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Intervention technology of aural perception controllable headset for children with autism spectrum disorder

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This study explored aural perception in children with autism using an aural perception test and electrophysiological responses to sound stimuli. The results demonstrated unique responses to sound stimuli at different sound intensity levels, emphasising the need for customised noise-control strategies targeting specific troublesome frequencies. To address this issue, headset intervention technology with a hybrid active noise control system integrated with an aural perception controlling function was developed for children with autism with distinct auditory perception based on their psychoacoustic characteristics. The results showed that the noise-control strategy was effective in mitigating unpleasant feelings and reducing the loudness and sharpness of daily stimuli. The proposed aural perception controllable headset can minimise noise, leading to a noticeable reduction in the magnitude of the auditory evoked potential at the midline central brain region for children with autism exposed to certain sounds, such as heavy vehicles and thunder, providing a more pleasant aural perception. A diminished auditory evoked potential response was associated with lower annoyance and pleasant aural perception. This study suggests that the proposed aural-perception-based noise-control method has the potential to alleviate behaviours related to auditory hyperreactivity in children with autism.

Keywords Autism, Electroencephalography, Noise cancellation, Sound perception

Urban noise affects daily life and poses substantial risks to the health and well-being of city residents. Children are particularly vulnerable to the adverse consequences of noise, which can affect their physical health, cognitive development, and overall quality of life[1–4]. Children with autism are often more sensitive to sensory stimuli, including noise[5,6]. Excessive noise can lead to sensory overload and increased anxiety in children with autism. Schreck et al.[7] highlighted how noise-induced sensory sensitivities can result in behavioural challenges and difficulties in social interactions in children with autism. Children with autism report experiencing unpleasant sensations at a significantly higher rate than their typically developing peers. In Tan's study of hearing abnormalities in children with autism, it was observed that children with autism displayed a higher prevalence of hearing abnormalities compared to children with delayed language development[8]. These abnormalities include extreme distress in response to high-pitched sounds and heightened sensitivity to the names of their favourite things. Notably, hypersensitivity to these sounds was observed even at low sound intensities. Another study focused on interventions targeting hyperreactivity to environmental auditory stimuli in children with autism[9]. This study highlighted children's intolerant averse reactions to commonplace daily sounds. Examples include aversive responses, such as crying and fleeing from specific environmental sounds including vacuum cleaners or toilet flushing. Extremely loud sounds occasionally induced sensations of pain. Even low-intensity noise, such as crunching food or breathing, could cause discomfort and serve as a distraction. Moreover, noise frequency played a role in heightened hearing perception, with high- and low-frequency sounds being the most uncomfortable. Environmental noise, which is predominant at these frequencies, can trigger intolerant reactions and discomfort. To reduce environmental noise, traditional approaches include erecting barriers in different shapes[10,11] or mounting different silencing device[12–15], using double windows[16,17] or silencer[18–21]. Beyond the

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boundary of engineering noise control, attempts have been made to engage human responses to the acoustic environment in more nuanced ways. In this regard, more attention has been paid to soundscape quality and design in relation to human aural perception.

A soundscape encompasses all the sounds in an environment, emphasising human perception and understanding of the acoustic environment[22–24]. Urban noise refers to disruptive human-made sounds, and understanding it is crucial for creating pleasant urban spaces. As exemplified in Ma's study, their research highlights the intricate dynamics of urban soundscapes[25]. Noise levels in urban areas vary widely, and these noises can disrupt peaceful, quiet environments and affect health and daily routines. In contrast, soothing natural sounds, such as flowing water or bird songs, can contribute to a calming and restorative urban environment[26,27]. However, the complexity of urban environments makes isolating and controlling specific acoustic factors challenging. A study on the knowledge and awareness of ear protection devices for individuals with autism and sound sensitivity gathered insights from professionals including audiologists, teachers, and graduate students through a survey. The findings indicated that most professionals observed the use of ear protection devices. Headphones are the most common, with more than twice as many observations as earmuffs and earplugs[28]. Headphones are favoured because they create a barrier between the ears and external environment, offering a degree of sound isolation. Noise-cancelling headphones have been meticulously engineered to optimise auditory experiences by eliminating extraneous environmental noise using active noise control (ANC). A single-design case study found that wearing noise-cancelling headphones helped children with autism with auditory hyperreactivity maintain attention on their work tasks[29]. A pilot study examining the effectiveness of noise-cancelling headphones in children with autism who experienced auditory hyperreactivity revealed improved behavioural responses, especially in those who struggled to tolerate noisy classroom environments[30]. Thus, to mitigate the adverse effects of noise, noise-cancelling headphones are recommended for children with autism and heightened sensitivity to sound[31]. However, conventional noise-cancelling headphones that rely on active noise control technology primarily aim to reduce sound pressure levels without considering the distinct auditory sensations experienced by children with autism.

To design a noise-control strategy for headphones that consider the diverse aural perceptions observed in children with autism, the objectives of the study were: (1) to examine the aural perception of children with autism and auditory hyperreactivity in terms of amplitude and frequency with tonal and daily sound stimuli; (2) to investigate the relationship between subjective aural response and physical parameters of sound for quantifying aural perception of children with autism; (3) to develop a noise-control strategy based on subjective aural perception for implementation in headphones, improving negative reactions resulting from auditory hyperreactivity in children with autism; (4) to determine the relationship between the psychoacoustic annoyance, subjective aural response, and neural responses to everyday sound stimuli.

Methods

In this study, experiments were conducted in two phases. Acoustic responses were assessed over two sessions in the first phase to better understand how children with autism differ from typically developing children in terms of auditory perception. The first session concentrated on the subjective assessments of the experiments, which accurately captured how different sound stimuli were subjectively perceived by participants. In the second session, physiological acoustic responses were incorporated to depict the intermediary neural reactions to sound stimulation and their associated emotional responses. In the second phase, a noise-control strategy was developed based on the subjective aural perception of pure tones collected in the first phase. This transition from the first to the second phase is vital because in real-world applications, the noise encountered is a combination of different frequencies and amplitudes. Therefore, the second phase was conducted to evaluate the effectiveness of the proposed noise-control strategy for everyday sound stimuli.

Participants

Children with autism spectrum disorder (ASD) and children with typical development (TD) were the two participant groups considered in the first phase. Participants with ASD were recruited using purposive and snowball sampling. Initial contacts were made to a few special schools and autism centres of non-governmental organisations known to the researchers. Parents who expressed interest in having their children participate in the study were followed up by the research teams. Further invitations were sent to other socially connected parents. The TD participants were recruited through online posters in the parents' group and through word-of-mouth. A group of 50 TD children (38 males and 19 females, with a mean age of 10 ± 1.4 years) and 83 participants with ASD (75 males and 8 females, with a mean age of 9 ± 1.7 years) were enrolled in the research investigation. In the second phase, a total of 35 participants with ASD (32 males and 3 females, with a mean age of 10 ± 1.6 years), a subset of the group in phase one, were recruited.

In both phases, selected children aged 7 to 12 years, who had completed primary school, were diagnosed with autism, autistic disorder, or Asperger's syndrome. The ASD group consisted of children who had been diagnosed with autism in early childhood, typically around 3 years of age, by licenced clinical psychologists or psychiatrists in Hong Kong. The initial diagnoses were based on the criteria outlined in the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) and involved comprehensive clinical assessments. To confirm the appropriateness of the ASD diagnosis in our study, we administered the autism quotient (AQ) questionnaire to all participants[32,33]. This additional step helped to ensure the presence of significant autistic traits in our sample at the time of the study. The children could verbally respond using a five-point Likert scale. The normal hearing function of the children was evaluated using a hearing ability test involving pure-tone audiometry[34]. Across all inspected frequencies (250, 500, 1000, 2000, 4000, and 8000 Hz), the children's average hearing levels were less than 15 dB HL. The children scored 85 or higher on the Test of Nonverbal Intelligence, Fourth Edition (TONI-4)[35]. The participants with ASD scored 87 to 135, while that of the participants with TD ranged from 91 to

141. Children were determined to have no neurological disorders before their neural reactions to the auditory excitation were recorded. Additionally, participants with autism underwent a screening process for auditory hyperreactivity evaluation using the Chinese version of the sensory profile (CSP)[36]. Participants scoring 30 or lower in the corresponding auditory profile of the CSP were classified as experiencing auditory hyperreactivity, which corresponds to approximately one standard deviation below the mean for typically developing children in the Chinese population[36,37]. Ethical approval for this study was granted by the Human Subjects Ethics Subcommittee of The Hong Kong Polytechnic University (No. HSEARS20200501001). All methods were performed in accordance with relevant guidelines and regulations. Informed consent was obtained from the parents or legal guardians of all participants.

Sound stimuli

First, acoustic perception and auditory responses of both groups were evaluated. Tonal signals characterised by a range of frequencies and amplitudes were used to achieve this goal. The complete set of sound stimuli comprised 36 unique sound tracks, incorporating six distinct frequencies (0.25 kHz, 0.5 kHz, 1 kHz, 2 kHz, 4 kHz, and 8 kHz) and six varying sound intensity levels, measured in decibels hearing level (dB HL) (30, 40, 50, 60, 70, and 78 dB HL). These six central octave frequencies effectively encompassed the majority of frequency ranges commonly encountered in environmental sounds in a community setting. Secondly, environmental sounds from daily activities were selected as sound stimuli to evaluate the effectiveness of the noise-control strategy developed based on subjective aural perception. A survey with a list of 26 everyday sounds was administered in phase one to investigate whether everyday sounds invoked unpleasantness in most participants with ASD. The survey results showed that shouting, thunder, car horns, heavy vehicles, toilet flushing, and band noises of certain frequencies, such as hand dryers and hair dryers, were common unpleasant sounds reported by participants. Thus, they were selected as the environmental sound stimuli in the second phase. The entire set of everyday sound stimuli consisted of 36 tracks with six types of everyday sounds and six sound pressure levels (40, 50, 60, 70, 80, and 90 dB SPL). Each sound stimulus with a corresponding amplitude was generated for a duration of 1 s and a 20-ms onset/offset ramp and calibrated using a head and torso simulator to ensure the accurate delivery of sound stimuli.

Aural perception test

Children's subjective auditory perception was assessed using a soundproof chamber. In the experiment, a computer connected to headphones with an audio amplifier was used to present sound stimuli. Using the experimental management tool E-Prime 2.0, a random sound-stimulus sequence was generated for each participant. The program enabled researchers to affix an interstimulus interval (a period of silence) with varied durations depending on the participant's responses. A black fixation cross was displayed in the centre of the screen prior to the introduction of each auditory stimulus to draw participants' attention. Each participant was assigned a five-point Likert scale and their respective emoticons subsequent to the sound were played. Children were instructed to verbally rate their level of liking or disliking the sound. The ratings were symbolised on the display by the emoticons: 5 denoted 'strongly like' with a broadly smiling face emoticon, 4 indicated 'like' with a smiling face emoticon, 3 for 'neutral' with a neutral face emoticon, 2 signified 'dislike' with a sad face emoticon, and 1 appeared for 'strongly dislike' with a very sad face emoticon displayed on the screen. The researcher repeated the sounds to participants who were unable to perceive the sounds. To prevent habituation effects, the interstimulus duration ranged from 2 to 10 s, according to the participant's reaction[38]. The intervals ranged from 8 to 10 s for trials that received ratings of dislike (2) or strong dislike (1). The interval was 5 s for trials with a rating of 3 ('neutral'). The intervals were spread between 2 and 4 s for trials that were given ratings of 4 ('like') or 5 ('strongly like'). A total of 36 tonal sound stimuli were used for filter evaluation. Another 36 environmental sound stimuli were tested before and after application of the ANC filter. To determine repeatability, the stimuli were repeated thrice.

Electroencephalography (EEG) test

To assess the reliability and consistency of the participants' perceptions of sound stimuli, an EEG test was conducted to gauge their neural responses. Sound stimuli from an aural perception test, which features everyday sounds, were used in this study. Two intensity levels (70 and 90 dB SPL) were used instead of all the available levels, resulting in 12 sound tracks. Additionally, 12 sound tracks were generated by implementing the proposed noise-control strategy. A total of 24 sound tracks were used for the EEG testing. All sound stimuli were delivered through headphones using an audio amplifier and controlled using E-Prime 2.0. The stimuli had a duration of 200 ms and featured a 20-ms onset/offset ramp.

During the study, participants were seated comfortably in a soundproof, electrically shielded, and dimly lit room. Throughout the experiment, the children were instructed to prioritise watching a silent movie of their choice while ignoring the accompanying sounds. They were advised to remain still and to minimise blinking. EEG was sampled at a rate of 1 kHz using 8 electrodes in a 10–20 system. Four additional Ag/AgCl cup electrodes were placed near the eye to monitor the eye movement. The electrode impedances were kept below 5 kΩ. Each sound stimulus was randomly generated 40 times for each participant, with the interstimulus interval varying between 2 and 3 s. The entire test included 720 and 960 trials in phase one and two, respectively. The session lasted for approximately 55 to 75 min.

Raw EEG data were processed offline and analysed using MATLAB to explore the potential connections between aural perception and neural responses to auditory stimuli. To establish a balanced reference that did not favour one hemisphere, the data were re-referenced to the mean values of both the left and right mastoids. A windowed-sinc filter was used as the notch filter at 50 Hz with a 1650-point kernel length to remove line noise. The filter kernel is given by $h[i] = \sin(2\pi f_c i)/i\pi$. Two other windowed-sinc filters with a filter kernel length of

3300 points were used as low-pass and high-pass filters with cutoff frequencies of 40 Hz and 1 Hz, respectively. These filters work in tandem to create a bandpass filter, effectively reducing both low-frequency noise such as that stemming from body movements and high-frequency noise such as muscle artefacts. To further enhance data quality, we used an artefact subspace reconstruction method, which helped eliminate problematic channels and correct noisy segments[39]. To investigate the electrophysiological responses triggered by auditory stimuli, the continuous EEG dataset was divided into 600-ms epochs, comprising 100 ms before and 500 ms after the onset of each stimulus. The 100-ms time segments preceding each stimulus onset were used for baseline correction. Epochs displaying signal amplitudes surpassing ± 90 μV in any channel were removed from the analysis.

To ensure the reliability of our findings, we included only data encompassing the time window corresponding to slow-wave cortical auditory-evoked potentials. In this study, we refer to the first and second positive peaks as P1 and P2, respectively, which occur at approximately 50 and 200 ms, respectively. We identified the first negative trough as N1, which typically peaks at approximately 100 ms. To quantify participants' neural responses to auditory stimuli, we measured the peak amplitudes and latencies of the P1, N1, and P2 components within the temporal signals of event-related electrical potentials. These response characteristics are significantly influenced by the physical attributes of the stimulus, including sound stimulus duration, rise time, intensity level, interstimulus interval, and specific stimulus features[40,41]. To identify these three components, we narrowed our search window to the following time intervals: 20 to 120 ms for the P1 and P2 peaks and 70 to 150 ms for the N1 trough point. In our analysis, a peak was recognised as the data point exhibiting the highest positive amplitude for P1 and P2 or the most negative amplitude for N1 within these predefined time windows. Peak amplitude was calculated by determining the average magnitude of data points within a ± 1 ms window around the peak. This window encompassed the peak value, as well as the values recorded 1 ms before and after the peak. We analysed the peak amplitudes and latencies of the P1, N1, and P2 components.

Results and discussion

Pure tone

Consistency of the aural perception test was evaluated by assessing participant consistency across three repeated tests using one-way random effects, absolute agreement, and multiple measurement intraclass correlation coefficients (ICC). Participants with scores less than or equal to 0.38 were excluded from the analysis as they were deemed inconsistent. Furthermore, participants with fewer than 540 epochs after data preprocessing and cleaning were excluded, resulting in 33 participants with ASD and 12 TD participants being excluded. In total, the analysis included 50 participants with ASD (47 males and 3 females, with a mean age of 9.79 ± 1.80 years) and 38 TD participants (22 males and 16 females, with a mean age of 10.11 ± 1.49 years). The comparison of the age and scores of TONI-4, CSP auditory profile and AQ are shown in Table 1. There were no significant between-group differences in mean age ($t(86) = 0.875$, $p = 0.384$) or mean TONI-4 score ($t(85.7) = -1.185$, $p = 0.239$). Significant between-group differences were observed in total AQ scores ($t(86) = -12.727$, $p < 0.001$) and CSP auditory profile scores ($t(80.8) = 15.013$, $p < 0.001$).

Aural perception test using tonal stimuli

To gauge aural perception, we calculated the mean score for each participant by averaging their responses to each sound stimulus across three repeated assessments in the aural perception test. This resulted in 36 mean scores for each participant that captured their unique response patterns. Figure 1 shows the response patterns of ten participants with ASD. The response of the ASD group is denoted by a solid black line, whereas the mean response pattern of the TD group is denoted by a solid grey line. The results showed that the responses of participants with ASD have different characteristics, such as their preference in terms of frequency and changes in intensity.

To systematically compare the ASD and TD groups, the average scores for all 36 sound stimuli were calculated for each participant, providing a measure of aural perception based on the uniform weighting of responses. A lower score indicates a greater aversion to sound stimuli, whereas a higher score reflects a more favourable response. The mean scores of all the TD participants were averaged to establish a cutoff for categorising children with autism into two groups. Those scoring above the TD cutoff were designated as ASD group 1 (38 members), whereas those scoring below this cutoff were classified as ASD group 2 (12 members).

Comparisons of aural perception responses between the ASD and TD groups are shown in Fig. 2. A univariate F-test was performed, with an alpha level of 0.05. Results with significant differences in the post hoc comparison are indicated by an asterisk. ASD group 1 generally scored higher than the TD group across most frequencies and sound levels, except at 250 Hz at 78 dB HL. At 30 and 40 dB HL, the scores rose from 250 Hz to 1 kHz and then dropped towards 8 kHz, indicating a preference for mid-range frequencies. At 50 and 60 dB HL, the differences at 250 Hz and 8 kHz became clearer, with scores around 3 at these frequencies and approximately 3.5

Variables	ASD group	TD group
(Mean ± SD)	($n = 50$)	($n = 38$)
Age	9.79 ± 1.80	10.11 ± 1.49
TONI-4	113.08 ± 12.45	110.24 ± 10.06
AQ total score	100.94 ± 17.37	55.84 ± 15.19
CSP auditory profile	22.18 ± 4.43	33.45 ± 2.55

Table 1. Comparison of the age, scores of TONI-4, CSP auditory profile and AQ total score.

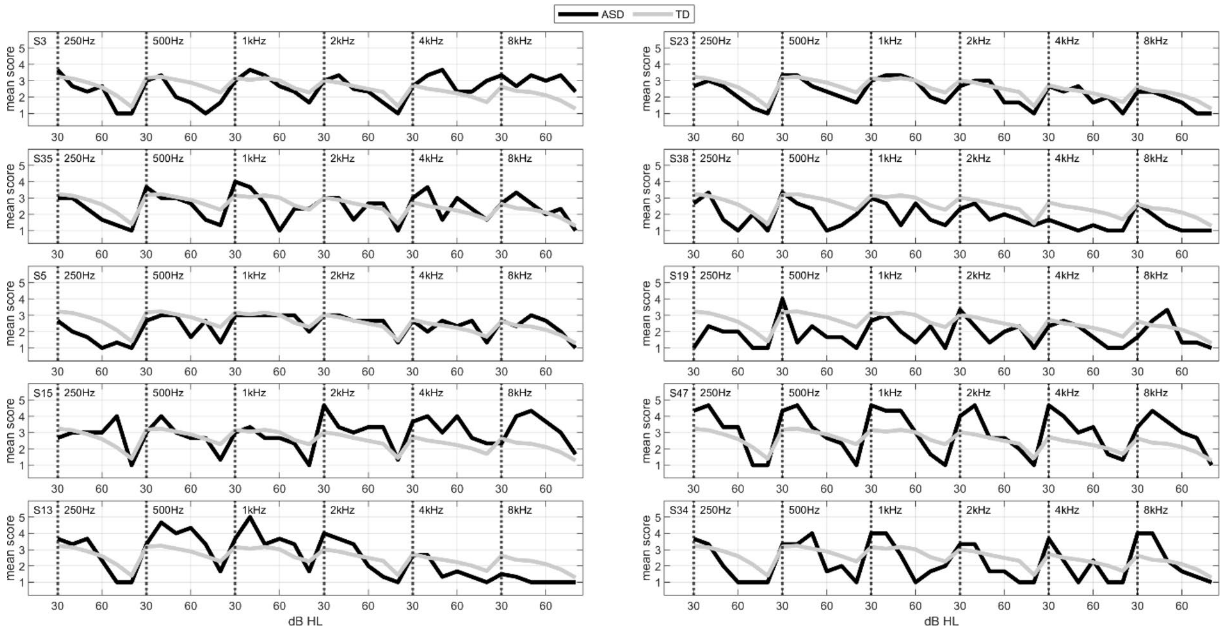

Fig. 1. Aural perception response patterns of ten participants with ASD compared with mean TD response using tonal stimuli.

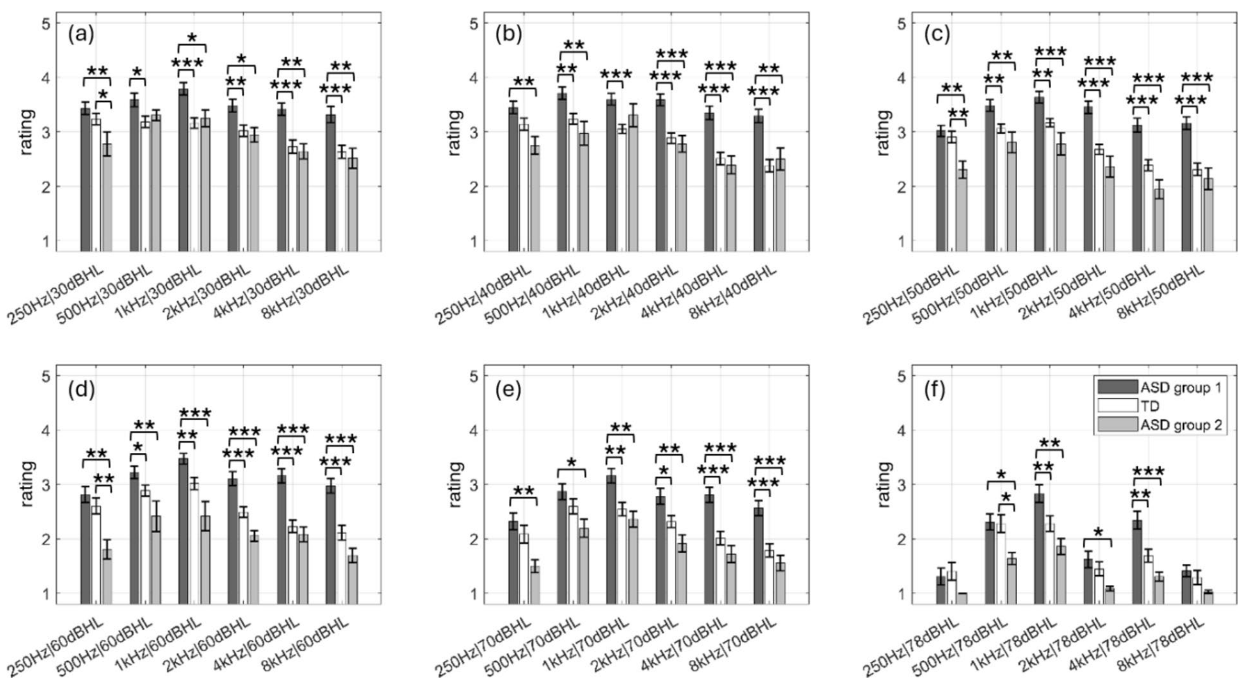

Fig. 2. Comparisons of aural perception response of the ASD group 1, ASD group 2 and TD at different sound intensity hearing level. (**a**) 30 dBHL; (**b**) 40 dBHL; (**c**) 50 dBHL; (**d**) 60 dBHL; (**e**) 70 dBHL; (**f**) 78 dBHL. (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

at 1 kHz. At 70 dB HL, most scores were below 3, indicating a dislike for sounds, except at 1 kHz. At 78 dB HL, the scores were below 3, with the lowest scores at 250 Hz, 2 kHz, and 8 kHz, indicating a more unpleasant feeling towards these particular frequencies. ASD group 1 showed less aversion to loud sounds than the TD group. ASD group 2 had lower scores than the TD group but followed a similar pattern. At 30 and 40 dB HL, the responses were similar to those of the TD group, except for a lower score at 250 Hz. From 50 to 70 dB HL, they exhibited an unpleasant response, with lower scores at all frequencies. At 78 dB HL, they disliked sounds at 250 Hz, 2 kHz, and 8 kHz and had a strong aversion at 4 kHz, indicating greater sensitivity than the TD group. The noise-control strategy proposed in the following sections of this study provides tuneable noise reduction according to the auditory profile of participants with ASD. The group of participants who displayed an unpleasant response to the presented stimuli benefited from noise attenuation, as shown by the neutral perception attained at the low sound intensity hearing level. The effect of noise attenuation on the group of participants who responded favourably to the presented stimuli was uncertain. Although all participants with ASD were classified as experiencing auditory hyper-reactivity, this group of participants scored higher than TD participants even at high sound intensity hearing levels. Further understanding of the underlying mechanism and effect of noise control is required, and this analysis will be conducted in another study.

Hearing perception curves

To tailor noise-control methods to meet the diverse needs of children with autism, hearing perception curves were plotted for each group. The goal was to create a noise-control strategy that could effectively cancel out bothersome frequencies in children with autism. As the ASD group had different aural perception profiles than the TD group, the noise-control approach focused on developing an algorithm that would cancel out the incoming noise to create a neutral perception (dashed line in Fig. 3(b)) for children with ASD. To achieve this neutral response, we examined the extent of noise reduction required at each frequency. This was accomplished by fitting a power function curve using the mean aural perception rating and sound intensity hearing level as variables. Subsequently, this curve was used to estimate the mean aural perception rating for sound intensity hearing levels at each frequency in the aural perception test. The power function was in the form of $y_i = a(x_i{}^b) + c$, where y_i is the *i*-th mean aural perception response at a specific frequency, x_i is the *i*-th intensity level at a specific frequency, and *a*, *b*, and *c* are the coefficients to be determined. The most suitable curve was identified using the nonlinear least squares method by selecting the curve with the lowest sum of square errors. The power function was chosen because we observed an inverse relationship between aural perception ratings and sound intensity hearing levels. In general, as the sound intensity hearing level decreased, the change in aural perception ratings decreased. The mean root-mean-squared error of the power function model of participants with ASD is 0.308, which shows that the model captured a good amount of variability in the dataset.

Using the hearing perception curve, we estimated the amount of noise reduction required to create a neutral perception at specific frequencies, based on the noise level presented to the participant. Figure 3(b) shows the calculation of the required noise reduction at a particular frequency. Initially, we determined the sound intensity hearing level corresponding to neutral perception by using a hearing perception curve (56 dB HL). The required noise attenuation was calculated by subtracting the noise level from the sound intensity hearing level (22 dB).

This process was used to establish a target curve for fine-tuning noise cancellation, specifically for children with autism. The target curve spanned frequencies ranging from 250 to 8000 Hz at octave intervals. Figure 3(a) and (b) present examples of target curves for noise cancellation and the hearing perception curve, respectively, along with the aural perception ratings at 500 Hz.

Active noise control (ANC) system in noise-cancelling headphones

Most noise-cancelling headphones available in the market allow users to customise the level of noise cancellation, thereby adjusting the overall effectiveness of noise reduction[42]. This feature allows users to modify the degree of reduction in the overall sound pressure levels. However, limited attention has been paid to crafting a noise-control strategy based on the human perception-response curve. This curve is represented as a function of both the frequency and acoustic magnitude.

Our study revealed that the aural perception of children with autism, particularly those with auditory hyperreactivity, was significantly influenced by sound intensity and frequency. This finding suggests that fine-

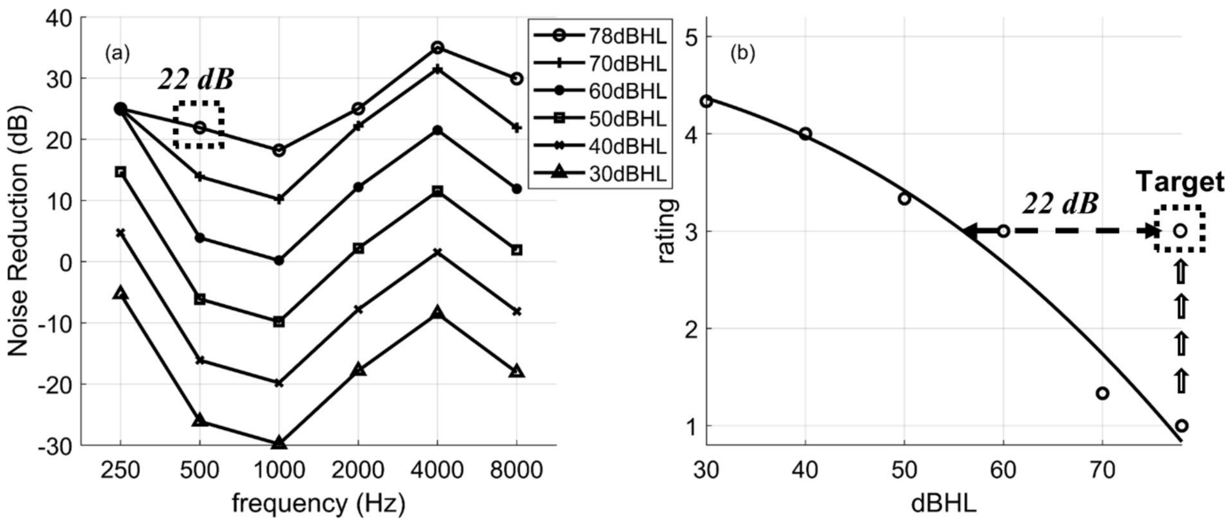

Fig. 3. (**a**) Target curves for noise cancellation; (**b**) Hearing perception curve and aural perception responses at 500 Hz.

tuning the frequency response of noise-cancelling functions is advantageous for this group of individuals. A block diagram of the ANC system with the proposed function and a circuit diagram of one side of the ANC system are presented in Fig. 4. To develop an ANC algorithm that can reduce aversive behaviours related to auditory hyperreactivity in children with autism, both the frequency response and the level of noise cancellation were adjusted based on the results of an aural perception test. The goal of the ANC algorithm is to achieve noise cancellation that enables children with autism to perceive incoming noise with a neutral feeling, thereby minimising the impact of noise disturbances on their behaviour. Following these procedures, the target noise reduction levels were obtained to achieve a neutral sensation. This established a set of noise reduction targets for different frequencies and intensities, which were used to tune the corresponding set of ANC filters. The circuit includes a commercial ANC chipset connected to an external audio codec. The feedforward microphone (FF mic) is connected to the hybrid ANC circuit and analogue input of the audio codec. The feedback microphone (FB mic) captures audio feedback from speakers. The audio codec includes a preamplifier, analogue-to-digital converter (ADC), audio mixer, digital-to-analogue converter (DAC), and audio power amplifier. The audio codec in the system is responsible for tuning different ANC performances using a set of noise-reduction targets computed using the aforementioned procedures. The hybrid ANC digital circuit provided fixed maximum noise cancellation. The filter configuration in an audio codec determines the deviation of the resulting ANC performance from the fixed ANC performance of a hybrid ANC digital circuit. This allows the tuning of the filter response to match the auditory profiles of individuals with ASD. In this study, a hybrid ANC system was used because it has the advantages of feedforward and feedback control systems and overcome the disadvantages of these systems such as the instability of the feedback system and poor adaptability to primary noise of the feedforward system[43]. The filters were adjusted until the actual noise cancellation performance deviated by no more than ± 1.5 dB from the target level at any frequency in interest. This maximum deviation from the target level was chosen based on the just-noticeable difference by average listeners in terms of the change in sound level.

Everyday sound stimuli

Aural perception test using everyday sound stimuli

Figure 5 shows a comparison of the mean subjective aural perception rating of 20 ASD participants before and after applying the proposed noise-control strategy. Before the noise control was applied, the mean aural perception rating for all daily sound stimuli was unpleasant (< 3) at 60 dB SPL or above. Participants with ASD experienced more unpleasantness with shouting and hand-drying noise, as shown by the less steep increase in rating from 90 to 60 dB SPL. At lower sound intensity hearing levels, the mean perception ratings were approximately 3, indicating that the everyday sound stimuli in this study provided similar aural perception at these intensity levels and may not provoke unpleasant sensations in participants with ASD. The proposed noise-control strategy aims to create a personal acoustic environment in which children with autism experience neutral

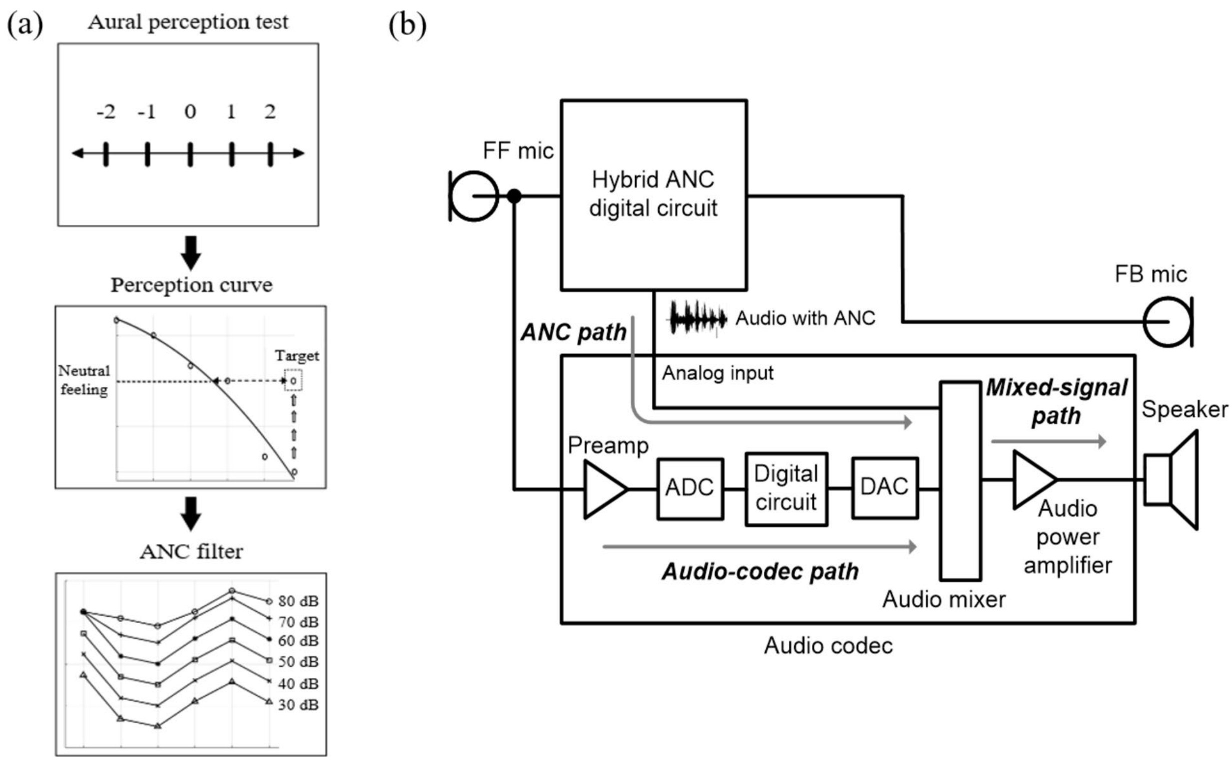

Fig. 4. (**a**) Block diagram of proposed ANC system. (**b**) Circuit diagram of one side of the proposed ANC system (adopted)[44].

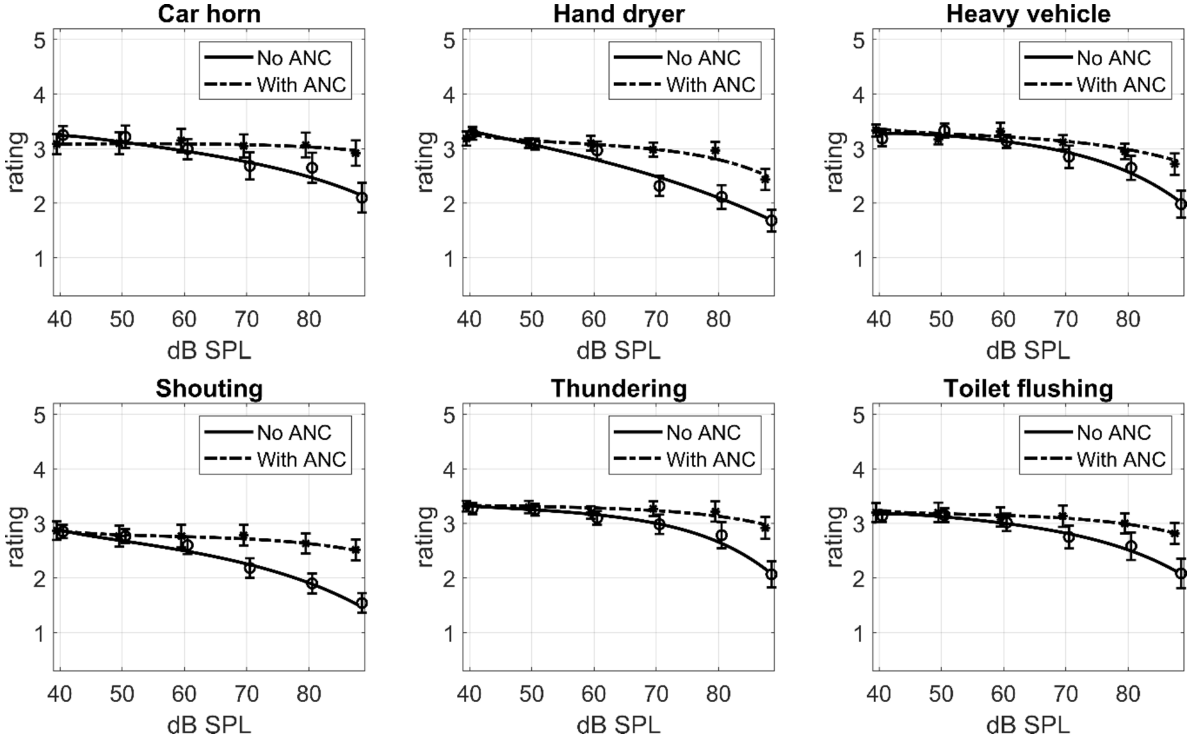

Fig. 5. Comparison of mean subjective aural perception rating before and after applying proposed ANC system.

feelings without unpleasantness. This was indicated by a rating of 3. As shown in Fig. 5, the perception ratings after applying the proposed noise-control strategy were closer to 3 for all sound stimuli at the highest sound-intensity hearing levels. In general, a noise-control strategy based on subjective aural perception is effective for mitigating unpleasant feelings caused by everyday sound stimuli.

Psychoacoustic annoyance

Psychoacoustic annoyance (PA) is the subjective perception of discomfort or displeasure in response to certain sound characteristics. It can be calculated using four psychoacoustic parameters: loudness (N), sharpness (S), roughness (R), and fluctuation strength (F)[45]. The PA calculation is shown in the following equations:

$$PA = N_5\left(1+\sqrt{\omega_s^2+\omega_{FR}^2}\right), \tag{1}$$

$$\omega_s = (S-1.75)\cdot 0.25\log_{10}(N_5+10), \tag{2}$$

$$\omega_{FR} = \frac{2.18}{(N_5)^{0.4}}(0.4\cdot F+0.6\cdot R), \tag{3}$$

where N_5 is the percentile loudness.

Figure 6 shows a comparison of the psychoacoustic parameters and PA of everyday sound stimuli at 90 dB SPL before and after applying the proposed noise-control strategy. A univariate F-test was performed, with an alpha level of 0.05. Results with significant differences are indicated by asterisks. The noise-control strategy was effective in reducing the loudness and sharpness of all tested everyday stimuli. The roughness of the car horn increased after the noise control was applied, whereas the other stimuli showed an improvement in roughness or remained unchanged. The noise-control method increased the fluctuation strength of car horns, hand dryers, shouting, and toilet flushing. A slight improvement was observed in heavy vehicles and thunder. PA considers the loudness and temporal structure of sounds and can be used to evaluate their annoyance or pleasantness. The results show that the proposed noise-control strategy performs well for broadband and dominant sounds in low-frequency regions, such as heavy vehicles and thunder. For sound stimuli with high tonality and rapid temporal changes, the noise-control strategy did not reduce the PA because of limitations in controlling fluctuation strength and roughness.

EEG test

To confirm this observation, the EEG spatiotemporal patterns with and without noise control were compared, as shown in Fig. 7. The average patterns from 50 to 250 ms were determined from the averages of all five channels. Neural activity after applying noise control was substantially lower in the central area between 150 and 200

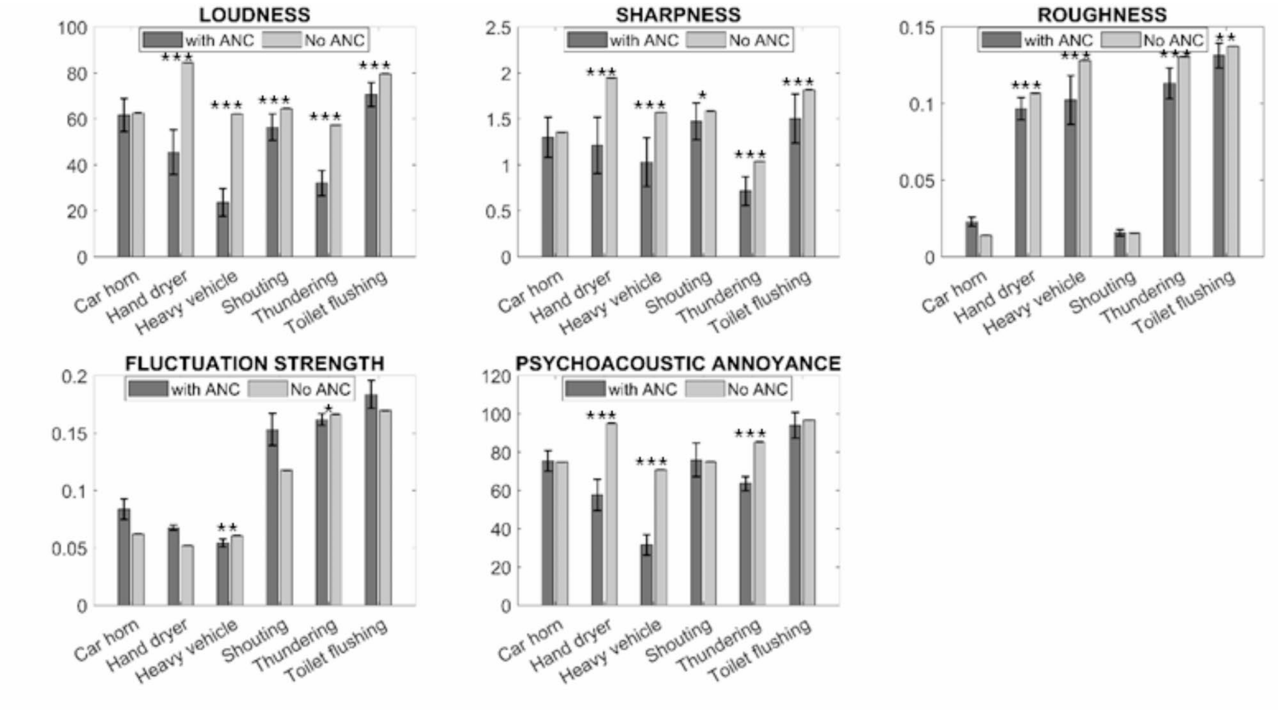

Fig. 6. Comparison of psychoacoustic parameters and PA before and after applying the proposed ANC system for everyday sound stimuli at 90 dB SPL. (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$)

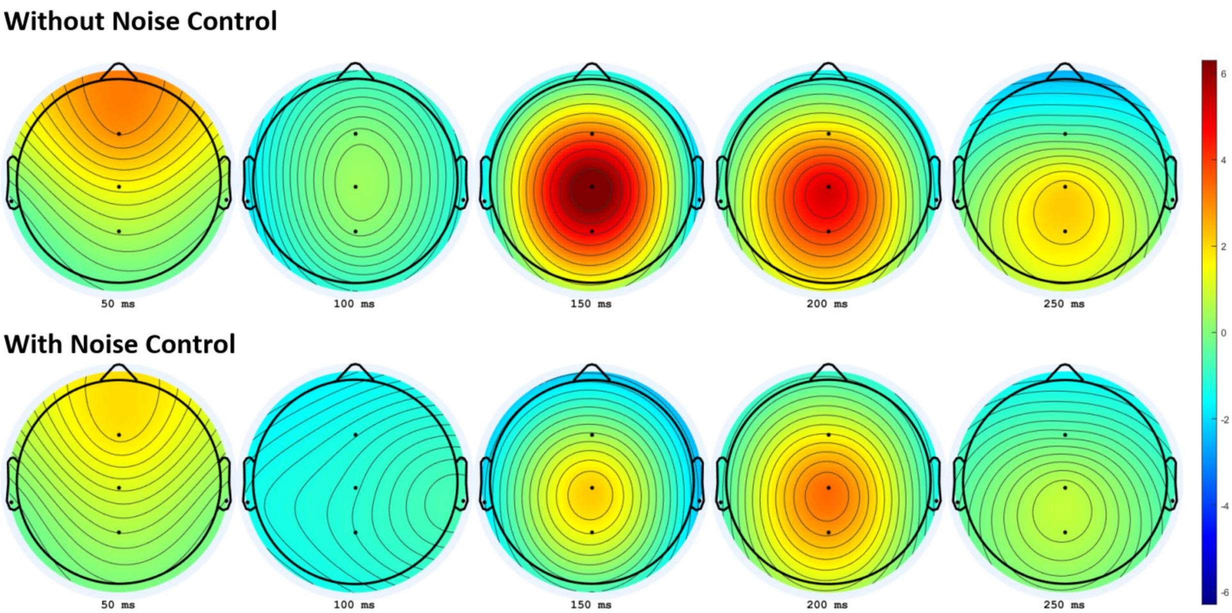

Fig. 7. Grand average scalp maps of evoked potential with and without noise control across all participants from 50 to 250 ms in 50-ms steps.

ms. This suggests that the proposed noise-control strategy may be effective in reducing the P2 amplitude in the central area in children with autism.

The grand average EEG responses from all environmental sound stimuli in children with ASD at channel Cz are shown in Fig. 8. This channel was chosen because EEG using auditory stimuli elicits a prominent response at this site. The neural responses with and without noise control showed substantial differences at time intervals between 150 and 200 ms, the time interval corresponding to the P2 component. The P2 peaks are indicated by the red and green circles in Fig. 8. When the sounds were louder, the P2 response was stronger, indicating a heightened reaction in the brain. In addition, the P2 peak appeared earlier, indicating a faster processing of

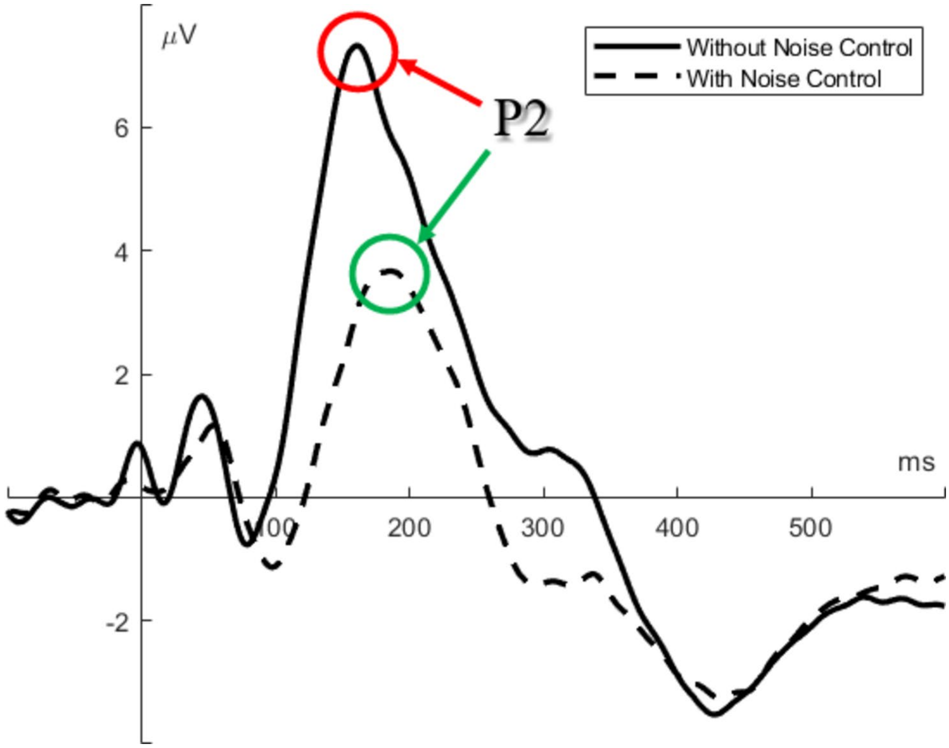

Fig. 8. Grand average waveform of evoked potential with and without noise control across all participants at channel Cz.

louder sounds. This explains the differences in the P2 peaks under the two conditions. Recent studies have shed new light on the complexity and significance of the P2 component in auditory processing. Steinmetzger and Rupp[46] proposed that the P2 may consist of two separate subcomponents, each reflecting a different stage of auditory processing. This finding suggests a more nuanced role of the P2 in sound discrimination and encoding processes than previously thought. Furthermore, Schneider et al.[47] demonstrated that short-term musical listening training can significantly increase the P2 amplitude, highlighting the plasticity of the component and its close relationship with auditory learning. These findings underscore the importance of P2 in understanding auditory perception and processing, particularly in clinical populations such as individuals with autism spectrum disorder.

To further understand the performance of the noise-control strategy for different types of noise, the EEG responses were separated according to the daily sound stimuli used in this study. A univariate F-test was performed, with an alpha level of 0.05. A pairwise comparison followed by a univariate F-test indicated significant differences in the Cz P2 peak amplitude with and without noise control for hand dryers ($p = 0.001$), heavy vehicles ($p = 0.007$), thunder ($p < 0.001$), and toilet flushing ($p = 0.012$). Figure 9 shows the temporal waveform at channel Cz based on the sound type. The responses with noise control showed a substantially lower P2 peak amplitude at channel Cz than the responses without noise control for all daily sound stimuli. The P2 peak reflects the sound discrimination and sound encoding process and is related to the allocation of attention and early attentive mechanism[48]. Our findings regarding P2 responses in children with autism align with and extend recent research in the field. The observed changes in the P2 amplitude following our noise-control intervention are particularly interesting in light of Schneider et al.'s[47] work on P2 plasticity. The observed reduction in the P2 amplitude may indicate a shift in auditory processing strategies, potentially reflecting improved auditory comfort or reduced cognitive load when processing auditory stimuli. In addition, decreased P2 peak amplitude has been linked to improved attention[49].

The relationship between the P2 peak amplitude at channel Cz, the aural perception response, and PA without using the proposed noise-control strategy was investigated. Pearson's correlation analysis was conducted between the P2 peak amplitude at channel Cz, the rating in the aural perception test, and the PA of the daily sound stimuli. The P2 peak amplitudes in channels Cz and PA were moderately correlated ($r(478) = 0.334$, $p < 0.001$). This indicated that the higher the P2 peak amplitude at channel Cz, the higher the PA experienced by children with autism. The ratings on the aural perception test and PA were negatively correlated ($r(478) = -0.304$, $p < 0.001$). This indicates that the higher the PA of a given stimulus, the more unpleasant it is for children with autism to experience aural perception. The ratings in the aural perception test and the P2 peak amplitude at channel Cz were negatively correlated ($r(478) = -0.243$, $p < 0.001$). This shows that the higher the peak amplitude, the more unpleasant the feelings towards sound stimuli. As shown in Fig. 8, the P2 peak amplitudes after noise control were lower for all the daily sound stimuli. This indicates that the noise-control strategy was effective in reducing the unpleasantness of sound and PA experienced by children with autism.

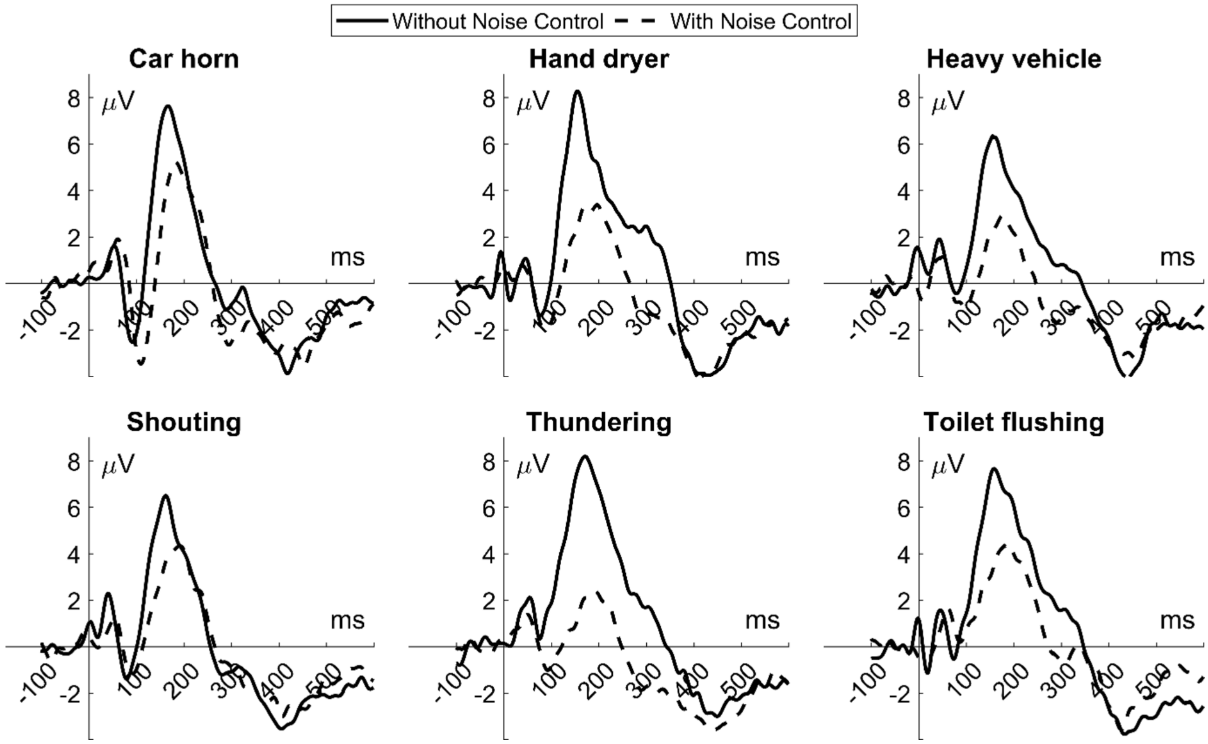

Fig. 9. Temporal waveforms of evoked potential with and without noise control across all participants at channel Cz for everyday sound stimuli used in this study.

The proposed aural perception-controllable headset provides tailored active noise cancellation based on the auditory profile of children. The proposed headset has several potential applications: Children with autism inevitably encounter noise that they are sensitive to in outdoor environments, for instance, the noise of public transportation and babble noise in crowded places. The proposed headset minimises the effects of noise on behaviour and improves acoustic comfort. The headset can also be used in rehabilitation, such as sensory integration training, to assist in the training process. In addition, by attenuating the noise in the surrounding environment, the headset can be used when performing tasks at home or school that require children's focus and attention. In addition, the results show that children with autism and auditory hyperreactivity have diverse auditory perceptions, which is a crucial element to consider when developing ANC headsets. With the widespread use of smartphones worldwide, a commercial ANC headset can be paired with a smartphone application that performs an assessment similar to the aural perception test proposed in this study to measure the user's auditory profile. Headsets can then be developed with few levels of noise reduction for different frequency bands to provide a customised ANC for the user based on the auditory profile.

Limitations

This study has several limitations that should be considered when interpreting the results. The extended EEG testing sessions posed challenges for participant engagement, necessitating the use of a token reward system and regular breaks, which may have influenced the participants' natural responses. Our sample, which was limited to children with autism and an IQ above 85, may not fully represent the broader spectrum of autism, potentially limiting the generalisability of our findings. Despite efforts to create a comfortable environment, two participants withdrew from the study: one owing to initial fear (who later returned) and the other owing to headphone intolerance, which may have introduced some bias. Interpreting EEG data was challenging for participants with movement issues or sensory discomfort, potentially affecting the data quality, although efforts were made to address these issues. The relatively small sample size, especially after excluding participants with inconsistent responses or insufficient EEG epochs, may limit the statistical power and generalisability. Another important limitation is that we did not explicitly control for the effects of absolute dB reduction on ERP amplitudes and latencies. Decreased sound intensity led to reduced ERP amplitudes and delayed latencies. Therefore, the observed reductions in the P2 amplitude may partially reflect this general acoustic principle rather than the specific effects of our intervention. Future studies should include appropriate controls to distinguish between these effects. Despite this limitation, the consistent relationship among P2 reduction, improved subjective ratings, and reduced psychoacoustic annoyance suggests that our intervention provides benefits beyond simple sound attenuation. Finally, the controlled laboratory setting may not accurately reflect real-world sound environments that children with autism encounter daily. Future research should address these limitations by including a larger and more diverse sample of children with autism and evaluating noise-control strategies in more naturalistic settings.

Conclusions

This study investigated aural perception in children with autism by using an aural perception test and electrophysiological responses to sound stimuli. The most unpleasant frequencies were 250 Hz and 8 kHz; 2 kHz was the second most unpleasant frequency. Each group exhibited unique responses to sound stimuli at different sound intensity levels, emphasising the need for customised noise-control strategies targeting specific troublesome frequencies. The aural-perception-based noise-control strategy was effective in mitigating unpleasant feelings caused by everyday sound stimuli. The perception ratings after applying the proposed noise-control strategy were closer to 3 (neutral) for all sound stimuli at the highest sound-intensity hearing levels. In addition, it was effective in reducing the loudness and sharpness of all the tested everyday stimuli. The noise-control strategy performed well for broadband and dominant sounds in the low-frequency region, but had little effect on reducing the annoyance of sound stimuli with high tonality or rapid temporal changes. Examining the relationship between the P2 peak amplitude, aural perception response, and PA, we found that higher P2 amplitudes were associated with increased annoyance and greater unpleasantness, with higher annoyance leading to more unpleasant aural perceptions. These findings indicate the potential of the proposed aural-perception-based noise control method to alleviate behaviours related to auditory hyperreactivity in children with autism.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

T.C.K. collected and analyzed the data, and drafted the main manuscript. H.-L.Y. collected the data. S.W.Y.M. and H.K.C. conceived and supervised the study. Y.S.C. conceived and supervised the study, and reviewed and edited the manuscript. Y.Y.C.L. and C.C.H.C. conceived and supervised the study. All authors approved the final version of the manuscript for submission.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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