



Effect of acoustic features on discrimination ability in individuals with auditory neuropathy spectrum disorder: an electrophysiological and behavioral study

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Abstract

Purpose The present study aimed to investigate the discrimination ability for acoustic cues in individuals with auditory neuropathy spectrum disorder (ANSD) using both behavioral and neural measures and to compare the result with normal hearing individuals.

Methods Four naturally produced syllables /ba/, /da/, /ma/ and /pa/ were used to study discrimination skills. They were combined in pairs such that the two syllables differ in acoustic features, that is place (/ba/–/da/), manner (/ba/–/ma/) and voicing (/ba/–/pa/) cues. Thirty individuals with ANSD and 30 individuals with normal hearing sensitivity were the participants. Syllable discrimination skill was assessed using behavioral (reaction time, sensitivity and D-prime) and neural (P300) measures.

Results There was prolongation in latency and reduction in amplitude of P300 in individuals with ANSD compared to individuals with normal hearing sensitivity. Individuals with ANSD showed better discrimination skill for stimulus pairs differing in the manner followed by place and the least perceived was voicing information.

Conclusion Discrimination ability of individuals with ANSD is found to be affected as evident on behavioral and neural measures. The discrimination ability varies with acoustic features of speech.

Keywords Auditory neuropathy spectrum disorder · P300 · Discrimination skills · Acoustic features · Scalp topography

Introduction

Auditory neuropathy spectrum disorder (ANSD) is a clinical condition characterized by the normal function of cochlear amplifier and disordered neural conduction in the auditory pathway [1]. Clinically these individuals will present absent or abnormal auditory brainstem responses in presence of otoacoustic emissions and/or cochlear microphonics. Acoustic stapedial reflexes are absent. Pure-tone hearing thresholds in these individuals can range from normal hearing sensitivity to profound hearing impairment [2–4]. Typically these individuals will have speech recognition scores that are disproportionate to the pure-tone hearing loss [2, 5,

6]. Perception of acoustic temporal information is severely affected in these individuals [7, 8]. The poor temporal processing in individuals with ANSD is believed to be primarily responsible for inexplicably poor speech perception skills in these individuals [9]. The proposed sites of lesion in individuals with ANSD include inner hair cells and ribbon synapse (presynaptic disorder), unmyelinated auditory nerve dendrite, auditory ganglion cells and their axons (postsynaptic disorder), and auditory brainstem pathway [10]. Temporal bone studies have shown normal outer and inner hair cells with loss of auditory nerve fibers and/or unmyelination of fibers in adults with ANSD [11–13].

Despite the absence or severe abnormality of the auditory brainstem response, the cortical auditory potentials are typically present in individuals with ANSD [14–16]. Several researchers have recorded cortical evoked potential—both obligatory responses [14, 16, 17], and pre-attentive (such as MMN) in individuals with ANSD [15, 16, 18, 19]. Even though these reports give important information about the subconscious processing of speech in individuals with ANSD, it lacks information about the role of active attention

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while discriminating speech sounds. Apeksha and Kumar [18] reported the P300 in individuals with ANSD using multichannel EEG recording. They reported differences in scalp topography between individuals with normal hearing and with ANSD. However, they used only place of articulation distinction (/ba/–/da/). Current study extends the findings to different syllable contrasts. This will provide an opportunity to examine the effect of acoustic features on speech discrimination skills in individuals with ANSD and their neural representation. Apart from providing complimentary evidence to behavioral measures, neural responses can be used to study the brain–behavioral relationship [20]. With this need, the present study aimed to investigate the behavioral and neural correlates of active speech sound discrimination in individuals with ANSD. This study also aimed to compare the result of measures obtained from individuals with ANSD with that of individuals with normal hearing sensitivity.

Materials and methods

Thirty individuals diagnosed as having ANSD (14 males and 16 females) and 30 age-matched individuals with normal hearing sensitivity were the participants. All the participants were in the age range of 16–48 years (mean age of 28.26 years). Individuals with ANSD were diagnosed based on the recommended given by Starr et al. [21]. As per the recommendation, all the participants with ANSD should have otoacoustic emission, abnormal auditory brainstem responses, and normal tympanometry results with absent acoustic reflexes. All the participants with ANSD reported of difficulty in understanding speech, especially in a noisy situation. The audiometric thresholds of the individuals with ANSD ranged from normal hearing sensitivity to moderate hearing loss bilaterally. The individuals with ANSD having speech identification scores greater than 30% were considered for the study as individuals with poor identification scores might not be able to perform the discrimination task. The individuals with scores less than 30% in both the ears were excluded from the study. The demographic and the audiological details of all the individuals with ANSD are given in Table 1. The individuals in the control group were recruited from the general population following random selection criteria. All the individuals in the control group had hearing sensitivity within normal limits, with normal otoacoustic emission, auditory brainstem response and immittance findings. Informed consent was taken from all the participants of this study using the form following the “Ethical Guidelines for Bio-behavioural Research Involving Human Subjects” [22]. Institutional ethical committee approval was taken prior to the commencement of the study.

Stimuli

Four naturally produced speech syllables /ba/, /da/, /ma/ and /pa/ were used to elicit P300 responses and behavioral discrimination scores in individuals with ANSD. All the four stimuli had duration of 240 ms and were made equal by editing the vowel portion of the syllables, in order to minimize the use of durational cues. Neuroscan Scan 4.5 system (Compumedics, Charlotte, NC, USA) along with QuickCap™ with 64 electrodes were used to record P300 response. Fastrack 3D digitizer (Polhemus, Colchester, USA) was used to digitize the location of the electrodes before the EEG recording.

P300 response was recorded in the oddball paradigm for the three syllable pairs (/ba/–/da/, /ba/–/ma/ and /ba/–/pa/) with stimuli /ba/ as the frequent stimuli (80%) and /da/, /ma/ and /pa/ as the infrequent stimuli (20%). These three syllable pairs were considered as they differ in acoustic features, place (/ba/–/da/), manner (/ba/–/ma/) and voicing (/ba/–/pa/) and the individuals with ANSD are found to have difficulty perceiving these syllables [23]. Total of 250 tokens was used for recording P300 response in the oddball paradigm. In the repetitive paradigm, 50 tokens of stimuli /da/, /ma/ and /pa/ were used to record the late latency response. The rationale for recording response in repetitive paradigm was to ensure the presence of P300 in the oddball paradigm. This was confirmed by comparing the response in oddball and in repetitive paradigm. The presentation sequence of syllable pairs was counterbalanced among participants in order to avoid order effect. The stimuli were presented at 75 dB SPL using loudspeaker kept at a 1-m distance and at 0° azimuth. The intensity of the signal reaching the ear was ensured to be loud enough to elicit the response and was at a most comfortable level for both the groups of participants with normal hearing sensitivity and with ANSD. EEG was recorded with left mastoid as reference and electrode between FPz and Fz as ground. The ocular movement was monitored using two sets of extraocular electrodes. One set is for monitoring vertical eye movement (above and below the eyes) and another set for horizontal (placed on outer canthi of both the eyes) eye movement. Response switch was provided to the participants in the oddball paradigm condition and was asked to press the button for the infrequent stimuli and to ignore the frequent stimuli. The reaction time (RT) and the sensitivity were calculated based on the button press response for the identification of the infrequent stimuli. The P300 latency and the amplitude of P300 response were noted and analyzed for three midline electrodes, Fz, Cz, and Pz. These three midline electrodes were chosen as they are found to have a maximum amplitude of P300 and a minimum of three electrodes are necessary to characterize the P300

Table 1 Demographic and audiological characteristics of individuals with ANSD

| Participant | Age (years)/ gender | Pure-tone | Speech identifi- | Auditory brain- | Otoacoustic emission (OAE) | Neurological evaluation | ENT evaluation |
|-------------|------------------------|-----------------------------|----------------------------|-------------------------------------|----------------------------|----------------------------|----------------|
| | | average (dB HL) RE/LE | cation scores (%) RE/LE | stem response (ABR) RE and LE | RE and LE | | |
| ANSD1 | 20/F | 32.5/36.2 | 45/40 | Response absent | Response present | ANSD | SNHL |
| ANSD2 | 16/F | 38.75/20 | 65/50 | Response absent | Response present | ANSD | SNHL |
| ANSD3 | 26/F | 15/22.5 | 90/90 | Response absent | Response present | ANSD | SNHL |
| ANSD4 | 55/M | 46.25/47.5 | 50/45 | Response absent | Response present | ANSD | SNHL |
| ANSD5 | 21/M | 30/6.25 | 50/10 | Response absent | Response present | ANSD | SNHL |
| ANSD6 | 36/M | 22.5/18.75 | 30/20 | Response absent | Response present | ANSD | SNHL |
| ANSD7 | 24/M | 43.75/30 | 35/35 | Response absent | Response present | ANSD | SNHL |
| ANSD8 | 18/M | 28.75/25 | 30/30 | Response absent | Response present | ANSD | SNHL |
| ANSD9 | 20/M | 18.75/25 | 15/60 | Response absent | Response present | ANSD | SNHL |
| ANSD10 | 21/M | 31.25/35 | 40/45 | Response absent | Response present | ANSD | SNHL |
| ANSD11 | 37/F | 20/16.25 | 40/15 | Response absent | Response present | ANSD | SNHL |
| ANSD12 | 35/M | 30/22.5 | 40/25 | Response absent | Response present | ANSD | SNHL |
| ANSD13 | 19/F | 36.25/23.75 | 30/20 | Response absent | Response present | ANSD | SNHL |
| ANSD14 | 26/F | 28.75/22 | 45/35 | Response absent | Response present | ANSD | SNHL |
| ANSD15 | 54/M | 41.25/36.25 | 40/35 | Response absent | Response present | ANSD | SNHL |
| ANSD16 | 20/M | 31.25/32.5 | 50/45 | Response absent | Response present | ANSD | ANSD |
| ANSD17 | 27/M | 35/30 | 45/40 | Response absent | Response present | ANSD | ANSD |
| ANSD18 | 18/F | 48.75/52.5 | 60/55 | Response absent | Response present | ANSD | SNHL |
| ANSD19 | 48/M | 31.25/30 | 45/35 | Response absent | Response present | ANSD | SNHL |
| ANSD20 | 36/F | 47.25/37.25 | 68/76 | Response absent | Response present | ANSD | ANSD |
| ANSD21 | 21/F | 10/12.5 | 45/65 | Response absent | Response present | ANSD | SNHL |
| ANSD22 | 30/M | 22.5/20 | 30/25 | Response absent | Response present | ANSD | SNHL |
| ANSD23 | 24/F | 35/45 | 35/45 | Response absent | Response present | ANSD | SNHL |
| ANSD24 | 37/F | 53.75/41.25 | 60/45 | Response absent | Response present | ANSD | SNHL |
| ANSD25 | 17/F | 37.5/28.75 | 75/40 | Response absent | Response present | ANSD | SNHL |
| ANSD26 | 17/F | 27.5/33.75 | 25/25 | Response absent | Response present | ANSD | SNHL |
| ANSD27 | 41/F | 8.75/7.4 | 30/45 | Response absent | Response present | ANSD | SNHL |
| ANSD28 | 20/F | 17.5/15 | 20/15 | Response absent | Response present | ANSD | SNHL |
| ANSD29 | 24/M | 28.75/31.25 | 35/40 | Response absent | Response present | ANSD | SNHL |
| ANSD30 | 40/F | 45/43.75 | 50/50 | Response absent | Response present | ANSD | SNHL |

ANSD auditory neuropathy spectrum disorder, RE right ear, LE left ear, SNHL sensorineural hearing loss, F female, M male

response [24]. Responses from all the 64 channels were used to study scalp topography.

Behavioral syllable discrimination scores were obtained by presenting pairs of stimuli in random order using ‘AX’ paradigm. Syllables were paired with another syllable that differed in one of the phonetic features that is, place (/ba/–/da/), manner (/ba/–/ma/) and voicing (/ba/–/pa/). Total of three pairs of stimuli (/ba/–/da/, /ba/–/ma/, and /ba/–/pa/) were presented in random order to the participants. The total number of the presentation was 50 inclusive of 20 catch trials. Catch trials included stimuli belonging to the same category (/ba/–/ba/, /da/–/da/, /ma/–/ma/ and /pa/–/pa/) and was presented in between the trials in random order. The participants performed a same–different judgment task. A

laptop was kept in front of the participants showing two blocks on the screen with the orthographic script “same” and “different” being displayed. The participants had to listen to the pair of stimulus and say whether both the stimuli presented are same or different.

Data analyses

A script was written for the analysis of the neural response in the oddball and repetitive paradigm. The script included DC offset correction, ocular artifact reduction, filtering, epoching, baseline correction and re-referencing to an average of the mastoids. The responses were epoched from 200 ms pre-stimulus to 800 ms post-stimulus. Filtering was done using

FIR filter with bandpass of 0.1 to 30 Hz. The amplitude, latency and scalp topography were analyzed using the Cartool software. A positive peak in the P300 recording for the infrequent stimuli after a time range of 300 ms in the oddball paradigm condition is considered as P300 response. The RT is measured as the time gap between the presentation of the stimulus and the response [25, 26]. It was measured in millisecond. Sensitivity measure the strength of the signal. It is a static incorporating both hit rate and false alarm rate [27]. Hit rate is the defined as the percentage of correct identification of the infrequent stimuli, whereas false alarm rate is defined as the percentage of incorrect identification of the infrequent stimuli in the control condition.

The scalp topography analysis was done using the Cartool software. The steps involved in this analysis were similar to that reported by other researchers [28–30]. The segmentation was based on the cluster analysis. The segmentation was carried out on the grand averaged waveforms. It was depicted as the color-coded global field power (GFPs) with each color representing different cluster map. The clustering method used for this study was topographic atomize and agglomerate hierarchical clustering implemented in Cartool.

For the behavioral discrimination task, D' -prime (d') was calculated for three pairs of syllables which differ in acoustic features on same–different judgement task. d' was calculated using formula, $d' = z(\text{hit rate}) - z(\text{false alarm rate})$. The hit rate and the false alarm rate are same as that defined for the sensitivity measure.

Results

The neural response from 30 individuals with normal hearing and 28 individuals with ANSD were considered for the final analysis, as the neural response from two individuals with ANSD showed large electrical artifacts and thus were

excluded from the analysis. The RT and the sensitivity values obtained from the button press response are shown in Fig. 1 and Table 2. From Fig. 1 and Table 2, it is clear that the individuals with ANSD took longer to identify the oddball compared to individuals with normal hearing sensitivity. Sensitivity also showed poorer response for individuals with ANSD but was found to be more than 90% for all the stimulus pairs. Furthermore, Mann–Whitney U test showed that individuals with ANSD had significantly poor sensitivity compared to normal hearing individuals in identifying the infrequent stimuli for all three stimuli contrasts $-/ba/-/da/$ ($z = 4.82$, $p < 0.001$), $/ba/-/ma/$ ($z = 4.16$, $p < 0.001$) and $/ba/-/pa/$ ($z = 4.75$, $p < 0.001$) with large effect size for all the three contrast ($r > 0.50$). Mann–Whitney U test also revealed that individuals with ANSD had significantly longer RT compared to normal hearing individuals in identifying the infrequent stimuli for all three stimuli contrasts— $-/ba/-/da/$ ($z = 4.48$, $p < 0.001$), $/ba/-/ma/$ ($z = 4.01$, $p < 0.001$) and $/ba/-/pa/$ ($z = 4.31$, $p < 0.001$) with large effect size ($r > 0.50$) for all the three contrasts.

Table 2 Reaction time and the sensitivity measures in normal hearing individuals and in individuals with ANSD for the three syllable contrast

| Measures | Stimulus pairs | Individuals with normal hearing | | Individuals with ANSD | |
|-------------|----------------|---------------------------------|--------|-----------------------|--------|
| | | Mean | SD | Mean | SD |
| RT (ms) | $/ba/-/da/$ | 441.69 | 106.20 | 592.37 | 109.03 |
| | $/ba/-/ma/$ | 451.63 | 100.58 | 582.31 | 122.38 |
| | $/ba/-/pa/$ | 441.06 | 102.83 | 589.67 | 103.23 |
| Sensitivity | $/ba/-/da/$ | 0.986 | 0.022 | 0.902 | 0.147 |
| | $/ba/-/ma/$ | 0.995 | 0.0008 | 0.971 | 0.065 |
| | $/ba/-/pa/$ | 0.992 | 0.012 | 0.927 | 0.095 |

SD standard deviation, ms millisecond, RT reaction time

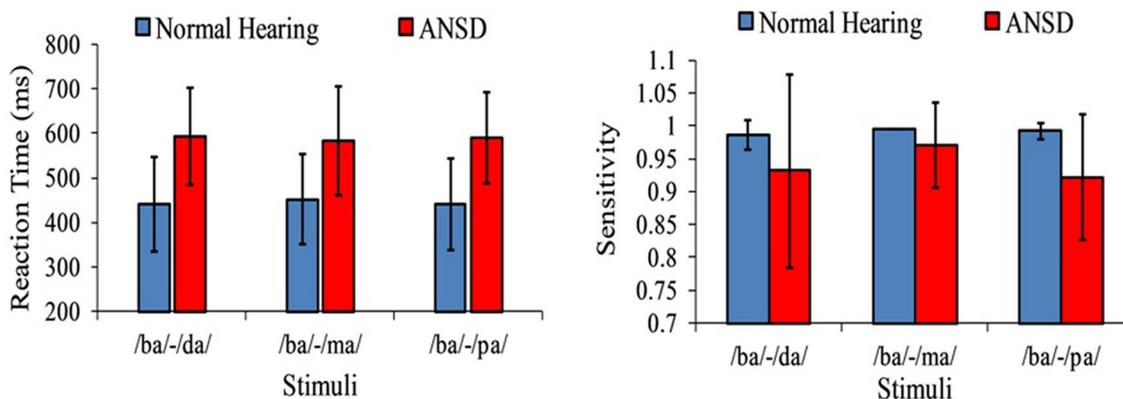


Fig. 1 Reaction time (RT) and sensitivity values obtained from individuals with normal hearing sensitivity and with ANSD. The error bar shows one standard error

Comparison of neural response in oddball and in repetitive paradigm showed a clear P300 response in both the groups of individuals with normal hearing and with ANSD as shown in Fig. 2. There was prominent P300 response for all the three stimulus pairs in the time range from 300 ms to 700 ms as observed from different channels and also on the GFP. Visual inspection of P300 response obtained from both the groups showed a significant difference in response pattern across time range. Presence of P300 was further statistically confirmed by performing a randomization test with 10,000 permutations at each time point between waveforms obtained from individuals with normal hearing and with ANSD and the result is shown in Fig. 3.

Mann–Whitney U test done to compare the latency and the amplitude parameters of P300 response across individuals with normal hearing and with ANSD, showed significantly longer latency ($p < 0.01$) for individuals with ANSD for all the three syllable contrast (/ba-/da/, /ba-/ma/ and /ba-/pa/) at three midline electrodes (Fz, Cz, and Pz). Amplitude of P300 showed significant reduction in individuals with ANSD for syllable pairs /ba-/da/ at Cz ($z = 2.66$, $p < 0.01$) and Pz ($z = 3.02$, $p < 0.01$), and for syllable contrast /ba-/ma/ at Cz ($z = 2.11$, $p < 0.05$) and Pz ($z = 2.01$, $p < 0.05$) electrode sites.

In individuals with ANSD, latency of P300 response was significantly longer for syllable pairs /ba-/da/ than /ba-/pa/ at Fz ($z = 2.37$, $p < 0.05$) and for /ba-/ma/ than for /ba-/pa/ at Cz ($z = 2.39$, $p < 0.05$) and Pz ($z = 2.44$, $p < 0.05$) electrode locations. Amplitude of P300 showed significantly higher amplitude only for /ba-/ma/ than for /ba-/pa/ at Fz ($z = 2.17$, $p < 0.05$) electrode location.

When compared across stimuli, P300 response obtained from individuals with normal hearing did not show significant difference in terms of latency and amplitude of P300 response. Individuals with ANSD showed significantly higher latency for /ba-/ma/ compared to /ba-/pa/ at Cz ($z = 2.39$, $p < 0.05$) and Pz ($z = 2.44$, $p < 0.05$) electrode location, whereas P300 amplitude of /ba-/ma/ at Fz location was significantly higher ($z = 2.17$, $p < 0.05$) than that of /ba-/pa/ stimuli.

Topographical pattern analysis was performed to check for the significant topographical configuration in both the groups of individuals with normal hearing and with ANSD. A total of 6 statistically significant template maps accounted for 90% of the variance with the group average data are shown in Fig. 4. From Fig. 4, it can be observed that the scalp activation pattern is similar across all the stimulus conditions in the time range from 300 ms to 450 ms with

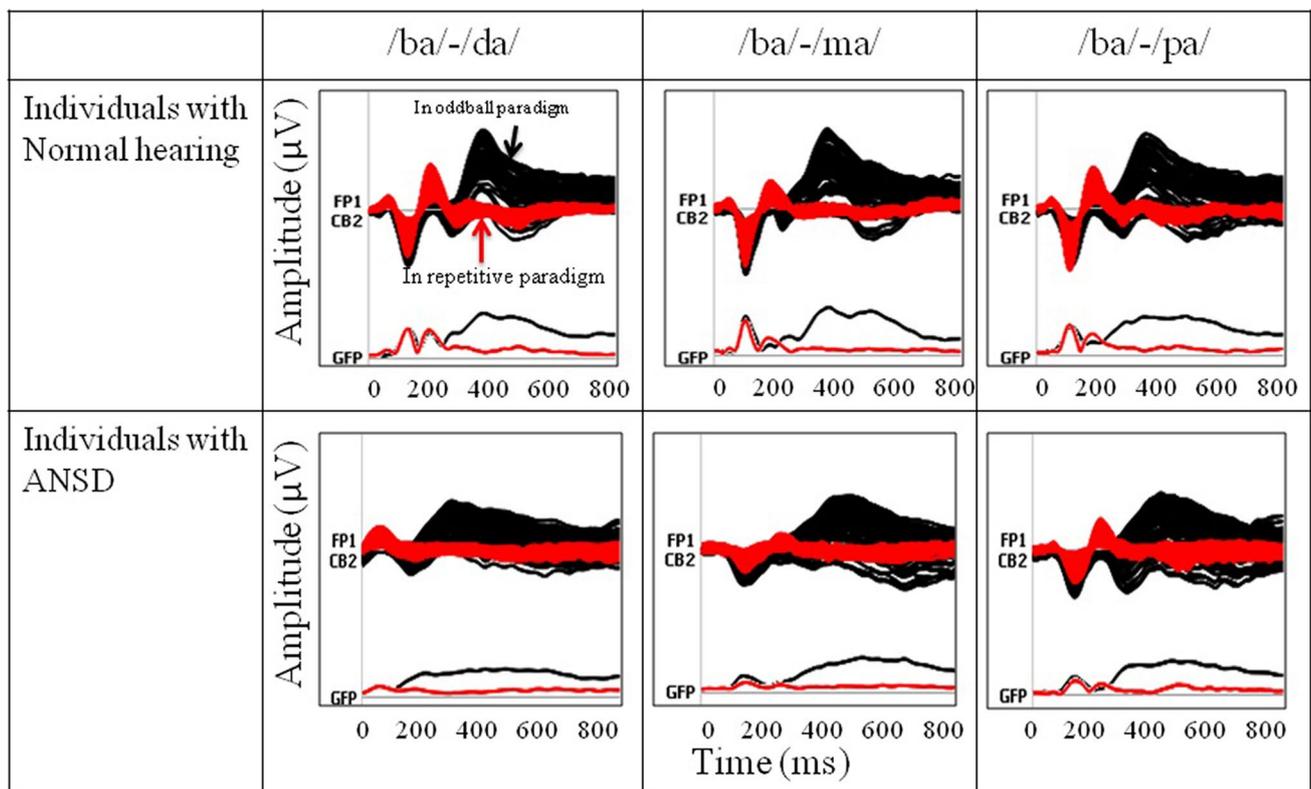


Fig. 2 The P300 response obtained for the three stimulus contrast (/ba-/da/, /ba-/ma/, and /ba-/pa/) from individuals with normal hearing and with ANSD. Tracing in black shows the response obtained in oddball paradigm and the tracing in red shows response in repetitive paradigm

Fig. 3 The neural response obtained from individuals with normal hearing (tracing in black) and with ANSD (tracing in red) in oddball paradigm for all the three stimuli pairs (/ba-/da/, /ba-/ma/, and /ba-/pa/). The lower panel of the figure shows the randomized unpaired *t* test result. The dark shaded region in the lower panel represents the area of significant difference ($p < 0.05$) between both the groups. *x*-axis represents time and *y*-axis represents scalp electrodes

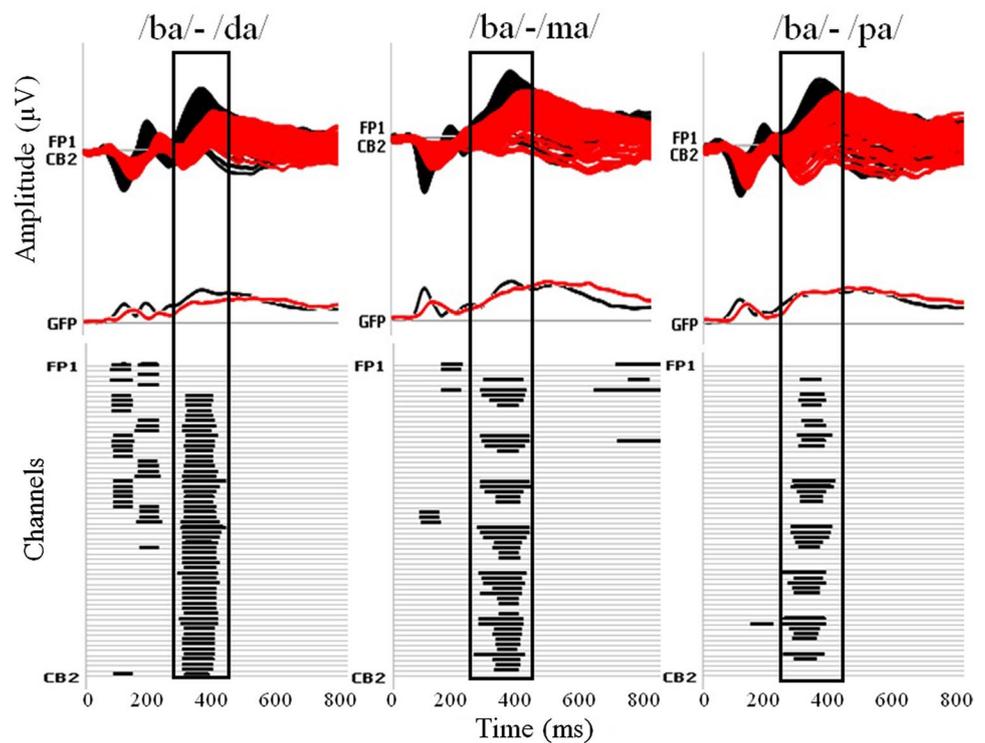
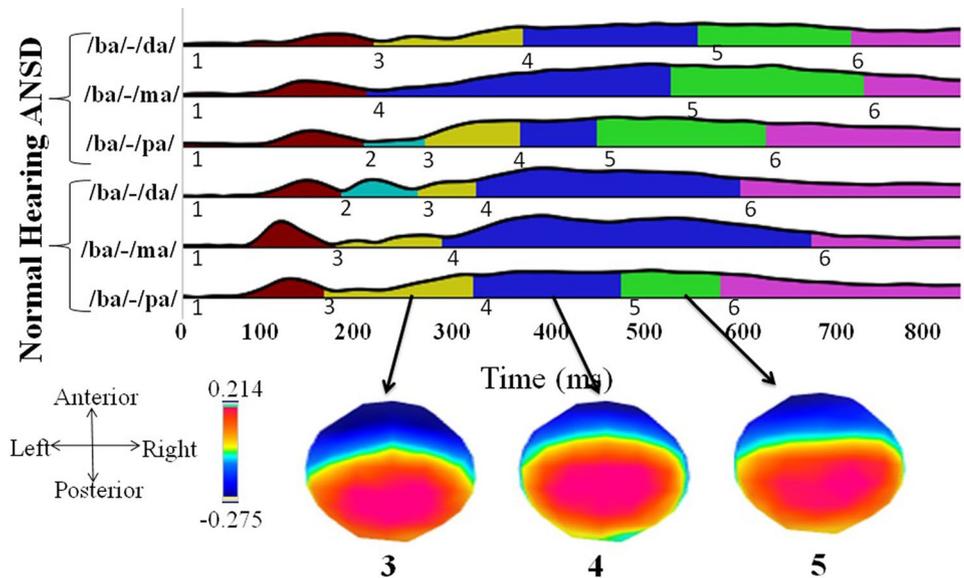


Fig. 4 Topographic pattern analysis result obtained from individuals with normal hearing and with ANSD for all the three syllable contrast (/ba-/da/, /ba-/ma/, and /ba-/pa/). The six global field power obtained from both the groups are shown. The figure shows three significant template maps obtained from both the groups in the P300 time range. The lower panel shows the difference in scalp topography across time



more activation in the centroparietal region (Template 4). Individuals with ANSD showed a slight but significantly different activation pattern after 450 ms with more centroparietal–occipital (Template 5) activation compared to individuals with normal hearing. Similar scalp activation pattern was seen for all the stimuli pairs as shown by the GFPs.

In behavioral discrimination task, the d' obtained from three individuals with ANSD showed negative values which might be because of the response confusion and thus the data obtained from these three individuals were excluded

from the data pool for the further statistical analysis. Figure 5 and Table 3 show the d' values obtained from individuals with normal hearing sensitivity and with ANSD. Mann–Whitney U test result showed significant lower d' values for /ba-/da/ ($z = 2.01$, $p < 0.05$), /ba-/ma/ ($z = 2.35$, $p < 0.05$) and /ba-/pa/ ($z = 4.25$, $p < 0.001$) for individuals with ANSD compared to individuals with normal hearing. When compared across stimulus pairs in individuals with ANSD, d' value was maximum for /ba-/ma/ followed by /ba-/da/ and was least for /ba-/pa/ pair. In individuals

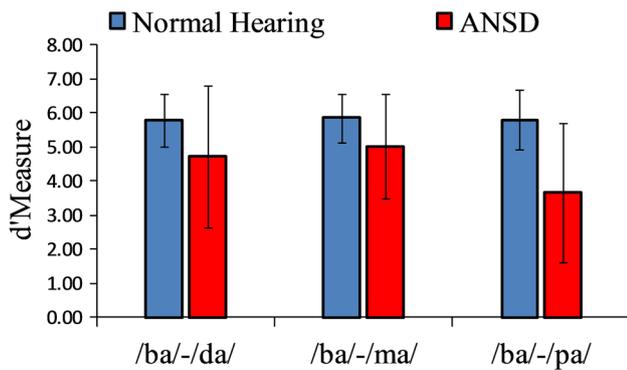


Fig. 5 The result of behavioral discrimination task (d' measure) obtained from individuals with normal hearing and with ANSD

Table 3 Mean and standard deviation of d' obtained from individuals with normal hearing and with ANSD

| | Individuals with normal hearing | | Individuals with ANSD | |
|-----------|---------------------------------|------|-----------------------|------|
| | Mean | SD | Mean | SD |
| /ba/-/da/ | 5.79 | 0.79 | 4.74 | 2.09 |
| /ba/-/ma/ | 5.86 | 0.72 | 5.03 | 1.53 |
| /ba/-/pa/ | 5.80 | 0.87 | 3.65 | 2.04 |

SD standard deviation

with ANSD, Wilcoxon signed rank test showed significantly higher d' values for /ba/-/da/ compared to /ba/-/pa/ pair ($z = 2.31$, $p < 0.05$) and /ba/-/ma/ compared to /ba/-/pa/ pair ($z = 3.34$, $p < 0.005$). Individuals with normal hearing did not show a significant difference for d' measure across any of the stimuli pairs ($p > 0.05$).

Discussion

Reliable P300 responses were elicited for all the three syllable contrasts (/ba/-/da/, /ba/-/ma/, and /ba/-/pa/) in both the groups of individuals with normal hearing and with ANSD. Behavioral results in individuals with ANSD indicated significantly longer RT and lower sensitivity compared to normal hearing individuals for all the three stimuli contrast indicative of additional processing time required for the discrimination of syllables in individuals with ANSD compared to normal hearing individuals. When compared across stimuli, the sensitivity was best for the manner contrast (/ba/-/ma/) followed by place (/ba/-/da/) and voicing (/ba/-/pa/) features. Similar pattern was seen on the d' measure suggesting poor processing skill for stimuli differing in place and voicing information than the manner information. The present finding is in compliance with the previous

reports using behavioral discrimination measure [31]. The discrimination of stimuli differing in place information was severely affected in individuals with ANSD compared to normal hearing individuals. Poor discrimination of place contrast could be because of the impaired ability of the individuals with ANSD to track changes in the spectrotemporal dynamic formant transition and the burst amplitude which is found to be important acoustic cues for the perception of place of articulation [6, 32, 33]. The abnormal perception of voicing contrast in individuals with ANSD could be because of the inherent low-frequency hearing loss in the majority of the individuals with ANSD and their inability to detect short-duration pre-voicing cues which contains information mainly at low frequency [34]. Coding of this low-frequency cues primarily depends on the phase-locking property of the auditory nerve fibers [35]. In individuals with ANSD, the phase-locking cues are not well represented, and hence the discrimination of syllables based on voicing information is disturbed. Manner feature was perceived best as it is represented by multiple cues and also represented by the frequency composition of the signal, found to be perceived better than the other cues in individuals with ANSD [31].

The neural response showed prolonged latency and reduced amplitude of P300 response for all the syllables contrast in individuals with ANSD compared to normal hearing individuals. Previous reports also suggest similar findings in individuals with ANSD [18, 19]. The prolongation in latency of P300 response in individuals with ANSD suggests either the sluggish in the decision-making process, or slowness in the neural conduction velocity. The prolongation in latency along with the prolongation of RT in individuals with ANSD shows their difficulty in stimulus evaluation process [36] and difficulty in speech sound discrimination. The reduction in amplitude of P300 response could be the result of an increase in memory load as the task processing demands increases [37]. Across syllable contrasts, P300 responses showed significantly better P300 amplitude and values for the /ba/-/ma/ stimulus contrast compared to /ba/-/pa/ contrast in individuals with ANSD. The poor neural encoding of /ba/-/pa/ contrast could be again because of the poor phase-locking property for the low-frequency pre-voicing cues. There was no significant difference in latency and amplitude of P300 observed between any of the stimuli pairs for individuals with normal hearing.

Topographical pattern analysis done to see the variance in scalp topography between both the groups for all the three syllable contrasts (/ba/-/da/, /ba/-/ma/ and /ba/-/pa/) showed centroparietal positivity for individuals with normal hearing sensitivity whereas activation was more in the central-parietal-occipital region in individuals with ANSD. The difference in scalp activation pattern between the individuals with normal hearing and with ANSD could be because of the difference in activation pattern of brain network and underlying

neural generators [18]. The reason for the difference in the finding in individuals with ANSD could be either because of the disturbed auditory processing at the level of the auditory nerve/brainstem or could be because of the peripheral hearing loss. This needs to be explored by including the third group of individuals with the peripheral hearing loss.

Summary and conclusion

The discrimination ability of individuals with ANSD was assessed using both behavioral as well as neural measures. The result showed poor discrimination ability for the syllables differing in voicing cues followed by place and manner was the best-perceived syllable contrast. To our knowledge, this is the first study assessing the neural discrimination ability of individuals with ANSD using multichannel EEG recording.

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Compliance with ethical standards

Conflict of interest The authors report no conflict of interest and are solely responsible for the content and writing of the paper.

Informed consent Informed consent was obtained from all individual participants included in the study.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee.

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