scientific reports

OPEN

Influence of loud auditory noise on postural stability in autistic children: an exploratory study

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Autistic children often experience sensory processing challenges and postural instability. While auditory noise has been reported to improve balance in various populations, its effects in autistic children remain unclear. This study examined whether auditory noise could similarly influence balance in this population. Sixteen autistic and sixteen typically developing (TD) children aged 6–12 years performed a tandem stance task with and without auditory noise. Postural stability was assessed via stance duration and center of pressure (CoP) velocity. Sensory processing difficulties were evaluated using a parent-report questionnaire. Autistic children stood longer in the presence of auditory noise, while all TD children reached the maximum duration regardless of condition. A reduction in CoP velocity with auditory noise was observed across both groups. Although postural stability was correlated with sensory processing difficulties, the effect of auditory noise was not. These findings suggest that the beneficial effect of auditory noise on postural stability is applicable to autistic children, regardless of individual sensory processing profiles. This exploratory study highlights the potential of sensory-based interventions to support postural control in autism. Future research with larger samples is needed to confirm these findings and to identify the auditory stimulus characteristics that most effectively improve balance in autistic individuals.

Keywords Autism spectrum disorder, Postural control, Sensory processing, Stochastic resonance, Auditory noise

Postural control is a fundamental motor skill in activities of daily living essential for maintaining balance under various circumstances. Generally, maintaining postural stability is facilitated by the integration of multiple sensory modalities, including vision, proprioception, and the vestibular system[1,2]. Recently, sensory augmentation has shown promise across various populations and age groups[3,4]. Studies have not only shown the effectiveness of sensory feedback in guiding postural control[5–7]but also demonstrated that constant sensory noise, such as vibrotactile and auditory stimuli, can improve postural control, regardless of the noise spectrum[8,9]. This suggests that sensory input can positively influence postural stability even in the absence of explicit augmented feedback.

How does sensory input enhance postural stability? As a mechanistic explanation for the association between sound and balance, auditory input may provide spatial information that aids in maintaining balance. Specifically, auditory input from multiple sound sources enables the brain to estimate the body's position relative to those sound sources[10]. However, this theory fails to explain improved postural stability when auditory input is delivered through headphones[11]. Stochastic resonance (SR) may be an alternative mechanism to explain the auditory noise effect on postural stability. SR suggests that adding random noise can help a weak neural signal reach the detection threshold, thereby enhancing sensory perception[12]. In postural control, the effect of SR has been studied predominantly in the tactile domain, including the effect of a vibration device attached to the Achilles Tendon to improve gait and posture in individuals across the lifespan[13–15]as well as in children with idiopathic toe walking[16]. Recent studies have demonstrated the effect of auditory noise in healthy young adults as well as elderly individuals[17]. In the context of auditory noise, the vibration of air in the auditory canal may mechanically stimulate nearby vestibular receptors. The mechanical noise, through SR, may enhance vestibular input, thereby improving postural control[18]. Despite evidence of improving postural control by various types of

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auditory input in clinical populations[9], such a phenomenon has not been tested in autistic individuals, who often exhibit atypical sensory processing.

Sensory processing is the brain's ability to organize and interpret sensory information from the environment, allowing adaptive responses to external stimuli[19]. In autistic children, sensory processing abilities are often altered, impacting many aspects of daily functioning[20,21]. Clinicians commonly employ a sensory processing assessment, such as the Sensory Processing Measure, second edition (SPM™−2), to gain insights into sensory characteristics in autistic children[22,23]. Sensory processing impairments are highly prevalent in autistic children, with estimates ranging from 45 to 95%[19,24]. These characteristics can be largely categorized into two types: Hypo-reactivity and hyper-reactivity. Hypo-reactivity involves under-responsiveness, where stimuli are perceived as underwhelming, prompting the individual to seek additional input. Conversely, hyper-reactivity refers to over-responsiveness, where typical stimuli are perceived as overwhelming. Auditory over-responsiveness, which affects approximately 50% of autistic individuals, highlights the unique sensory challenges faced by autistic children[25].

Studies have reported postural challenges in autism spectrum disorder (ASD) in quiet standing[26,27] and dynamic postural control[28–30], which may influence gross motor skills and social interactions[31–35]. Recent findings suggest that individuals on the autism spectrum frequently struggle with tactile, proprioception, and vestibular processing difficulties that fundamentally affect motor performance[26,36,37]. These sensory inputs play a key role in maintaining postural stability in autistic individuals. Despite previous studies showing reduced postural sway with auditory inputs in various populations[8–10], the effect of auditory noise on postural control has not been studied in autistic children.

We aimed to examine the influence of auditory noise on postural control in autistic children. Since the effect of SR arises from auditory noise being physically transmitted to the vestibular organs, it is plausible that auditory noise may similarly reduce postural sway in autistic children. We therefore hypothesized that auditory noise would decrease postural sway in this population. However, testing this hypothesis poses challenges due to the low sound tolerance commonly observed in autistic children[38]. An observational study reported a positive correlation between classroom noise levels and the frequency of autistic behaviors in school settings[39]. Laboratory studies have also shown that auditory noise can negatively impact autonomic arousal and working memory in autistic adolescents[40]and that autistic individuals often fail to habituate to repeated loud auditory stimuli[41]. These findings suggest that the adverse effects of auditory noise might outweigh the potential benefits of SR in autistic children. To mitigate this risk, we assessed balance performance in a child-friendly environment using naturalistic auditory stimuli. Additionally, we examined the relationship between postural sway and individual differences in sensory processing. We expected that postural control would vary based on sensory processing difficulties, but that the reduction in sway due to SR would remain independent of these higher-level sensory traits, as SR operates primarily at the level of sensory receptors.

Methods
Participants
Autistic children were recruited from a summer camp hosted by Board-Certified Behavioral Analysts (BCBAs) at the University of Texas at San Antonio (UTSA) between June and July 2023. The summer camp primarily provided applied behavioral analysis (ABA) services to autistic children across a wide range of ages and autism severity levels. The campers were informed about the study during the summer camp orientation. If interested, parents and legal guardians completed a comprehensive questionnaire to determine eligibility. Inclusion criteria for both groups included: (i) age between 6 and 12 years; (ii) the ability to comprehend and follow simple instructions; (iii) no current or recent injuries or medical conditions affecting mobility; (iv) normal hearing; (v) normal or corrected vision; (vi) absence of concurrent genetic syndromes; and (vii) no history of seizures. Eligibility for the ASD group required: (i) a formal ASD diagnosis from a physician or school qualifying them for special education in accordance with DSM-5 regardless of the level of support, and (ii) a total t-score on the Social Responsiveness Scale, 2nd Edition (SRS-2), indicating autism severity within the 'mild' to 'severe' range[42]. Typically developing (TD) children were recruited through various channels, including social media parent groups, the distribution of flyers to local businesses, and word-of-mouth referrals from acquaintances. Eligibility for the TD group required: (i) no formal diagnosis of developmental disorders, and (ii) an SRS-2 total t-score within the 'within normal limits' range. Interested parents received an email with a study overview and watched an informative video presentation outlining the study procedures before providing consent. For the ASD group, 21 children were initially recruited and deemed eligible to participate. However, 5 children declined to participate or demonstrated an inability to stand on the force plate as instructed. Thus, 16 autistic children participated in the study, with an average age of 8.9 years, including 11 males and 5 females. The TD group consisted of 16 children (10 males, 6 females), with a mean age of 9.1 years (see Table 1 for detailed demographics). Thus, a total

Group	Age	Sex	Height (cm)	Body mass (kg)	SRS-2
ASD (n = 16)	8.9 years (± 1.89)	11 males 5 females	139.4 (± 15.26)	38.6 (± 15.86)	67.2 (± 15.82)
TD (n = 16)	9.1 years (± 1.75)	10 males 6 females	137.8 (± 13.52)	35.7 (± 12.55)	45.7 (± 6.29)

Table 1. Participant demographics. Note: Each number represents the mean ± standard deviation. SRS-2 stands for the Social Responsiveness Scale 2nd Edition.

of 32 children completed participation in the study. For both groups, all participants performed the motor tasks between 9am and 11am.

Ethical approval for the research protocol was obtained from the Institutional Review Board (IRB) at the University of Texas at San Antonio (#22–23-227). All data collection adhered to institutional ethical requirements and the 1964 Helsinki Declaration and its amendments. Written informed consent was obtained from the legal guardians or parents of all participants before their involvement in the study. In accordance with the study protocol approved by the IRB, the researchers assured that the child participants expressed a verbal assent to the study participation before data collection began.

Apparatus

Participants were escorted to a designated playroom (5 m X 3 m) for a data collection session assessing various motor skills such as walking, throwing, kicking and balancing (Fig. 1). Only data from the balancing task were analyzed, as other tasks were beyond the scope of this study. The room was set up to create a playful and child-friendly atmosphere encouraging task completion while avoiding excessive distractions. To create a playful environment and reduce anxiety, lyric-free, child-friendly music was played softly throughout the session, except during the postural control task. Upon arrival, participants were granted a maximum of 10 min of unstructured playtime to acclimate to the environment and feel comfortable with the equipment and researchers they would be interacting with. Subsequently, researchers explained the general sequence of tasks to be performed by the participants using a social story that facilitated transition between tasks. Narratives used to explain these tasks to the child participants centered around the search for six plastic toys (rubber ducks; 5.6 cm (height) X 4.6 cm (width) X 4.6 cm (depth), 11 g each) with six different colors to be collected and kept secure during the entire session and returned to the researcher in exchange for a reward at each task's conclusion. A visual map frequently reminded participants of remaining tasks and facilitated session progression. The entire session lasted for approximately 30 min including the playtime.

Task

In the postural control task, participants stood on a force plate (AMTI, Watertown, MA) in a tandem stance, placing one foot directly in front of the other as the heel of the front foot touches the toes of the back foot, for 20 s under two auditory conditions (NORMAL and NOISE) to examine auditory noise effects on postural control. Tandem stance was chosen to increase the difficulty of static standing while still being manageable for participants to perform the task. Participants were asked to stand on a force plate with footprint marks at the center of the force plate to guide proper positioning. Which foot was placed in the front/back was self-selected by the participants. Participants completed a practice trial to familiarize themselves with the correct foot placement before starting. The participants were instructed to avoid any contact with walls or other objects to maintain balance. A tablet (iPad Mini, Apple, Cupertino, CA) was placed 150 cm away from the participant and at eye level. To encourage completion of the task and to provide a focal point for participants, the tablet displayed a round (10 cm diameter) counter gradually revealing a child-friendly image for 20 s. The participant was instructed to stand as still as possible and to focus on the counter for both conditions. A cloth bag containing the plastic toys (86 g including the toys) was held against the chest while on the force plate for all the trials. The bag was used to keep the participants' arms close to the center of mass (CoM) and to avoid arm movements that would influence postural stability. A set of two speakers next to the force plate (one on each side) emitted auditory environmental noise with minimal sound fluctuations (i.e., sound of constant heavy rain without thunderstorms) for both conditions. Figure 2 shows the distribution of the power spectral density in the frequency domain. Notably, the

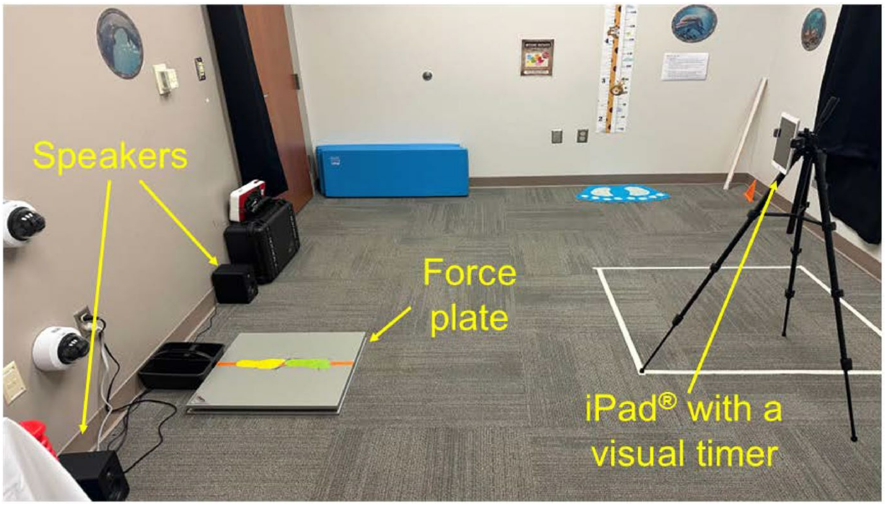

Fig. 1. Experimental setup. Illustration of the setup used to measure postural sway under NORMAL and NOISE conditions.

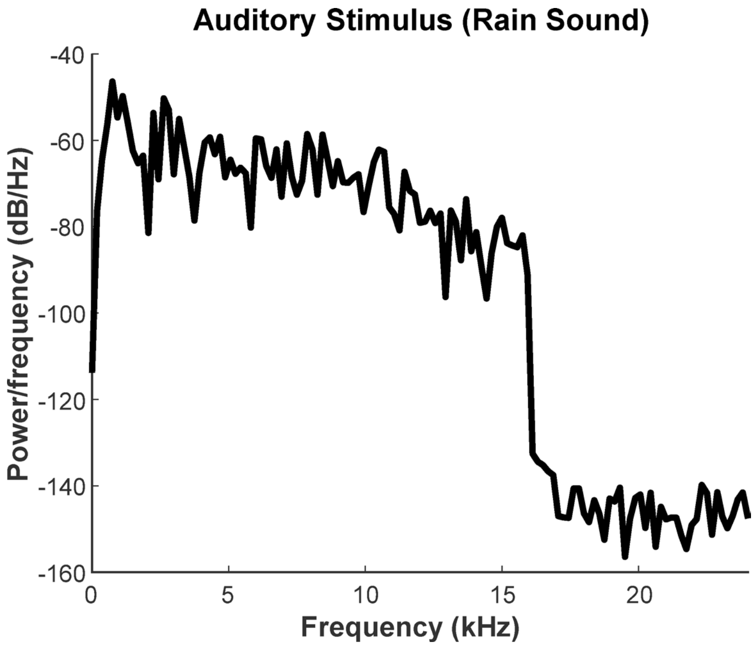

Fig. 2. Power spectral density of the auditory stimulus. The power spectral density of the rain sound stimulus (5,760,000 samples, 48 kHz sampling rate) was computed using a periodogram implemented in MATLAB 2024b. The stimulus exhibits broad spectral content in the low-frequency range.

frequency distribution is not a white noise, but closer to a pink (1/f) noise, which is commonly found in natural sound and classical music[43,44].

In the NORMAL condition, the intensity of the noise was 45–47 dB, analogous to normal conversation or quiet office. In the NOISE condition, the intensity of the noise was increased to 75–80 dB, analogous to city traffic or construction zone, which is far from the sound optimized for calming the listeners[45]; pink noise as a sleep aid is typically used at an intensity of around 60 dB[46]. A standard lighting condition (550–570 lx) was maintained for both conditions. Participants were allowed to get in place and feel balanced before the counter began. Researchers monitored foot placement to ensure proper tandem stance throughout the entire session. In case of failure to follow the instructions in an attempt, participants were given additional attempts. All participants included in the analysis needed no more than 3 attempts per condition and the number of attempts was not significantly different between the two conditions within each group. Since not everyone was able to complete the 20-second-long trial, we measured the duration of tandem stance as a preliminary metric of postural stability. The order of the conditions was counter-balanced to avoid any practice effects. Between the two conditions, participants were granted a brief intermission for a walk to prevent fatigue and frustration. One valid trial for each condition of each participant was included for subsequent analyses.

Sensory processing assessment

To assess the sensory processing abilities across various environments, we adopted the SPM™−2. While not a diagnostic tool for ASD, SPM™−2 is a parental survey designed to help identify challenges across six sensory domains (i.e., vision, hearing, touch, taste and smell, proprioception and vestibular function). The sum of these six sensory domain scores forms a total score indicating a child's overall sensory processing ability. The questionnaire includes two additional domains: Planning and ideas (praxis) and social participation. They both represent higher level skills influenced by the processing of multiple sensory information and a child's cognitive abilities. The SPM™−2 quantifies the sensory processing difficulties and vulnerabilities of children, with a series of questions given to the respondent, who has observed the child for at least one month. The Home Form (adopted for this study) requires 15 to 20 min to complete. Different sensory processing characteristics can be categorized as sensory under-reactivity, sensory over-reactivity, sensory seeking, or perceptual problems in response to external sensory stimuli[47]. Sensory under-reactivity is characterized by high threshold for sensory input, leading to unresponsiveness or lack of awareness to stimuli. Sensory over-reactivity is characterized by a low threshold for sensory input, resulting in overactivity to stimuli that are typically not perceived as overwhelming. Sensory seeking involves an insatiable drive for sensory inputs. Perceptual problems involve issues processing stimuli and generating movement or behavior outputs. The SPM™−2 was completed by all the primary caregivers of participants in an interview format. Caregivers completed the form via phone or in-person interview. Conversations were recorded for reliability checks with an occupational therapist involved in the study. All phone interview forms were marked by the researcher to match the caregiver's response.

Postural data analysis

For trials in which the child lost balance in the middle of the trial, the length during which the child successfully stood on the force plate was recorded during the session and the recorded time was confirmed by a visual inspection afterward. The raw dataset collected from the force plate was recorded at 1 kHz sampling rate and contained ground reaction force and moment in 3D. We confirmed that all data were free of missing data points or artifacts. Postural stability has been quantified with the CoP as a reliable metric in quiet standing without external perturbation[48]. The CoP, calculated from continuous ground reaction force data, is proportional to the participant's CoM of the individual standing on the force plate[49]. The CoP may reflect both spontaneous postural sway and postural adjustment to prevent a fall. Recent studies suggest that separating CoP into low- and high-frequency components allows for a more detailed analysis. The low-frequency component of CoP represents the slower postural sway that reflects feedback-based corrective processes. The high-frequency component of CoP represents the faster open-loop and exploratory processes[50]. Hence, analyzing both CoP components enabled us to characterize the postural challenges in autistic children.

To calculate the CoP variables, we first down-sampled the raw dataset to 20 Hz. The down-sampled signals helped us avoid spurious detections of the high frequency components of postural sway, which otherwise would over-estimate the length of excursion. We then calculated the CoP in the anterior-posterior (AP) and mediolateral (ML) direction. The CoP in AP and ML direction was calculated by $-M_{ML}/F_z$ and $-M_{AP}/F_z$, respectively, where M_{AP} and M_{ML} are the moment in the AP and ML direction and F_z is the ground reaction force in the vertical direction.

To split the low and high frequency component of the CoP profile, a fourth-order Butterworth filter was applied bidirectionally to the CoP profile in each direction at the cutoff frequency of 0.3 Hz[51]. A low-pass filter was used to extract the low frequency component (lower than 0.3 Hz) and a high-pass filter was used for the high frequency component (higher than 0.3 Hz). For each frequency component, we analyzed the mean CoP velocity, the excursion of the CoP profile divided by the duration of the tandem stance, in the AP and ML direction separately as the metric of the postural stability because the CoP velocity has been known to be reliable to measure postural sway with sensitivity to individual characteristics and experimental conditions[52,53]. Figure 3 shows the CoP trajectories from an example trial: the original trajectory before the split (Fig. 3a, d), as well as the low-frequency (Fig. 3b, e) and high-frequency (Fig. 3c, f) components, for both the NORMAL and NOISE conditions.

SPM data analysis

A spreadsheet containing the list of any missing or unclear responses was kept throughout the survey process. The spreadsheet documented the number of the question and the time stamp of the audio recording to be submitted for clarification. All questions added to the spreadsheet and audio recordings were submitted to an occupational therapist to clarify caregivers' responses. After all the questions or missing responses were clarified,

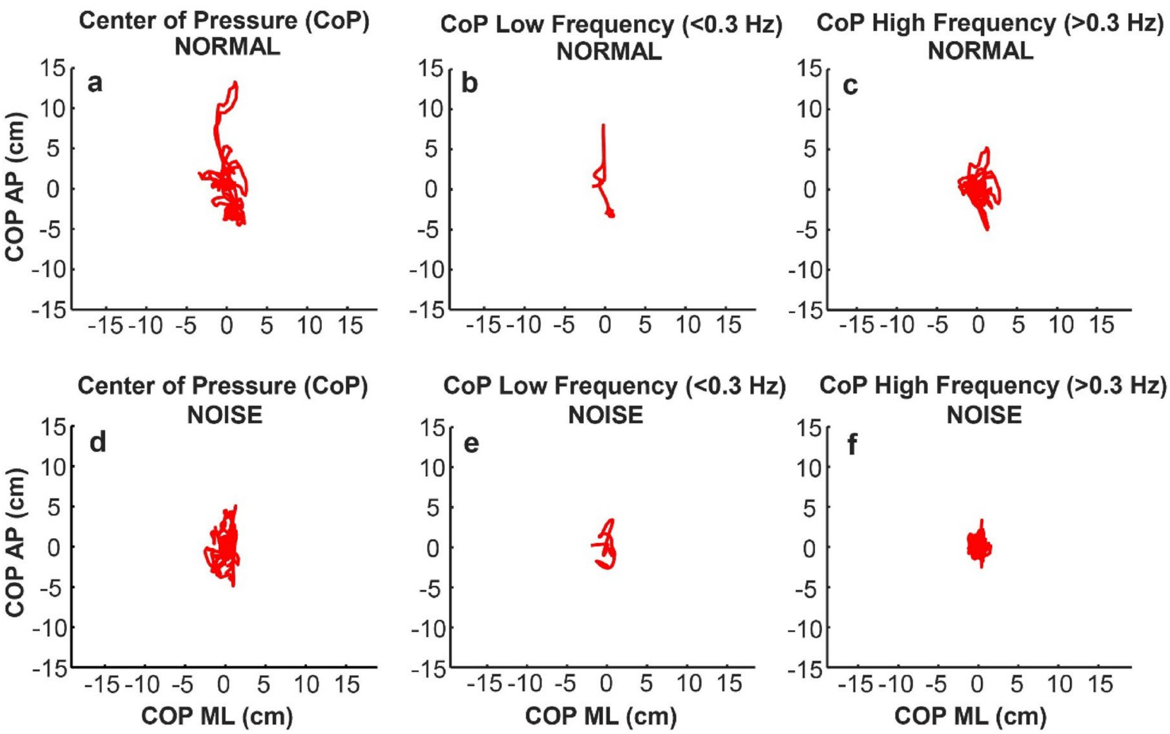

Fig. 3. Two-dimensional CoP profiles for a representative child in the ASD group. Raw CoP trajectories are shown for the NORMAL **(a)** and NOISE **(d)** conditions. Corresponding low-frequency (< 0.3 Hz) components are shown in panels **(b)** and **(e)**, and high-frequency (> 0.3 Hz) components in panels **(c)** and **(f)**.

one researcher graded the SPM^{TM}–2 responses by following the instructions on the form (SPM^{TM}–2 Child Autoscore Home Form Age 5–12 years). And a second researcher double checked all answers to rectify any issues in the grading process. Results were submitted to an occupational therapist to further interpret the results by making clinical decisions to specify sensory characteristics. The sensory characteristics of each domain were used to analyze the postural stability of autistic children with respect to their sensory processing difficulty categories.

Statistical analysis

The duration of tandem stance was compared between NORMAL and NOISE condition within ASD using a signed rank test, a non-parametric counterpart of a paired-sample t-test. To compare the CoP velocity between the NORMAL and NOISE conditions across the ASD and TD groups, a 2 × 2 mixed ANOVA was employed with the auditory input condition (NORMAL vs. NOISE) as a within-subject factor and the group (ASD vs. TD) as a between-subject factor. When a significant condition x group interaction was found, post hoc analyses were conducted. Paired t-tests examined the effects of auditory condition within each group. Independent t-tests examined the group effect within each condition. The CoP velocity was analyzed in the AP and ML directions separately. Results were considered significant if the p-values were less than 0.05. Effect sizes were estimated by partial η^2.

We also analyzed whether the CoP velocity depends on the degree of sensory processing difficulty in autistic children. First, we included both TD and ASD to analyze a Pearson correlation between the SPM-2 t-scores and the CoP velocity of the low- and high-frequency components in the AP and ML direction in the NORMAL and NOISE conditions as well as the difference between the two conditions (NORMAL – NOISE). Within the ASD group, we used independent t-tests to compare the CoP variables between participants with moderate sensory processing challenges and those with severe sensory processing challenges in hearing and balance domain of SPM-2. The Kolmogorov-Smirnov test confirmed that all datasets met the normality assumption required for analysis. We conducted the ANOVA using SPSS v28 (SPSS Inc., Chicago, IL). Other statistical tests were conducted using MATLAB 2022b built-in functions in the Statistics Toolbox (Mathworks, Natick, MA).

Results

Duration of tandem stance

We first assessed the ability to maintain balance for the required time (20 s). While all TD participants completed the 20-s-long trial in both conditions, some ASD participants moved their feet in the middle of the trial due to inability to stand still for 20 s. We thus compared the duration of tandem stance between the two auditory conditions within the ASD group. In the NORMAL condition, 7 out of 16 autistic children stood for the full 20 s while the mean duration for the remainder of the ASD group was 15.4 s (SD = 2.4 s). In contrast, 15 out of 16 autistic children stood for the full 20 s in the NOISE condition, with one autistic child standing for 15 s. A Wilcoxon signed rank test confirmed that the duration was significantly longer in the NOISE condition (p = 0.008).

Postural sway in cop velocity

Figure 4a shows the postural sway quantified by the low frequency component (< 0.3 Hz) of the CoP velocity in the AP direction in ASD and TD with respect to the NORMAL and NOISE condition. Overall, the children displayed reduced postural sway in the NOISE condition. To statistically examine the difference between the two conditions regarding the two groups, the dependent variable was submitted to a 2 × 2 mixed ANOVA with the two conditions as a within-subject factor and the two groups as a between-subject factor. The analysis revealed a significant condition ($F_{1,30}$=9.155, p = 0.005, partial h^2 = 0.23) and group ($F_{1,30}$=22.784, p < 0.001, partial η^2 = 0.43) effect without a significant condition x group interaction ($F_{1,30}$=3.437, p = 0.07, partial η^2 = 0.10).

Figure 4b shows the postural sway quantified by the high frequency component (> 0.3 Hz) of the same dependent variable in ASD and TD with respect to the NORMAL and NOISE condition. A similar trend was shown regarding the two conditions and the two groups. The 2 × 2 mixed ANOVA revealed a significant condition effect ($F_{1,30}$=12.619, p = 0.001, partial η^2 = 0.30) and group effect ($F_{1,30}$=4.904, p = 0.03, partial η^2 = 0.14). However, a condition x group interaction ($F_{1,30}$=5.034, p = 0.03, partial η^2 = 0.144) was also significant, implying inconsistent condition effects across the two groups. To identify the group that has a condition effect, we ran paired-sample t-tests within each group as *post hoc* analyses. In ASD, there was a significant difference between NORMAL and NOISE condition (t_{15} = 3.12, p = 0.007) whereas no significant difference between the two conditions was found in TD (t_{15} = 1.76, p = 0.10). For comparisons between ASD and TD within each auditory input condition, independent t-tests revealed that the group difference was significant in the NORMAL condition (t_{30} = 2.47, p = 0.015), but not in the NOISE condition (t_{30} = 1.30, p = 0.51). The same 2 × 2 ANOVA was run to test the postural sway in the ML direction. For the low frequency component, while the CoP velocities were generally lower than those in the AP direction, the statistical results were consistent with the results in the AP direction (Fig. 4c). A significant condition effect ($F_{1,30}$=8.699, p = 0.006, partial h^2 = 0.23) and group effect ($F_{1,30}$=9.056, p = 0.005, partial h^2 = 0.23) were found without a condition x group interaction ($F_{1,30}$=1.803, p = 0.19, partial h^2 = 0.06). In Fig. 4d, the high frequency component showed a significant condition effect ($F_{1,30}$=10.214, p = 0.003, partial h^2 = 0.25) without a group effect ($F_{1,30}$=3.682, p = 0.07, partial h^2 = 0.11) or a condition x group interaction ($F_{1,30}$=1.526, p = 0.23, partial h^2 = 0.05).

Relationship between sensory processing difficulties and cop velocity

The correlation between the COP velocity in the AP direction for the low-frequency component and the SPM-2 sensory total t-scores are shown in Fig. 5 across TD and ASD groups (n = 32). COP in the AP direction was weakly correlated with the SPM-2 sensory total in the NORMAL condition (Fig. 5a) while the correlation

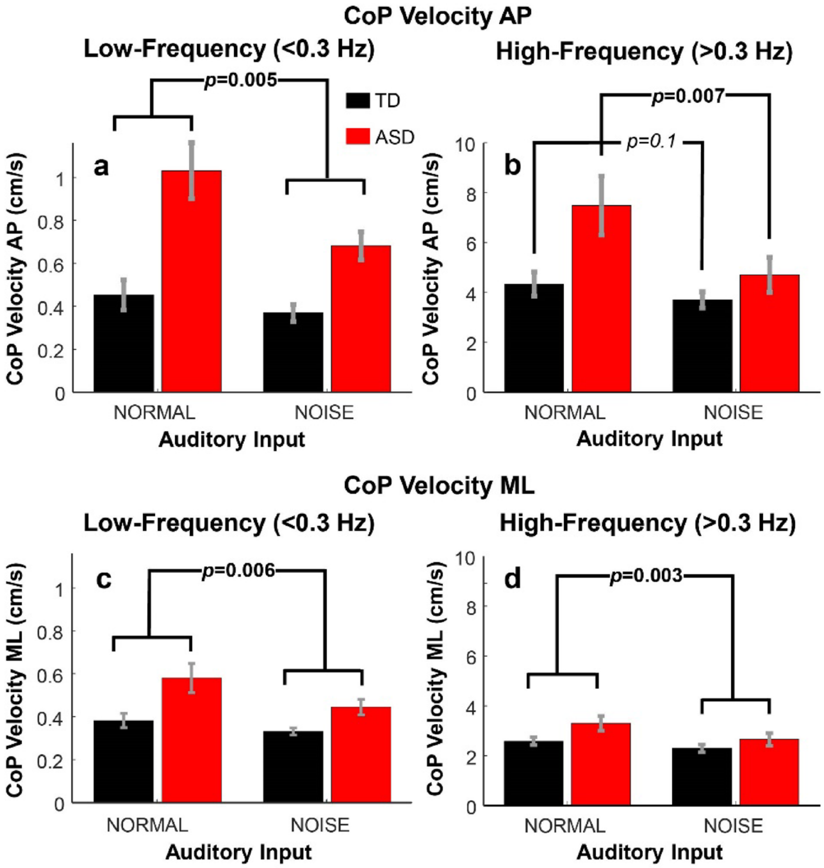

Fig. 4. Group-level CoP velocity under NORMAL and NOISE conditions. Mean CoP velocity for ASD (red) and TD (black) children along the anterior–posterior (AP) direction, separated into low- **(a)** and high-frequency **(b)** components, and along the medial–lateral (ML) direction in panels **(c)** and **(d)**. Error bars represent the standard errors of the mean.

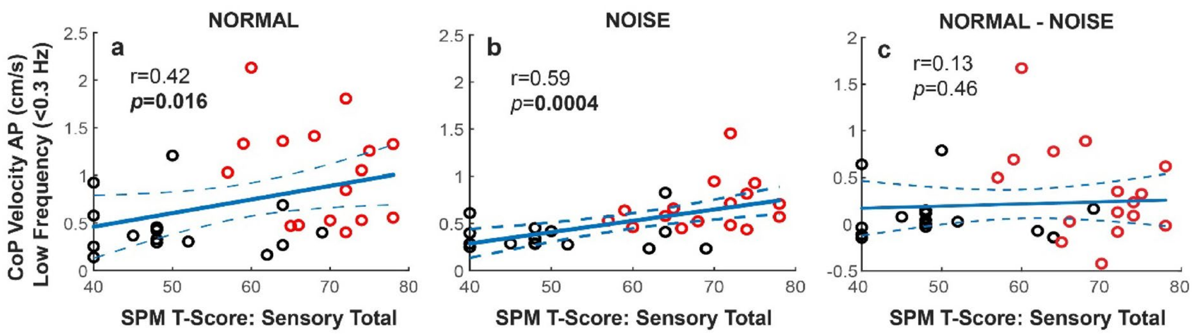

Fig. 5. Correlation between sensory processing scores and postural sway. Sensory processing difficulty was assessed using the SPM sensory total t-score. CoP velocity of the low-frequency component is shown for the NORMAL **(a)**, NOISE **(b)** conditions, and the difference between the two (NORMAL – NOISE) **(c)** across the TD (black circles) and ASD (red circles) groups (n = 32). The blue dotted lines represent 95% confidence intervals.

became stronger in the NOISE condition (Fig. 5b). However, the effect of auditory noise (NORMAL – NOISE) was not correlated with the SPM-2 sensory total (Fig. 5c). Additional correlation results involving high-frequency components of the COP velocity in AP and ML directions and SPM-2 t scores in the hearing and balance domains are shown in Table 2. Overall, the COP velocity in the ML direction was not strongly correlated with the SPM-2 scores compared with the COP velocity in the AP direction.

To examine whether the postural stability influenced by auditory noise depends on the degree of sensory processing difficulties, the CoP velocity in AP direction in NOISE condition was compared between autistic

COP Velocity Anterior-Posterior direction						
	Low Frequency (< 0.3 Hz)			High Frequency (> 0.3 Hz)		
SPM-2 t-score	NORMAL	NOISE	NORMAL-NOISE	NORMAL	NOISE	NORMAL-NOISE
Sensory Total	$r = 0.42^*$ $p = 0.016$	$r = 0.59^{**}$ $p < 0.001$	$r = 0.13$ $p = 0.46$	$r = 0.41^*$ $p = 0.018$	$r = 0.39^*$ $p = 0.028$	$r = 0.18$ $p = 0.34$
Hearing	$r = 0.44^*$ $p = 0.012$	$r = 0.60^{**}$ $p < 0.001$	$r = 0.13$ $p = 0.48$	$r = 0.30$ $p = 0.10$	$r = 0.33$ $p = 0.063$	$r = 0.09$ $p = 0.61$
Balance	$r = 0.52^{**}$ $p = 0.002$	$r = 0.62^{**}$ $p < 0.001$	$r = 0.25$ $p = 0.17$	$r = 0.45^*$ $p = 0.01$	$r = 0.22$ $p = 0.22$	$r = 0.33$ $p = 0.06$
COP Velocity Medial-Lateral direction						
	Low Frequency (< 0.3 Hz)			High Frequency (> 0.3 Hz)		
SPM-2 t-score	NORMAL	NOISE	NORMAL-NOISE	NORMAL	NOISE	NORMAL-NOISE
Sensory Total	$r = 0.27$ $p = 0.14$	$r = 0.41^*$ $p = 0.019$	$r = 0.05$ $p = 0.79$	$r = 0.27$ $p = 0.14$	$r = 0.35^*$ $p = 0.04$	$r = -0.10$ $p = 0.57$
Hearing	$r = 0.25$ $p = 0.17$	$r = 0.40^*$ $p = 0.022$	$r = 0.04$ $p = 0.79$	$r = 0.20$ $p = 0.28$	$r = 0.30$ $p = 0.09$	$r = -0.13$ $p = 0.48$
Balance	$r = 0.30$ $p = 0.10$	$r = 0.35$ $p = 0.05$	$r = 0.14$ $p = 0.45$	$r = 0.31$ $p = 0.087$	$r = 0.21$ $p = 0.24$	$r = 0.04$ $p = 0.82$

Table 2. Correlations between postural sway and SPM-2 scores across the two groups ($n = 32$). Notes: r's represent Pearson correlation coefficients and p's represent uncorrected p-values for the corresponding correlation coefficients. * $p < 0.05$, ** $p < 0.005$.

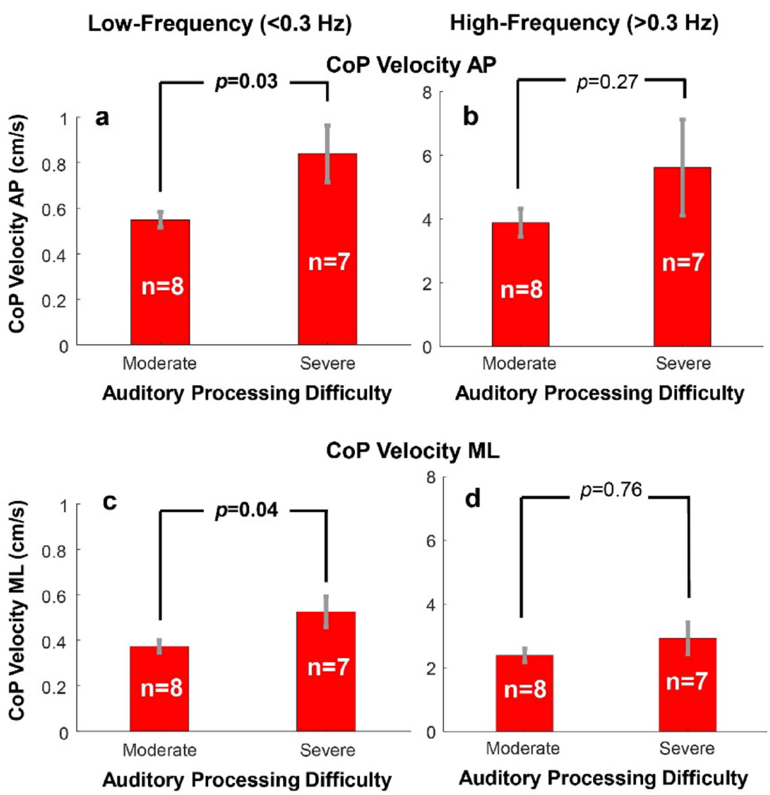

Fig. 6. Comparison of CoP velocity in the NOISE condition within ASD subgroups. Children were grouped by SPM-2 hearing processing difficulty into moderate ($n = 8$) and severe ($n = 7$) subgroups. Panels **(a)** and **(b)** show CoP velocity along the AP direction for low- and high-frequency components, respectively; panels **(c)** and **(d)** show the same measures along the ML direction. Error bars denote the standard errors of the mean.

children that showed moderate difficulties ($n = 8$) and that showed severe difficulties ($n = 7$) in the domain of hearing processing. An independent t-test revealed a significant difference between the two subgroups for the low frequency component in NOISE condition ($p = 0.03$; Fig. 6a). However, the group difference was not significant for the high-frequency CoP component ($p = 0.27$; Fig. 6b). The difference between the two subgroups was not significant ($p = 0.11$). Figure 6c and d show the same results in the ML direction. Again, the group difference was only significant in the low-frequency component.

Discussion

With the increasing number of studies that have shown the effect SR in postural control[54–56] the present study investigated the influence of loud auditory noise on reducing postural sway in autistic children, a population generally characterized by sensory processing challenges. Not only did the duration of tandem stance increased in the NOISE condition, but the CoP velocity also reduced in the NOISE condition for both the low and high-frequency components of the continuous CoP profile in autistic children. This robust finding supports our hypothesis that adding loud auditory noise reduces postural sway in autistic children. To our knowledge, this is the first study to show a positive effect of adding environmental auditory noise during a postural control task with autistic children.

We analyzed postural sway along the AP and ML directions separately. Overall, larger postural sway was found in the AP direction due to the foot placement of the task. The tandem stance allows a larger base of support in the AP direction. Therefore, producing more postural sway along the AP direction could be a result of the biomechanical demands due to the change in base of support. Despite the difference in the magnitude of postural sway, the effect of auditory noise was consistently shown in both AP and ML directions. The relatively small effects of the auditory noise in the TD group may be due to a ceiling effect, i.e., the balance task was not sufficiently challenging for TD children. It is also possible that the effect of auditory noise is specific to those who initially have postural difficulties or populations with neurodevelopmental conditions. Assessing the extent to which auditory noise may improve postural control across various populations is suggested as future studies with sufficiently challenging postural tasks.

The experimental setup was implemented in a playful environment with child-friendly narratives that children on a broader range of autism spectrum can understand. Additionally, we conducted outreach efforts at an inclusive summer camp, differing from typical research facility invitations. This allowed us to recruit autistic children within a short time frame and across a broader autism spectrum. Our observation of children during the balance task suggests that the experimental procedure we implemented is suitable for studying postural control in autistic children with moderate to severe social and sensory difficulties. Notably, 5 out of 21 eligible ASD children were unable to stand in tandem stance on the force plate. This failure to collect data is attributed to the nature of community outreach data collection; participants were pulled from their summer camp classes. Although all parents were informed about the data collection schedule, it is possible that the child participants perceived participation as an abrupt change, potentially inducing anxiety[57,58].

What is the underlying mechanism by which auditory noise influences postural stability? The principle of SR provides an explanation for the mechanical effects of auditory noise. Paradoxically, the addition of acoustic noise increases the signal-to-noise ratio of neural signals in nearby vestibular organs. Analyzing the relationship between postural sway on the force plate and individual sensory processing difficulties based on caregiver observations provided insights about the neural underpinnings regarding the effectiveness of auditory noise in postural control. Expectedly, our results show positive correlations between postural sway and sensory processing difficulty in the NORMAL and NOISE conditions. In contrast, we found a lack of correlation between the effectiveness of auditory noise (NORMAL-NOISE) and sensory processing difficulty, which supports the idea of an independent neural mechanism that separates the improved signal-to-noise ratio in the vestibular organs[12] from higher-level sensory processing, which is known as a top-down process across the brain[21]. Although our findings support this proposed SR mechanism, it is worth noting that a recent study using transcranial random noise stimulation did not find evidence of a beneficial effect of electrical noise to the vestibular system[59]. Hence, more direct evidence under systematically controlled experimental conditions is needed to better understand the underlying mechanism[60].

We acknowledge several limitations of our study. First, the present study was unable to obtain IQ scores or administer any instruments that measure intellectual abilities from the participants. However, since our primary goal of the study was to assess the effect of loud auditory noise with autistic children, it is of note that our findings remain valid without IQ measures. Nevertheless, the group difference warrants a follow-up study with an IQ-matched group to rule out the possibility that the difference between ASD and TD came from the lower IQ in ASD[27]. Although the effect of auditory noise appears to be consistent across various dependent variables, a study with various types and intensity of auditory noise is necessary to further investigate the underlying mechanism of the effectiveness. The present study only examined postural stability in a single type of auditory noise. In addition, the effectiveness of auditory noise should also be tested in various contexts including different stances rather than only a tandem stance. This will help us understand the degree to which auditory noise is effective in postural control. A more systematic study design with multiple sensory domains will help to understand the relationship between sensory processing and postural control. For example, future studies should examine the relationship between postural stability and auditory noise with various colors of noise, intensity and the quality of sound (whether the sound is pure noise, music, or natural sound). We hope that the suggested studies will identify an optimal sensory environment that will lead to the most effective therapeutic intervention to alleviate motor difficulties in autistic children.

In summary, we examined changes in postural stability in autistic children exposed to loud auditory noise. The child-friendly, play-based procedures allowed us to assess postural control even in children with severe sensory processing difficulties. Our findings demonstrated that auditory noise significantly reduced postural sway in autistic children. Additional analyses that examined the relationship between postural sway and sensory processing difficulty support SR as a signal booster in the vestibular organs independent of the neural networks for sensory processing. However, confirming this relationship will require studies with larger sample sizes and various experimental conditions. Future research using diverse types and intensities of auditory stimuli may help elucidate the neural mechanisms underlying sensory processing difficulties in autism and inform strategies to enhance postural stability. These findings suggest a novel application of stochastic resonance stimulation, an established sensory-based therapeutic technique[61]as a potential intervention for improving motor control in autistic children.

Data availability

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

Received: 13 January 2025; Accepted: 28 May 2025
Published online: 06 June 2025

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Acknowledgements

Support for this work was made possible by a Clinical & Translational Research Pilot Grant Award from the Institute for Integration of Medicine & Science (IIMS) at UT Health San Antonio (SO, S-WP and M-LL). We want to thank all participants and their families for their time and cooperation. We would also like to express our gratitude to Giselle Gonzalez, Amber Valdez and Aneri Patel for their assistance in collecting data.

Author contributions

Conceptualization: S-WP, SO, M-LL, Methodology: S-WP, M-LL, SO, Investigation: JS, KH, Visualization: JS, S-WP, Statistical analysis: JS, S-WP, Supervision: S-WP, SO, LN, M-LL, AC, WL, Writing—original draft: JS, KH, S-WP, Writing—review & editing: JS, KH, M-LL, LN, AC, WL, SO, S-WP.

Declarations

Competing interests
S-WP is an Editorial Board Member of Scientific Reports. Other authors declare no conflicts of interest.

Additional information
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