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Research Paper

Mismatch Negativity as a Tool to Detect the Intensity Just Noticeable Difference

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Mismatch negativity (MMN) essentially reflects auditory change detection. Although auditory change detection can potentially be assessed through behavioral auditory testing methods, the increased reliability of objective methods, such as MMN, makes them more valuable. The aim of this study was to detect and compare the intensity just noticeable difference using the MMN and a behavioral method. The level at which the intensity difference between the frequent stimulus and the infrequent stimulus was the lowest and the MMN wave elicited was accepted as the MMN threshold. A total of 60 subjects, 30 females (mean age 21.70, SD = 1.91 years) and 30 males (mean age 22.77, SD = 3.01), aged 20–30 years, were included in the study. In the whole sample, a significant difference was found between MMN thresholds obtained from the right ear side and MMN thresholds obtained from the left ear side, regardless of sex ($p < 0.05$). In the comparison of the values obtained using the behavioral method and MMN, no significant difference was found for either the right or the left side in both sexes ($p > 0.05$). The results showed that the values determined by the behavioral method and MMN on both the right and left ear sides were similar in both sexes.

Keywords: behavioral measurement; intensity just noticeable difference; auditory discrimination; mismatch negativity; loudness discrimination.

1. Introduction

There are challenges in behavioral measurement methods, such as understanding the task, maintaining attention on the task ,and changes in motivation. For this reason, research is needed to determine whether auditory evoked potentials can be an alternative to behavioral measurement methods. Studies conducted in this context have shown that methods using auditory evoked potentials provide objective and reliable findings when measuring central auditory processing abilities, such as auditory discrimination (Harris *et al.*, 2007). The mismatch negativity (MMN) is an objective and electrophysiological measurement that reflects the neural encoding of the dissonance occurring when infrequent stimuli with different physical properties are presented against information stored in sensory memory, where the physical properties of frequent stimuli are stored (Johnson *et al.*, 2021; Pakarinen *et al.*, 2007; Sendesen *et al.*, 2022). Acoustic parameters that are changed for infrequent stimuli include frequency, intensity, location, and duration (Rao *et al.*, 2020).

Intensity is the most fundamental property of an auditory signal. It influences a multitude of functions, from sound source localization to the neural processing of the signal (Recanzone, Beckerman, 2004). It has been reported that central auditory processing regions play a role in intensity discrimination independent of performance (Belin *et al.*, 1998; Bench, 1969). There are studies suggesting that the coding of loudness in the central auditory system may be based on the firing rate of afferent neurons (Maslin *et al.*, 2015). Therefore, it is valuable to measure intensity discrimination performance using auditory evoked late latency responses, which bring us closer to the central auditory system, and to examine the compatibility of these results with behavioral measures. In our review of the literature, we found that loudness discrimination performance has been investigated using objective methods (Harris *et al.*, 2007; He *et al.*, 2012). However, in our study, we specifically investigated and compared the smallest level of intensity that we can discriminate using MMN and behavioral methods.

The MMN serves as an auditory processing index (Rana *et al.*, 2022). It has been proposed that MMN responses arise in the primary and secondary auditory cortices, as well as the frontal cortex (Bonetti *et al.*, 2018). Reports indicate sexual dimorphism in the auditory cortex (Berchicci *et al.*, 2021). Sexual dimorphism is known to impact event-related potential (ERP) results (Berchicci *et al.*, 2021; Ikezawa *et al.*, 2008). Dimorphic effects on ERPs are typically analyzed through comparisons of latency and amplitude (Nagy *et al.*, 2003). No previous studies have compared male and female responses to MMN stimuli with minimal reductions (1 dB) in the difference between frequent and infrequent stimuli. Therefore, we conducted a study examining the smallest intensity difference (i.e., the difference in intensity level between frequent and infrequent stimuli) occurring during MMN and compared it between both sexes.

Previous studies investigated the intensity difference using MMN and compared it to the behavioral method, but the intensity change was not made in small steps as in our study (Näätänen *et al.*, 2004; O'Reilly, 2021; Pakarinen *et al.*, 2007; Rinne *et al.*, 2006). In our study, we aim to identify the lowest possible intensity difference that can produce MMN. Therefore, we examine changes in intensity in smaller steps (1 dB) to detect thresholds.

The primary aim of this study is to investigate whether MMN is a valid tool for assessing intensity just noticeable difference (intensity JND). Our main hypothesis is that MMN can be used as an objective tool for intensity JND. In addition to the primary aim, it is of interest to determine whether there is a significant difference between men and women in the values of the smallest intensity change that can be detected both electrophysiologically and behaviorally.

2. Method

This study was approved by the Üsküdar University Ethics Committee (61351342/February 2021-33). Young adults with normal hearing, aged of 20–30 years, were selected based on otoscopic examination, audiometric evaluations (Mehta, Oxenham, 2018; Wiley *et al.*, 1987), tympanometric examination (Mishra *et al.*, 2021), acoustic reflex thresholds (Wiley *et al.*, 1987), and distortion product otoacoustic emission (Harris, 1990) among all volunteers. A total of 60 normal-hearing participants were included in our study (30 women – mean age 21.70, SD = 1.91, and 30 men – mean age 22.77, SD = 3.01), first enrolled in the MMN session, followed by the behavioral session.

The MMN was recorded with the Eclipse system by the Interacoustic device to detect the minimum amount of change in intensity. Stimuli were presented in a traditional oddball paradigm. The infrequent stimulus was set to differ only in intensity from the frequent stimulus, and all other parameters remained the same. The stimulus parameters are demonstrated in Table 1. A sampling number of 200 was used for each measurement. The wave with the most negative peak occurring 150 ms–250 ms after the onset of the stimulus was accepted as the MMN. MMN amplitudes were calculated by placing one reference cursor on the positive peak of the preceding wave and the other on the MMN trough.

Table 1. Stimulus parameters.

Frequency	1000 Hz tone burst
Time	70 ms (10–50–10)
Rate	0.7 Hz
Polarity	Rarefaction
Gain	±80 μV
High pass filter	1.0 Hz (6 dB/oct)
Low pass filter	100 Hz
Frequent stimulus rate	80 %
Infrequent stimulus rate	20 %
Stop criteria/number of stimuli	100
Reject rate	<20 %
Impedance	2 kΩ–3 kΩ

In the study, the frequent stimulus was set at 60 dB nHL for a comfortable audible level. The infrequent stimulus was presented with 1 dB decrements, starting from 70 dB nHL (+10 dB), 69 dB nHL (+9 dB), ..., 66 dB nHL (+6 dB), 65 dB nHL (+5 dB), ..., 61 dB nHL(+1 dB), up to the final level at which the MMN wave could be elicited. In order to ensure the reliability of the waveform, two measurements were taken. Specifically, if the MMN waveform was elicited again in the second measurement, the wave was considered reliable. The level at which the intensity difference between the frequent stimulus and the infrequent stimulus was the lowest and the MMN wave was elicited again was accepted as the MMN threshold, representing the intensity JND that the participants could objectively detect.

The areas on the head where the electrodes were to be placed were cleaned and the reference electrodes were placed on the right and left mastoids, the active electrode on the hairline (Fz), and the ground electrode on the middle region of the forehead (Fpz).

Stimuli were presented unilaterally with 3M E-A-R tone insert earphones. Participants were seated in a chair with their eyes open and were instructed not to pay attention to the stimulus. Instead, they were asked to count from 100 to 0 is steps of 3 (e.g., 100–97–94, ...). Since ocular monitorization was not available in the clinic, participants were asked not to move their eyes as much as possible to keep the reject rate low.

Behavioral measurements were conducted in the silent cabin where the audiological evaluation was made. Pairs of stimuli, each with a length of 500 ms and a frequency of 1000 Hz, were presented to the participants. They were asked to indicate the pairs as "different" or "the same" in terms of their intensity. The intensities of the stimuli were sent in such a way that the difference between them was high at the beginning, so that individuals could adapt to the experiment. The differences were then gradually decreased, as in the MMN protocol.

The pairs of stimuli were first sent as 60 dB HL–70 dB HL, 60 dB HL–69 dB HL, ..., 60 dB HL–66 dB HL, 60 dB HL–65 dB HL, ..., 60 dB HL–61 dB HL, with the first stimulus remaining constant and the second stimulus was decreased in 1 dB steps. The behavioral threshold, which represented the intensity JND that participants could detect, was defined as 1 dB above the level at which participants identified the pairs as the same.

Stimuli used in both electrophysiological and behavioral tests were presented monaurally and the two ear sides were tested separately.

2.1. Statistical analysis

IBM SPSS Statistics (v.25) was used in all statistical analyses. The Mann-Whitney U-test was used to compare numerical measurements based on sex, and the Wilcoxon signed-rank test was used for comparisons between the ear sides of the same individuals. The level of significance was set at $\alpha = 0.05$. Correlation analyses were conducted to examine the relationship between electrophysiological thresholds and behavioral threshold measures. Pearson correlation analysis was used for normally distributed data, and Spearman correlation analysis was used for non-normally distributed data. The significance value was accepted as $p < 0.05$. Correlation analyses were evaluated according to the classification proposed by Evans (1996).

3. Results

According to the MMN test, the mean amplitude value obtained from the right ear side was 2.92 μV (SD = 1.34), the mean latency value was 223.37 msn (SD = 35.57), the mean amplitude value obtained from the left ear side was 2.95 μV (SD = 1.37), and the mean latency value was 211.77 msn (SD = 32.49).

There was no significant difference between women (mean = 2.91 μV, SD = 1.26) and men (mean = 2.93 μV, SD= 1.43) in terms of MMN amplitude values obtained from the right side ($p = 0.988$). Likewise, there was no significant difference between women (mean = 220.46 msn, SD = 39.79) and men (mean = 226.26 msn, SD = 31.20) in terms of MMN latency values obtained from the right side ($p = 0.871$). Furthermore, there was no significant difference between women (mean = 2.91 μV, SD = 1.26) and men (mean = 2.93 μV, SD = 1.43) in terms of MMN amplitude values obtained from the left side ($p = 0.988$). Moreover, there was no significant difference between women (mean = 213.33 msn, SD = 36.83) and men (mean = 210.20 msn, SD = 28.03) in terms of MMN latency values obtained from the left side ($p = 0.790$).

When the MMN threshold values were compared between the right and left sides, the values obtained from the right side (mean = 5.41 dB, SD = 1.75) were significantly lower than those from the left side (mean = 5.88 dB, SD = 1.77) ($p < 0.01$).

When the behavioral threshold values were compared between the right and left sides, no significant difference was found between the values obtained from the right side (mean = 5.70 dB, SD = 2.05) and those from the left side (mean = 5.80 dB, SD = 2.04) ($p = 0.635$).

When the MMN threshold values were compared between the sexes, there was no significant difference between women (mean = 5.26 dB, SD = 1.85) and men (mean = 5.56 dB, SD = 1.67) on the right side ($p = 0.514$). Likewise, no significant difference was found on the left side between women (mean = 5.66 dB, SD = 1.72) and men (6.10 dB, SD = 1.82), ($p = 0.349$). In the comparison of the behavioral threshold values by sex, there was no significant difference on the right side between women (mean = 5.83 dB, SD = 2.29) and men (mean = 5.56 dB, SD = 1.81), ($p = 0.619$). Likewise, no significant difference was found on the left side between women (mean = 6.03 dB, SD = 2.39) and men (mean = 5.56 dB, SD = 1.61), ($p = 0.380$).

Furthermore, there was no significant difference between the MMN threshold (mean = 5.41 dB, SD = 1.75) and the behavioral threshold (mean = 5.70 dB, SD = 2.05) values obtained from the right side ($p = 0.359$). Likewise, there was no significant difference between the MMN threshold (mean = 5.88 dB, SD = 1.77) and the behavioral threshold (mean = 5.80 dB, SD = 2.04) values obtained from the left side ($p = 0.502$) (Fig. 1).

An exploratory analysis was performed due to the observation of a majority of perceptible values above 5 dB when the data were collected. The results obtained from the right side showed that the behav-

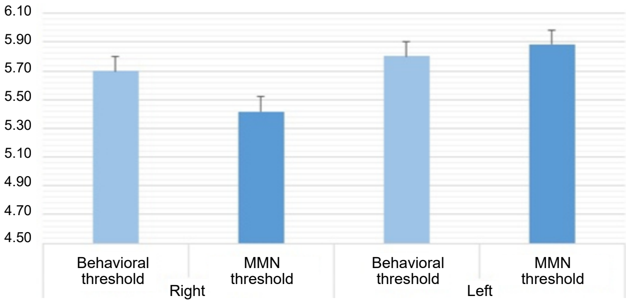

Fig. 1. Comparison of behavioral threshold and MMN threshold.

ioral thresholds (mean = 7.56 dB, SD = 1.50) were significantly higher than the MMN thresholds (mean = 5.25 dB, SD = 1.29) in women with a behavioral threshold above 5 dB on their right side ($p < 0.05$). Likewise, the behavioral thresholds (mean = 7.70 dB, SD = 1.56) were significantly higher than the MMN thresholds (mean = 6.00 dB, SD = 1.41) in men with a behavioral threshold above 5 dB on their right side ($p < 0.01$) (Table 2).

Table 2. Comparison of MMN and behavioral threshold values in male and female participants with behavioral threshold above 5 dB on the right side.

Sex	Threshold	n	Mean	SD	Z	P^1
Women	Behavioral threshold	16	7.56	1.50	−2.44	0.014*
	MMN threshold	16	5.25	1.29		
Men	Behavioral threshold	10	7.70	1.56	−3.15	0.002**
	MMN threshold	10	6.00	1.41		

[1] Wilcoxon test; * $p < 0.05$; ** $p < 0.01$.

Moreover, the results obtained from the left side showed that no significant difference was found between the behavioral thresholds (mean = 7.20 dB, SD = 1.93) and the MMN thresholds (mean = 7.00 dB, SD = 1.25) in women with a behavioral threshold above 5 dB on their left side ($p = 0.587$). However, the results obtained from the left side indicated that the behavioral thresholds (mean = 7.20 dB, SD = 1.93) were significantly higher than the MMN thresholds (mean = 5.70 dB, SD = 1.68) in men with a behavioral threshold above 5 dB on their right side ($p < 0.05$) (see Table 3).

Table 3. Comparison of MMN and behavioral threshold values in male and female participants with behavioral threshold above 5 dB on the left side.

Sex	Threshold	n	Mean	SD	Z	P^1
Women	Behavioral threshold	20	6.80	1.14	−0.54	0.587
	MMN threshold	20	7.00	1.25		
Men	Behavioral threshold	15	7.20	1.93	−2.35	0.018*
	MMN threshold	15	5.70	1.68		

[1] Wilcoxon test; * $p < 0.05$.

As a result of the correlation analysis, on the right side, no significant correlation was found between MMN thresholds and behavioral thresholds in all participants ($p = 0.509$); however, on the left side, a significant but weak correlation was observed between MMN thresholds and behavioral thresholds in all participants ($r = 0.259$, $p = 0.044$).

4. Discussion

In our study, the mean behavioral threshold was 5.7 dB (SD = 2.05) for the right side and 5.8 dB (SD = 2.04) for the left side. The threshold values obtained for the right and the left sides were similar. When we look at the studies in the literature investigating intensity discrimination using behavioral measures, it is observed that the intensity JND is between 3 dB–5 dB (Dorta *et al.*, 2017; He *et al.*, 1998). Participants whose level of intensity JND was greater than 5 dB were statistically evaluated separately. The proportion of participants with a behavioral threshold higher than 5 dB, regardless of right-left side and sex, was 58.30 %. When analyzed in terms of sex, women constituted 60 % of this group and men accounted for 41.20 %.

Moreover, in a study conducted with children, auditory discrimination was investigated with frequency variation and it was also examined whether there was a sex effect on the results. It was found that boys were better than girls at discriminating frequencies (Zaltz *et al.*, 2014). In another study evaluating magnitude estimations, the sample consisted of 22 young adults and it was found that there was no sex difference in the results (Weder *et al.*, 2020). Consistent with these findings, our results showed that intensity JND for both the right and left sides was similar for men and women. That is to say no sex difference was observed. In addition, the behavioral thresholds for the right side and left side showed similarity across the entire sample, regardless of sex.

Several studies investigated auditory discrimination with different variables such as frequency, duration, and intensity by both behavioral and electrophysiological methods. These studies have mostly shown that electrophysiological and behavioral methods are related in terms of the frequency, intensity, and duration parameters. He *et al.* (2012) tested the auditory discrimination performance with electrophysiological and behavioral methods and compared the results. In their study, the acoustic change complex (ACC) is used as an electrophysiological method. For each of the frequency, intensity and duration variables, the minimum levels that can elicit the ACC were accepted as objective thresholds. As a result, the mean of the objective threshold for intensity discrimination was obtained as 2 dB and it was understood that it showed a significant correlation with behavioral thresholds.

Furthermore, in another study, which was conducted to determine whether ACC can be an objective indicator of intensity discrimination in children with central auditory processing disorder, it was understood that ACC could be an objective tool for detecting the minimum amount of change in intensity as a result of comparing the behavioral discrimination thresholds (Kumar *et al.*, 2020). In our study, the average objective and behavioral thresholds were obtained in the control group in the range of 2 dB–4 dB, as expected.

In another study, using the $N1$–$P2$ response as the electrophysiological method, behavioral thresholds and $N1$–$P2$ thresholds were compared, and it was shown that they were similar (Harris *et al.*, 2007). Electrophysiological tests, as demonstrated in exemplary studies, have proven to be viable alternatives to behavioral methods. In this context, our study, while comparing behavioral and electrophysiological thresholds in terms of intensity JND, showed that behavioral thresholds and MMN thresholds were similar for both the right and left sides.

Studies have found that behavioral hearing tests, which identify cortical areas stimulated by pure tones, show a broad distribution across the cortex (Belin *et al.*, 1998; Bianchi *et al.*, 2017; Zhang *et al.*, 2006). However, the MMN response, which originates from the frontotemporal region, is more specific (Fitzgerald, Todd, 2020; Wagner *et al.*, 2023). Our study compared behavioral thresholds and MMN thresholds, and found that participants with behavioral thresholds above 5 dB had significantly higher thresholds compared to MMN thresholds. This difference in performance was likely due to cognitive fatigue from the involvement of multiple cortical regions in the behavioral task. Interestingly, on the left side, the behavioral thresholds and MMN thresholds for women were similar (Table 3), which may be due to the small sample size rather than the expected increase in behavioral responses associated with a larger number of cortical regions.

On the left side, there was a weak correlation between MMN thresholds and behavioral thresholds. When we searched the literature, we could not find any grounds for discussion that could explain this result, so we hypothesize that the result was due to the inhomogeneous sample distribution (we used the Mann-Whitney U-test). It is anticipated that if the sample were more homogeneous, the significant correlation observed on the left side might also be evident on the right side. In such a case, the MMN could become a reliable tool for objectively detecting individual intensity JND.

Barrett and Fulfs (1998) reported that there was no significant difference in MMN latency values between sexes in healthy young adults when measured with a frequency of 1000 Hz. Our current study showed similar results in terms of latency as there was no significant difference in latency between men and women for both the right and left sides. In another study investigating the effect of sex on MMN in healthy young adults, it was found that the MMN latencies were significantly longer in females compared to males (Toufan *et al.*, 2021). On the other hand, there is no study in which the MMN amplitude was compared by sex. Hence, further research with larger samples is needed to compare both amplitude and latency values of MMN with respect to sex and ear side.

The role of attention in the MMN test is a controversial topic in the literature. There are studies reporting that MMN formation requires active attention (Sussman *et al.*, 2014; Rahne *et al.*, 2014), while others report that it does not require active attention – such as when participants are watching a film or performing a mental task (Ikezawa *et al.*, 2008; Näätänen, 1990; 1995; Näätänen, Winkler, 1999). We developed our methodology based on references supporting the notion that "MMN can occur without active attention". Furthermore, there is little information in the literature about ERPs elicited by passive listening. This information is crucial for better understanding on how the brain prepares and responds to sounds without an active task. As the result of our study confirms our hypothesis, MMN may have potential for clinical use for assessing JND intensity in populations that are unable to direct active attention to the task and are difficult to test behaviorally, such as children and the elderly.

The reliability of the traditional oddball paradigm is controversial, primarily because the infrequent stimulus differs from the frequent stimulus both physically and numerically (Wiens *et al.*, 2019). Alternative models to the traditional oddball paradigm have been created (Ruhnau *et al.*, 2012; Schröger, Wolff, 1996). However, the problem with these models is that the MMN response is considerably reduced for various reasons (Jacobsen, Schröger, 2003). The discussion on this subject is ongoing. Since the studies we used in our method were conducted with the traditional oddball paradigm, we preferred to use the traditional oddball paradigm in our study, in which 20 % of the infrequent stimuli and 80 % of the frequent stimuli were presented (Sadia *et al.*, 2013; Sussman, 2007).

Although the use of MMN as an alternative to behavioral methods in auditory discrimination is controversial (Sussman *et al.*, 2014), there was no significant difference between MMN thresholds and behavioral thresholds in our study. In other words, according to our study, MMN can be used as an alternative tool to behavioral methods.

5. Conclusions

In this study, we compared MMN and behavioral thresholds across the entire sample without discriminating the sample in terms of factors that may affect auditory discrimination performance, such as sex, intelligence level, and hemispheric dominance. However, since a significant portion of the sample had behavioral discrimination thresholds above 5 dB, we performed a comparison of MMN and behavioral thresholds in this subgroup, accounting for sex discrimination. Future studies should analyze a larger sample and consider all the factors mentioned to provide a more comprehensive understanding.

6. Limitations

Since the equipment used for the behavioral study did not have the same setup as the MMN equipment, there was a discrepancy in stimulus duration; while 1000 Hz tone bursts with a duration of 70 ms were used in the MMN, the duration of 1000 Hz tone stimuli could be reduced to a maximum of 500 ms in the behavioral assessment. This variation in stimulus duration was considered a limitation because it introduced a difference in duration between the behavioral test and MMN stimuli.

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