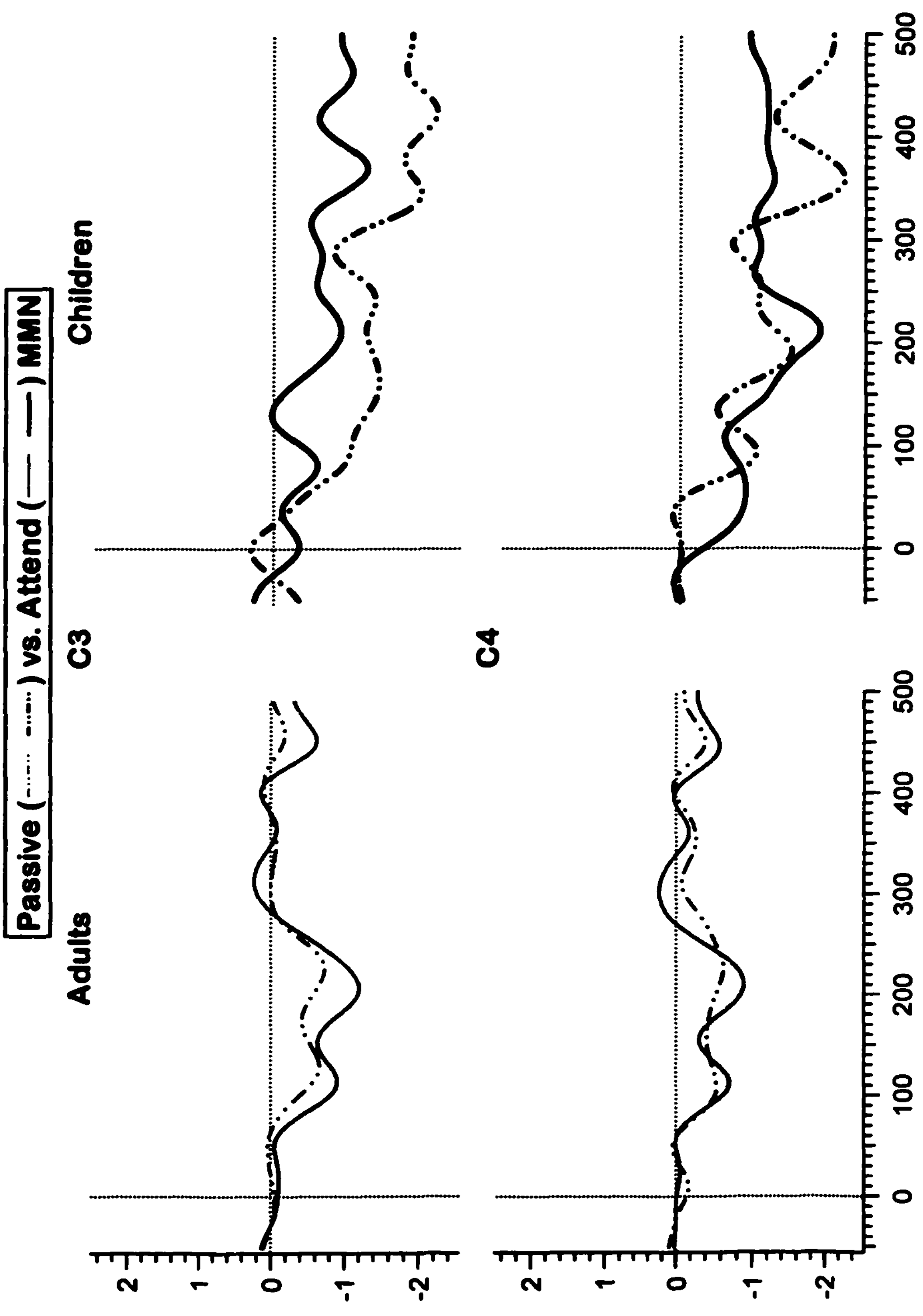

Passive (........) vs. Attend (——) MMN
Adults
Children
C3
C4
2
1
0
-1
-2
0
100
200
300
400
500

Figure 13

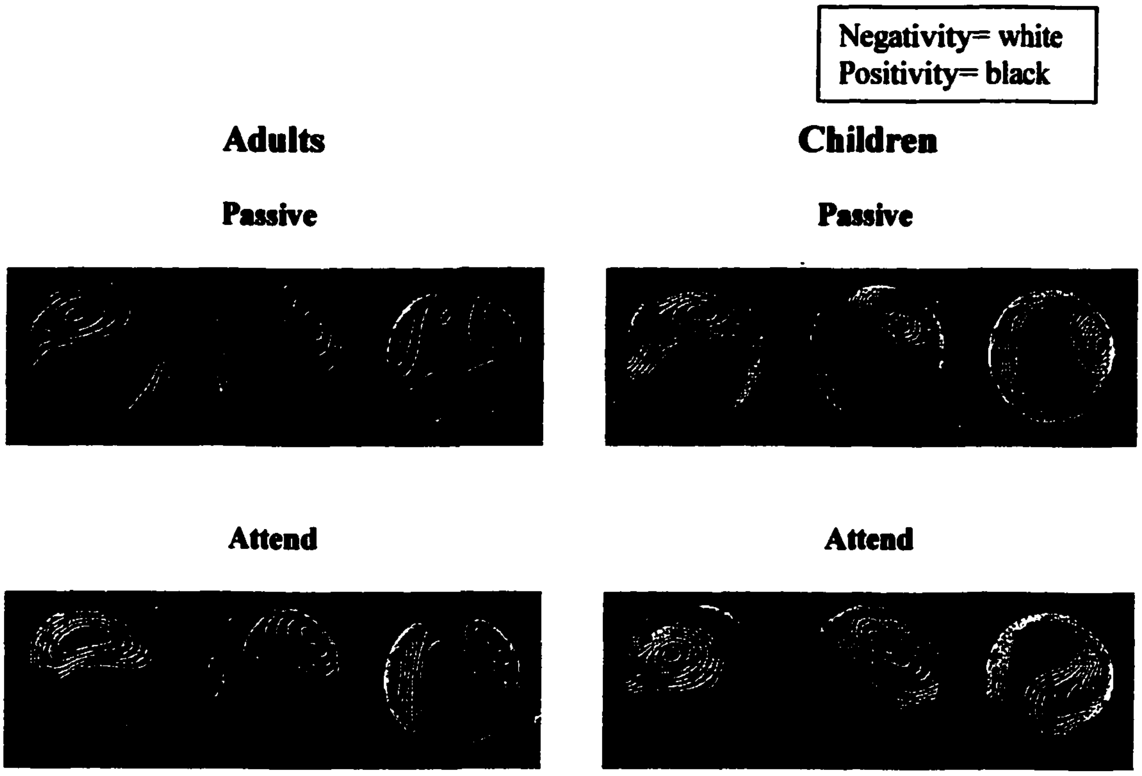

Negativity= white
Positivity= black
Adults
Children
Passive
Passive
Attend
Attend

Figure 14

Appendix A

Table A1. Means and standard deviations (in parenthesis) for the Goodness Rating.

Stimulus	Mean Rating	% ID as [I]	% ID as [ε]
1	2.03 (0.84)	97.22	2.78
2	2.23 (0.89)	98.33	1.67
3	***2.41 (0.97)***	***97.22***	***2.78***
4	2.67 (0.96)	86.67	13.33
5	3.25 (0.94)	72.62	27.38
6	3.24 (1.04)	75.24	24.76
7	2.23 (0.63)	6.67	93.33
8	1.79 (0.73)	5.56	94.44
9	***1.75 (0.77)***	***2.22***	***97.78***

Appendix B. Summary of the F-value's for the F tests of Variance.

Condition1: Standard Stimulus=9[ε]

Deviant=3[I]

Elec	101	131	161	191	221	251	281
Fz	7.80*	2.63	2.45	7.63*	5.94*	3.41*	9.91*
Cz	7.90*	2.79	3.16*	11.30*	16.55*	4.48*	10.09*
Pz	11.28*	5.61*	8.53*	16.55*	8.03*	3.63*	3.17*
C3	4.37*	1.08	2.05	9.79*	12.07*	4.94*	5.76*
C4	20.21*	13.75*	7.86*	15.31*	18.80*	11.73*	22.66*
FC5	2.49	*1.55*	*1.25*	4.07*	4.87*	5.03*	5.30*
FC6	9.59*	4.72*	4.53*	11.70*	12.34*	5.64*	19.09*
CP5	3.38*	1.83	3.17	6.23*	4.77*	4.30*	2.71
CP6	18.31*	38.89*	14.57*	13.38*	8.14*	8.48*	6.57*
LM	2.12	1.95	2.62	3.52*	2.36	1.19	2.84
RM	11.91*	4.46*	3.66*	5.48*	2.71	2.01	2.08

Deviant=5[I]

Elec	101	131	161	191	221	251	281
Fz	2.24	2.01	1.35	1.77	1.64	*1.05*	1.62
Cz	2.58	2.44	1.12	1.39	3.99*	2.14	1.87
Pz	1.99	2.80	1.79	1.76	6.67*	3.48*	1.81
C3	4.02*	2.92	1.51	2.26	7.01*	4.01*	2.95
C4	5.67*	4.36*	1.21	1.53	2.47	2.06	1.73
FC5	3.47*	2.91	1.44	2.04	3.93*	3.22*	2.89
FC6	4.66*	7.97*	1.63	1.02	1.27	1.18	*1.20*
CP5	3.75*	3.81*	2.20	2.63	5.62*	3.56*	2.39
CP6	9.99*	8.92*	2.84	1.75	2.26	2.50	2.77
LM	2.46	3.00	3.62*	5.51*	4.94*	4.07*	4.33*
RM	2.26	4.81*	3.23*	3.80*	4.04*	4.79*	4.14*

Deviant=7[ε]

Elec	101	131	161	191	221	251	281
Fz	1.31	6.90*	4.51*	4.73*	10.01*	5.92*	3.20*
Cz	1.30	6.30*	5.06*	3.15*	5.72*	4.63*	5.81*
Pz	4.94*	6.03*	8.61*	5.97*	16.75*	8.00*	21.63*
C3	*1.32*	4.95*	2.24	2.21	3.74*	4.80*	3.82*
C4	2.63	7.11*	10.62*	5.78*	29.64*	8.98*	8.79*
FC5	1.22	3.38*	2.74	2.30	4.25*	8.06*	5.31*
FC6	1.59	5.48*	8.01*	11.31*	9.40*	4.18*	3.15*
CP5	2.58	6.94*	2.87	2.23	6.07*	8.16*	4.67*
CP6	5.41*	9.84*	21.48*	11.15*	28.26*	15.50*	17.22*
LM	3.58*	2.81	1.93	1.19	2.50	13.88*	11.76*
RM	1.88	3.95*	4.17*	1.74	2.98	15.33*	8.03*

Note. The asterisk indicates that the variance for the given time interval is F-values that were calculated when the adult variance was greater than the

Appendix B continued.

Condition2: Standard Stimulus=3[I]

Deviant=9[ε]

Elec	101	131	161	191	221	251	281
Fz	3.25*	4.24*	3.93*	2.21	1.73	*1.06*	2.11
Cz	3.86*	4.20*	3.84*	5.13*	3.25*	1.68	2.20
Pz	3.19*	3.14*	1.92	3.52*	7.66*	2.02	2.35
C3	5.62*	6.63*	6.72*	20.78*	8.04*	3.93*	5.23*
C4	2.59	1.74	1.65	2.90	5.11*	1.15	1.81
FC5	7.65*	7.91*	6.17*	11.78*	6.25*	6.59*	6.93*
FC6	1.32	*1.43*	*1.47*	1.99	2.70	*1.36*	1.28
CP5	4.44*	5.11*	5.76*	12.06*	14.52*	9.79*	7.86*
CP6	2.93	1.45	*1.49*	*1.13*	4.55*	*1.28*	1.75
LM	1.42	*1.61*	*1.18*	1.75	1.31	2.43	1.59
RM	1.01	2.16	2.05	1.10	1.51	1.33	2.73

Deviant=7[ε]

Elec	101	131	161	191	221	251	281
Fz	1.18	1.93	3.08	2.17	3.97*	4.70*	4.08*
Cz	2.31	3.05	4.18*	3.33*	8.73*	6.98*	7.35*
Pz	8.91*	9.05*	9.46*	7.18*	9.29*	5.34*	6.58*
C3	1.40	3.54*	4.19*	4.18*	7.42*	6.36*	6.73*
C4	3.73*	2.33	3.62*	5.14*	9.13*	3.89*	4.36*
FC5	1.21	2.35	3.25*	3.29*	4.27*	4.07*	3.11
FC6	2.34	2.09	2.37	2.18	3.92*	2.17	1.78
CP5	4.16*	7.12*	6.30*	6.15*	7.18*	5.26*	5.78*
CP6	6.14*	7.29*	5.28*	4.87*	6.61*	2.10	2.31
LM	3.53*	3.36*	2.61	3.82*	1.30	2.79	1.87
RM	7.99*	6.47*	2.93	1.45	1.29	*1.24*	0.78

Deviant=5[I]

Elec	101	131	161	191	221	251	281
Fz	3.26*	2.57	*1.17*	*2.62*	1.24	2.25	2.83
Cz	2.45	2.27	0.77	0.42	0.82	1.15	0.97
Pz	2.75	3.03	*1.09*	*1.30*	1.16	1.17	1.08
C3	1.43	2.51	*1.28*	*1.59*	1.18	2.07	*1.04*
C4	6.01*	4.47*	2.33	1.41	1.74	1.24	1.11
FC5	1.77	2.05	1.22	*1.06*	1.82	2.04	1.55
FC6	5.60*	5.17*	3.17*	2.51	2.33	*1.23*	1.18
CP5	2.06	3.24*	1.27	1.10	2.18	2.15	*1.31*
CP6	8.49*	7.55*	5.37*	2.61	2.64	1.98	2.06
LM	4.64*	3.37*	2.46	4.98*	7.04*	9.37*	4.02*
RM	1.54	1.57	3.72*	6.13*	5.21*	4.43*	6.18*

significant ($F(10,9)=3.14$, $p<0.05$). The italicized numbers represent the children ($F(9,10)=3.02$, $p<0.05$).

Appendix C. Summary of the F-values of the between-group variance for Experiment 2.

	Passive							Attend						
Elec	101	131	161	191	221	251	281	101	131	161	191	221	251	281
Fz	3.34*	3.00	1.30	2.18	2.82	2.10	3.12	12.95*	7.19*	5.20*	3.33*	2.54	3.19*	1.85
Cz	2.81	6.25*	5.76*	2.23	1.98	1.23	2.88	9.24*	4.02*	2.69	3.03	4.62*	2.07	1.22
Pz	1.17	3.18*	5.34*	3.04	*1.63*	*1.38*	1.76	6.92*	3.73*	4.45*	6.37*	4.54*	2.12	2.13
C3	3.77*	4.62*	4.27*	5.09*	3.50*	1.36	4.51*	6.10*	5.17*	3.70*	3.76*	3.11	2.65	1.00
C4	3.13	3.61*	1.72	1.77	1.90	*1.01*	1.47	11.93*	5.67*	2.54	8.49*	10.05*	3.43*	1.32
FC5	2.42	1.74	1.93	2.70	2.71	1.16	2.55	7.12*	6.79*	4.70*	7.41*	3.68*	4.26*	1.77
FC6	3.79*	5.75*	2.66	2.57	1.92	1.08	1.27	19.81*	8.74*	5.69*	7.94*	7.48*	5.00*	2.10
CP5	3.49*	2.82	3.28*	9.21*	3.57*	1.21	1.77	7.79*	4.90*	4.92*	5.08*	*1.55*	1.42	2.26
CP6	2.40	5.18*	1.79	1.78	1.59	1.10	2.37	5.61*	4.24*	1.72	6.06*	4.16*	3.81*	3.18*
LM	0.65	0.35	*1.41*	4.49*	3.58*	2.93	2.15	2.07	1.02	1.20	*1.10*	1.01	2.70	3.17
RM	1.60	1.61	*1.15*	2.62	2.31	2.89	4.31*	*1.05*	2.93	2.31	2.08	2.68	6.21*	11.12*

Note. The asterisk indicates that the variance for the given time interval is significant ($F(9,9)=3.18$, $p<0.05$). The italicized numbers represent the f-values that were calculated when the adult variance was greater than the children.

Endnotes

1. Specific details about the stimuli used in the experiments described by Csépe (1995) were not provided by the author.

2. Csépe (1995) does not indicate whether synthetic- or naturally-produced speech sounds were presented.

3. As previously indicated, specific details about the stimuli used in the experiments described by Csépe (1995) were not provided by the author.

4. The nonsense stimuli were old Finnish words no longer in use.

5. Due to occasional extraneous environmental noise a level of 25 dB HL at 500 Hz was accepted as a passing score.

6. Stimuli 3, 5, 7, and 9 were used for all test paradigms, except for the adult identification where all nine stimuli were presented.

7. A 'goodness' rating of the vowel stimuli was conducted using a different group of adult listeners (see Appendix A). The subjects were asked to identify the vowel presented by circling either [I] or [ɛ]. They were also asked to rate the vowel sound to determine whether it was a good exemplar of that vowel. The rating ranged from 1-5, with 1 suggesting a "good" prototype of the vowel sound and 5 indicating "not sure". Stimulus 3 was found to be a better exemplar of its vowel class compared to stimulus 5. Furthermore, the boundary vowels received poorer identification and goodness ratings, compared to stimuli farther from the boundary.

8. As in the first experiment, due to occasional environmental noise a level of 25 dB at 500 Hz was accepted as a passing score.

References

Aaltonen, O., Eerola, O., Lang, A. H., Uusipaikka, E., & Tuomainen, J. (1994). Automatic discrimination of phonetically relevant and irrelevant vowel parameters as reflected by mismatch negativity. *Journal of the American Academy of Audiology,96(3),* 1489-1493.

Aaltonen, O., Niemi, P., Nyrke, T., & Tuhkanen, M. (1987). Event-related brain potentials and the perception of a phonetic continuum. *Biological Psychology, 24,* 197-207.

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

Alho, K. (1995). Cerebral generators of mismatch negativity (MMN) and its magnetic counterpart (MMNm) elicited by sound changes. *Ear and Hearing, 16(1),* 38-51.

Alho, K., Sams, M., Paavilainen, P., Reinikainen, K., & Näätänen, R. (1989). Event-related brain potentials reflecting processing of relevant and irrelevant stimuli during selective listening. *Psychophysiology, 26(5),* 514-528.

Alho, K. & Sinervo, N. (1997). Preattentive processing of complex sounds in the human brain. *Neuroscience Letters, 233,* 33-36.

Alho, K., Winkler, I., Escera, C., Huotilainen, M., Virtanen, J., Jääskeläinen, I. P., Pekkonen, E., & Ilmoniemi, R. J. (1998). Processing of novel sounds and frequency changes in the human auditory cortex: magnetoencephalographic recordings. *Psychophysiology, 35,* 211-224.

Alho, K., Woods, D. L., Algazi, A., & Näätänen, R. (1992). Intermodal selective attention. II. Effects of attentional load on processing of auditory and visual stimuli in central space. *Electroencephalography and clinical Neurophysiology, 82*, 356-368.

Bradlow, A. R., Kraus, N., Nicol, T. G., McGee, T. J., Cunningham, J., Zecker, S. G., & Carrell, T. D. (1999). Effects of lengthened formant transition duration on discrimination and neural representation of synthetic CV syllables by normal and learning-disabled children. *Journal of the Acoustical Society of America, 106(4),* 2086-2096.

Čeponienė, R., Cheour, M., & Näätänen, R. (1998). Interstimulus interval and auditory event-related potentials in children: evidence for multiple generators. *Electroencephalography and clinical Neurophysiology, 108*, 345-354.

Čeponienė, R., Service, E., Kurjenluoma, S., Cheour, M., & Näätänen, R. (1999). Children's performance on pseudoword repetition depends on auditory trace quality: evidence from event-related potentials. *Developmental Psychology, 35(3),* 709-720.

Cheour, M., Alho, K., Čeponienė, R., Reinikainen, K., Sainio, K., Pohjavuori, M., Aaltonen, O., & Näätänen R. (1998). Maturation of mismatch negativity in infants. *International Journal of Psychophysiology, 29*, 217-226.

Cheour, M., Korpilahti, P., Martynova, O., & Lang, A. H. (2001). Mismatch negativity and late discriminative negativity in investigating speech perception and learning in children and infants. *Audiology & Neuro-Otology,6(1),* 2-11.

Cheour-Luhtanen, M., Alho, K., Kujala, T., Sainio, K., Reinikainen, K., Renlund, M., Aaltonen, O., Eerola, O., & Näätänen, R. (1995). Mismatch negativity indicates vowel discrimination in newborns. *Hearing Research*, *82*, 53-58.

Csépe, V. (1995). On the origin and development of the mismatch negativity. *Ear and Hearing, 16(1)*, 91-104.

Dalebout, S. D. & Stack, J. W. (1999). Mismatch negativity to acoustic differences not differentiated behaviorally. *Journal of the American Academy of Audiology, 10,* 388-399.

Frumkin, B. & Rapin, I. (1980). Perception of vowels and consonant-vowels of varying duration in language impaired children. *Neuropsychologia, 18,* 443-454.

Gomes, H., Molhom, S., Ritter, W., Kurtzberg, D., Cowan, N., & Vaughan, H. G., Jr. (2000). Mismatch negativity in children and adults, and effects of an attended task. *Psychphysiology, 37(6),* 807-816.

Gomes, H., Sussman, E., Ritter, W., Kurtzberg, D., Cowan, N., & Vaughan, H. G., Jr. (1999). Electrophysiological evidence of developmental changes in the duration of auditory memory. *Developmental Psychology*, *35*, 294-302.

Grier, J. B. (1971) Nonparametric indexes for sensitivity and bias: computing formulas. *Psychological Bulletin, 75(6),* 424-429.

Javitt, D. C., Grochowski, S., Shelley, A., & Ritter, W. (1998). Impaired mismatch negativity (MMN) generation in schizophrenia as a function of stimulus deviance, probability, and interstimulus/interdeviant interval. *Electroencephalography and clinical Neurophysiology*, *108*, 143-153.

Kathmann, N., Frodl-Bauch, T., & Hegerl, U. (1999). Stability of the mismatch negativity under different stimulus and attention conditions. *Clinical Neurophysiology, 110,* 317-323.

Korpilahti, P & Lang, H. A. (1994). Auditory ERP components and mismatch negativity in dysphasic children. *Electroencephalography and clinical Neurophysiology, 91,* 256-264.

Kraus, N., Koch, D. B., McGee, T. J., Nicol, T. G., & Cunningham J. (1999). Speech-sound discrimination in school-age children: psychophysical and neurophysiologic measures. *Journal of Speech, Language, and Hearing Research, 42,* 1042-1060.

Kraus, N., McGee, T., Carrell, T., Sharma, A., Micco, A., & Nicol, T. (1993). Speech-evoked cortical potentials in children. *Journal of the American Academy of Audiology, 4,* 238-248.

Kraus, N., McGee, T. J., Carrell, T. D., Zecker, S. G., Nicol, T. G., Koch, D. B. (1996). Auditory neurophysiologic responses and discrimination deficits in children with learning problems. *Science, 273,* 971-973.

Kraus, N., McGee, T., Micco, A., Sharma, A., Carrell, T., & Nicol, T. (1993). Mismatch negativity in school-age children to speech stimuli that are just perceptibly different. *Electroencephalography and clinical Neurophysiology, 88,* 123-130.

Kraus, N., McGee, T., Sharma, A., Carrell, T., & Nicol, T. (1992). Mismatch negativity event-related potential elicited by speech stimuli. *Ear and Hearing, 13(3),* 158-164.

Kurtzberg, D., Vaughan H. G., Jr., Kreuzer, J. A., & Fliegler, K. Z. (1995). Developmental studies and clinical application of mismatch negativity: Problems and prospects. *Ear and Hearing, 16(1)*, 105-117.

Leonard, L. B., McGregor, K. K., & Allen, G. D. (1992). Grammatical morphology and speech perception in children with specific language impairment. *Journal of Speech and Hearing Research, 35,* 1076-1085.

Liebenthal, E., Lee, W. W. T., Shafer, V. L., Kurtzberg, D., & Vaughan, H. G., Jr. (in preparation). Pre-conscious speech discrimination is dependent on the attentional state.

Maiste, A. C., Wiens, A. S., Hunt, M. J., Scherg, M., & Picton, T. W. (1995). Event-related potentials and the categorical perception of speech sounds. *Ear and Hearing, 16(1),* 68-90.

Martin, B.A., Shafer, V.L., Morr, M.L., Kreuzer, J., & Kurtzberg, D. (2001). Maturation of the mismatch negativity: A topographic analysis. *The Cognitive Neuroscience Society Annual Meeting*, New York.

Maul, K. K., Morr, M. L., Shafer, V. L., & Kurtzberg, D. (2001). Attention effects on MMN to consonants in children and adults. *The Cognitive Neuroscience Society Annual Meeting*, New York.

Mody, M., Studdert-Kennedy, M., & Brady, S. (1997). Speech perception deficits in poor readers: auditory processing or phonological coding? *Journal of Experimental Child Psychology, 64,* 199-231.

Moore, B. C. J. (1997). *An Introduction to the Psychology of Hearing.* New York: Academic Press.

Morr, M. L., Shafer, V. L., Davidson, C., Kreuzer, J. A., & Kurtzberg, D. (in preparation). Rapid interstimulus interval effects on mismatch negativity in children and adults.

Morr, M. L., Shafer, V. L., Kreuzer, J. A., & Kurtzberg, D. (2002). Maturation of mismatch negativity in typically-developing infants and pre-school children. *Ear and Hearing, 23(2),* 118-136.

Näätänen, R., Lehtokoski, A., Lennes, M., Cheour, M., Huotilainen, M., Iivonen, A., Vainio, M., Alku, P., Ilmoniemi, R. J., Luuk, A., Allik, J., Sinkkonen, J., & Alho, K. (1997). Language-specific phoneme representations revealed by electric and magnetic brain responses. *Nature, 385,* 432-434.

Näätänen, R., Paavilainen, P., Tiitinen, 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(4),* 375-425.

Novak, G., Ritter, W., & Vaughan, H. G., Jr. (1992). The chronometry of attention-modulated processing and automatic mismatch detection. *Psychophysiology, 29(4),* 412-430.

Oades, R. D. & Dittman-Balcar, A. (1995). Mismatch negativity (MMN) is altered by directing attention. *NeuroReport, 6,*1187-1190.

Paavilainen, P., Tiitinen, H., Alho, K., & Näätänen, R. (1993). Mismatch negativity to slight pitch changes outside strong attentional focus. *Biological Psychology, 37,* 23-41.

Pang, E. W., Edmonds, G. E., Desjardins, R., Khan, S. C., Trainor, L. J., & Taylor, M. J. (1998). Mismatch negativity to speech stimuli in 8-month-old infants and adults. *International Journal of Psychophysiology, 29*, 227-236.

Pernier, J., Perrin F., & Bertrand, O. (1988). Scalp current density fields: concept and properties. *Electroencephalography and clinical Neurophysiology, 69*, 385-389.

Perrin, F., Bertrand, O., & Pernier, J. (1987). Scalp current density mapping: value and estimation from potential data. *IEEE Transactions on Biomedical Engineering, 34(4),* 283-288.

Picton, T. W., Alain, C., Otten, L., Ritter, W., & Achim, A. (2000). Mismatch negativity: different water in the same river. *Audiology & Neuro-Otology, 5*, 111-139.

Sabri, M., & Campbell, K. B. (2001). Effects of sequential and temporal probability of deviant occurrence on mismatch negativity. *Cognitive Brain Research, 12,* 171-180.

Sams, M., Paavilainen, P., Alho, K., & Näätänen, R. (1985). Auditory frequency discrimination and event-related potentials. *Electroencephalography and clinical Neurophysiology, 62*, 437-448.

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

Scherg, M., Vajsar, J., & Picton, T. W. (1989). A source analysis of the late human auditory evoked potentials. *Journal of Cognitive Neuroscience, 1(4)*, 336-355.

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.

Shafer, V. L., Morr, M. L., Kreuzer, J. A., & Kurtzberg, D. (2000). Maturation of mismatch negativity in school-age children. *Ear and Hearing, 21(3)*, 242-251.

Shafer, V. L., Schwartz, R. G., & Kurtzberg, D. (submitted). Language-specific memory traces of phonemes in the brain. *Journal of Cognitive Neuroscience.*

Sharma, A. & Dorman, M. F. (1998). Exploration of the perceptual magnet effect using the mismatch negativity auditory evoked potential. *Journal of the Acoustical Society of America, 104(1)*, 511-517.

Sharma, A., Kraus, N., McGee, T., Carrell, T., & Nicol, T. (1993). Acoustic versus phonetic representation of speech as reflected by the mismatch negativity event-related potential. *Electroencephalography and clinical Neurophysiology, 88*, 64-71.

Stark, R. E. & Heinz, J. M. (1996). Vowel perception in children with and without language impairment. *Journal of Speech and Hearing Research, 39(4)*, 860-869.

Steinschneider, M. & Dunn, M. (in press). Electrophysiology in developmental neuropsychology. In I. Rapin & S. Segalowitz (Eds.), *The Handbook of Neuropsychology, Volume 7*. Amsterdam: Elsevier Pres.

Sussman, J. E. (1993). Perception of formant transition cues to place of articulation in children with language impairments. *Journal of Speech and Hearing Research, 36*, 1286-1299.

Sussman, J. E. & Carney, A. E. (1989). Effects of transition length on the perception of stop consonants by children and adults. *Journal of Speech and Hearing Research, 32,* 151-160.

Sussman, E., Ritter, W., & Vaughan, H. G., Jr. (1998a). Predictability of stimulus deviance and the mismatch negativity. *NeuroReport, 9,* 4167-4170.

Sussman, E., Ritter, W., & Vaughan, H. G., Jr. (1998b). Attention affects the organization of auditory input association with the mismatch negativity system. *Brain Research, 789,* 130-138.

Szymanski, M. D., Yund, E. W., & Woods, D. L. (1999). Phonemes, intensity and attention: differential effects on the mismatch negativity (MMN). *Journal of the Acoustical Society of America, 106(6),* 3492-3505.

Tallal, P. & Piercy, M. (1973). Developmental aphasia: impaired rate of non-verbal processing as a function of sensory modality. *Neuropsychologia, 11,* 389-398.

Tallal, P. & Piercy, M. (1974). Developmental aphasia: rate of auditory processing and selective impairment of consonant perception. *Neuropsychologia, 12,* 83-93.

Tallal, P. & Piercy, M. (1975). Developmental aphasia: the perception of brief vowels and extended stop consonants. *Neuropsychologia, 13,* 69-74.

Tallal, P. & Stark, R. E. (1981). Speech acoustic-cue discrimination abilities of normally developing and language-impaired children. *Journal of the Acoustical Society of America, 69(2),* 568-574.

Tallal, P., Stark, R. E., Kallman, C., & Mellits, D. (1980). Developmental dysphasia: relation between acoustic processing deficits and verbal processing. *Neuropsychologia, 18,* 273-284.

Trejo, L. J., Ryan-Jones, D. L., & Kramer, A. F. (1995). Attentional modulation of the mismatch negativity elicited by frequency differences between binaurally presented tone bursts. *Psychophysiology, 32,* 319-328.

Tremblay, K., Kraus, N., Carrell, T. D., & McGee, T. (1997). Central auditory system plasticity: generalization to novel stimuli following listening training. *Journal of the Acoustical Society of America, 102(6),* 3762-3773.

Vihla, M, Lounasmaa, O. V., & Salmelin, R. (2000). Cortical processing of change detection: dissociation between natural vowels and two-frequency complex tones. *Proceedings of the National Academy of Sciences, 97(19),* 10590-10594.

Winkler, I., Kujala, T., Tiitnen, H., Sivonen, P., Alku, P., Lehtokoski, A., Czigler, I., Csépe, V., Ilmoniemi, R. J., & Näätänen, R. (1999). Brain responses reveal the learning of foreign language phonemes. *Psychophysiology, 36,* 638-642.

Woldorff, M. G., Hackley, S. A., & Hillyard, S. A. (1991). The effects of channel-selective attention on the mismatch negativity wave elicited by deviant tones. *Psychophysiology, 28(1),* 30-42.

Woldorff, M. G., Hillyard, S. A., Gallen, C. C., Hampson, S. R., & Bloom, F. E. (1998). Magnetoencephalographic recordings demonstrate attentional modulation of mismatch-related neural activity in human auditory cortex. *Psychophysiology, 35,* 283-292.

Woods, D. L., Alho, K., & Algazi, A. (1992). Intermodal selective attention. I. Effects on event-related potentials to lateralized auditory and visual stimuli. *Electroencephalography and clinical Neurophysiology, 82,* 341-355.