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Article

Auditory Challenges and Listening Effort in School-Age Children with Autism: Insights from Pupillary Dynamics during Speech in Noise Perception

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Abstract: Purpose: School-age children with autism spectrum conditions (ASC) often experience difficulties in speech-in-noise (SiN) perception, leading to increased listening effort that impacts their well-being and academic performance. This study aimed to investigate the SiN processing challenges faced by Mandarin-speaking children with ASC and its impact on their listening effort. **Methods:** Participants completed sentence recognition tests in both quiet and noisy conditions, with a steady-state noise masker presented at 0 dB signal-to-noise ratio in the noisy condition. We compared recognition accuracy and task-evoked pupil responses from 23 Mandarin-speaking children with ASC to 19 age-matched neurotypical (NT) counterparts to gauge their behavioral performance and listening effort during these auditory tasks. **Results:** The ASC group demonstrated notably decreased accuracy in noise compared to their NT peers, suggesting poorer SiN perception. Pupillometric data further revealed significantly larger peak dilations in the ASC group than in the NT group under comparable conditions. Importantly, the ASC group's peak dilation in quiet mirrored the NT group's in noise. However, the ASC group exhibited shorter peak latencies and reduced mean dilations than the NT group in similar conditions. Such patterns indicate the ASC group might initially experience a heightened cognitive load but utilize fewer cognitive resources as the task continued, indicating an atypical allocation of cognitive resources and a potential tendency towards relatively superficial and automated auditory processing. **Conclusion:** Our findings highlight the unique SiN processing challenges children with ASC face, underscoring the importance of a nuanced, individual-centric approach for interventions and support.

Keywords: autism spectrum conditions; atypical resource allocation; listening effort; pupillometry; speech-in-noise recognition

Introduction

In everyday communication, people often encounter noisy environments, which affect their ability to listen effectively. Everyday listening is typically manageable due to the brain's ability to focus on relevant sounds and filter out distractions (Kerlin et al., 2010). However, individuals with auditory challenges, such as those with autism spectrum conditions (ASC), may struggle to ignore background noise and would hear and attend to sounds that others did not notice, leading to effortful

listening and heightened sensitivity to sounds (Kirby et al., 2015; Landon et al., 2016). ASC individuals often exhibit reduced attention to language and atypical noise response, affecting their speech-in-noise (SiN) perception (O'Connor, 2012; Schwartz et al., 2018). In school settings, where effective communication is crucial, excessive listening effort can negatively impact learning, memory, and social interactions (Keen et al., 2016). This is concerning as inadequate SiN processing is linked to such challenges (Alcántara et al., 2004; Ashburner et al., 2008; Mallory & Keehn, 2021). Meanwhile, prolonged exposure to the listening effort can cause cognitive overload, resulting in negative health impacts, such as headaches, fatigue, and even depression (Pichora-Fuller et al., 2016).

Despite its importance, research into listening effort for ASC individuals remains underexplored. Individuals with ASC exhibit distinct speech processing differences even in quiet conditions (Huang et al., 2018; Key & D'Ambrose Slaboch, 2021; Wang et al., 2017; Yu et al., 2015; 2018; 2021, 2022). Similarly, NT children may also struggle with speech perception in noisy environments (McGarrigle et al., 2017; Prodi et al., 2019). To understand the nuanced between-group differences, previous research often focused on perception performance using task-based measures such as recognition threshold and accuracy rate, or assessed listening effort through questionnaires and scales like the Short Sensory Profile and the Listening Inventory for Education (Groen et al., 2009; Mair, 2013; Schafer et al., 2020). However, the performance data have limitations as listeners may expend varying amounts of effort with different cognitive strategies to achieve similar intelligibility scores (Koelewijn et al., 2012). Self-reported measures and caregiver questionnaires may indicate listening effort, but they lack objective quantification and can be biased or inaccurate sometimes. To our knowledge, two ASC studies have used objective measures for listening effort. Rance et al. (2017) compared the cortisol response of 26 children with ASC before and after a word-level SiN recognition task and found a non-significant increase over the course, but a significant correlation between poorer recognition and higher cortisol levels. More recently, Feldman et al. (2022) adopted a dual-task paradigm on 32 children and adolescents with ASC, revealing longer response times for complex stimuli compared to simpler ones during SiN recognition tasks.

The two studies are informative, but certain aspects warrant further exploration. Both studies lacked matched neurotypical (NT) comparison groups. Previous research indicates that NT children also struggle with processing speech in noisy environments, showing poorer performance or more effort compared to quiet settings (e.g., McGarrigle et al., 2017; Prodi et al., 2019). It is necessary to examine whether children with ASC truly underperform their NT peers or show extra effort during SiN perception tasks. These studies also failed to fully account for the potential impact of atypical speech perception in ASC children when evaluating their SiN processing. Preceding studies have highlighted atypical speech-specific processing in the ASC population (Key & D'Ambrose Slaboch, 2021). Subpar performance or heightened effort in autism might exist even in quiet conditions, not just due to background noise. To assert that noise significantly affects children with ASC, baseline data on their speech perception in quiet settings is crucial. Furthermore, both studies lacked comprehensive demographic considerations like bilingualism and socioeconomic status, which are known to influence SiN processing in different ways (Schwab & Lew-Williams, 2016; Skoe & Karayanidi, 2019). Noticeably, previous measurements could be indirect and process-independent to the discussion on listening effort. The cortisol response is engendered by the hypothalamic-pituitary-adrenal axis activity associated with particularly psychosocial stressors and feelings of distress (Francis & Love, 2020). However, listening effort as a cognitive demand might not directly lead to increased stress or related neurochemicals. The dual-task paradigm offers insights into resource allocation but falls short of revealing real-time cognitive processes underpinning auditory behaviors.

Pupillometry, as an objective and non-invasive tool to measure online pupil dilation, has proven effective for assessing listening effort (Koelewijn et al., 2015; Koelewijn et al., 2017; Wendt et al., 2018; Zekveld et al., 2014). It is a sensitive and viable measure suitable for testing ages as young as 2 years old (Blaser et al., 2014). To date, a few studies have adopted this method to assess the listening effort in children during SiN processing (e.g., Cooper et al., 2015; McGarrigle et al., 2017). While these studies demonstrated the feasibility of using pupillometry for up to 40 minutes in school-aged children, its potential for ASC individuals remains largely untapped. Extant pupillometric studies on

autism primarily address pupillary light reflex and task-evoked pupillary response to visual stimuli, with limited focus on speech processing (see de Vries et al., 2021 for a review). Nevertheless, pupillometry can be particularly advantageous when functional auditory measures are not available or sufficiently reliable due to participants' inadequate cooperation or restricted verbal ability, which are both particularly common in cases of children with ASC. It is also a promising and translational tool to assess listening effort and illuminating precise temporal indications of online speech perception processes in the ASC population, offering a novel avenue for understanding their SiN difficulties and the different patterns behind them.

Pupillary response analysis typically centers on three metrics: peak dilation/amplitude (the maximum pupil size within a post-stimulus interval), peak latency (the time taken to reach the peak dilation), and mean dilation over the same time window (Zekveld et al., 2011). Specifically, peak dilation is a robust indicator of maximum task-elicited cognitive load, marking the zenith of listening effort at a particular moment. Mean dilation gauges the sustained cognitive load throughout a task, reflecting the overall allocation of cognitive resources. Peak latency reflects the time required for an individual's cognitive system to fully engage and reach its peak load in response to an auditory stimulus. These metrics provide insights into the cognitive load, processing complexity, and working memory (Koelewijn et al., 2012; Wendt et al., 2016; Winn & Moore, 2018; Zekveld et al., 2010, 2011). Cumulative evidence indicates that interindividual capacity differences affect speech perception specifically in difficult conditions where greater allocated capacity boosts performance and processing load (Zekveld et al., 2018). ASC individuals often focus on details rather than global context, which can hinder their capacity to process more intricate linguistic or social information and curtail their ability for multimodal integration (Thye et al., 2018; Yi et al., 2022). Goldknopf (2013) postulated that in autism, especially in those with pronounced sensory symptoms, resources might be either narrowed or reduced, potentially with atypical intensity in restricted aspects (such as fewer modalities, less processing, and smaller cortical areas) or with a reduced amount allotted to each of those. Such allocation patterns might manifest as reduced peak latency and increased peak amplitude during SiN perception.

So far, it has remained unclear how the aforementioned metrics behave in the ASC population and which aspects best distinguish ASC from NT populations during auditory tasks. To address these gaps, we adopted a 2×2 mixed factorial design to examine the effects of the subject group (ASC vs. NT) and listening conditions (Quiet vs. Noise) on the three pupillometry indices of listening effort in Mandarin-speaking school-age children. The study aimed to uncover how ASC individuals allocate cognitive resources during listening tasks. It hypothesized that noise would increase listening effort for both groups, and ASC individuals would demonstrate unique patterns regardless of listening conditions. An interaction effect between conditions and groups was also anticipated, indicating increased differences in ASC individuals' listening effort under noisy conditions. The findings will shed light on the nature of listening effort for SiN on group and individual levels, potentially paving the way for targeted interventions.

Method

Participants

This study was approved by the Institutional Review Board of Shanghai Mental Health Center. Written informed consent was obtained before experiments. A total of 45 children were tested, and three children with ASC were excluded due to failure to capture substantial pupillometric data, resulting in age- and sex-matched cohorts of 23 ASC and 19 NT individuals. All participants were from middle-class families in nearby cities including Shanghai, primarily speaking Mandarin Chinese and Wu dialects. Most had prior English learning experience, except two young ASC participants. All were right-handed with no history of visual or hearing impairments, neurological injuries, or disorders such as Fragile X syndrome, Down syndrome, and epilepsy, which can co-occur with autism but have distinct physical symptoms. Due to the symptom overlap between ASC and attention-deficit/hyperactivity disorder (ADHD) that could skew results, participants were screened

for ADHD using the Chinese version of the Swanson, Nolan, and Pelham version IV scale (SNAP-IV; Gau et al., 2009), revealing no significant between-group differences between groups (Table 1).

Table 1. Participants’ demographic information and SRT results, with data range and mean±SD listed. (SRT=speech recognition threshold; SD=standard deviation; ASC=autism spectrum condition; NT=neurotypical; M/F=Males/Females; IQ= intelligence quotient; SNAP-IV=the Chinese version of the Swanson, Nolan, and Pelham version IV scale).

	ASC (n=23)	NT (n=19)	t value	p ¹
Age(year)	6.8–12 (9.01±1.33)	6.6–11.2 (8.42±1.39)	1.86	.43
Sex (M/F)	21/2	17/2	N/A	.78
IQ	79 – 130(112.93±13.79)	96–137(121.16±11.33)	-2.08	.04
SNAP-IV-sub 1	6 – 11(8.1±2.2)	6–9(6.9±2.3)	1.72	.09
SNAP-IV-sub 2	6–12(7.9±2.8)	4–11(6.3±2.1)	1.60	.05
SRT	-6.9 – -1.4(-4.11±2.01)	-6.9 – -1.9(-4.42±1. 53)	0.55	.58

¹ p for sex was computed using the two-tailed Fisher’s exact test while the others, the independent two-tailed t-test.

Both groups were evaluated using the Chinese version of the Autism Behavior Checklist (ABC; Krug et al., 1980) under the supervision of licensed psychologists. The ASC group scored above the threshold of 68, indicating a high probability of autism, while the NT group scored below 31. Diagnoses in the ASC group were confirmed through comprehensive assessments adhering to American Psychiatric Association criteria (2013), conducted by accredited pediatric neurologists using the Childhood Autism Rating Scale (CARS; Schopler et al., 1980). ASC group scores fell within the mild to moderate range (30 to 36).

Participants were informed to refrain from caffeine and adrenergic-related medications 48 hours before testing to avoid affecting pupillary responses (Abokyi et al., 2017; Reimer et al., 2016). Cognitive abilities were assessed by two certified examiners using the Wechsler Intelligence Scale for Children 4th edition-Chinese version (WISC-IV-Chinese; Zhang, 2009). All had IQ scores above 70, indicating no intellectual disability, though a slight between-group IQ difference was noted (Table 1). A certified audiologist measured the pure-tone hearing thresholds of participants. Both ears were ≤ 20 dB hearing level (HL) at frequencies of 250, 500, 1000, 2000, and 4000 Hz, and ≤ 30 dB HL at 6000 and 8000 Hz. As prior research (Ohlenforst et al., 2018; Wendt et al., 2018) suggests a correlation between the peak dilation and speech recognition thresholds (SRTs, the minimum sound intensity level for identifying speech at 50% accuracy), we also measured participants’ SRTs using an adaptive procedure. Subsequent analysis revealed no significant between-group SRT differences (Table 1).

Stimuli

Sentences from the Mandarin Hearing in Noise Test for Children (MHINT-C; Chen & Wong, 2020), spoken by a male speaker, were delivered at a fixed 65 dBA as stimuli. Prior research linked peak pupillary dilation with receptive vocabulary knowledge, suggesting that comprehension might affect pupillary responses. A questionnaire assessed word familiarity in ASC children's parents. Sentences with similar unfamiliar word percentages were chosen for pupillometric tests. Word familiarity's potential impact on pupillary dilation was examined through Pearson's correlation, showing a weak and significant association (r = 0.18, p = 0.005) with limited influence on pupillary responses in our study.

During SiN perception tasks, a speech-spectrum-shaped steady-state masker was presented at 0 dB signal-to-noise ratio (SNR), ensuring equal signal and noise power. Normal-hearing adults' listening effort peaks around their SRT value, nearly -4 dB SNR (Wendt et al., 2018). In general, children require more favorable SNRs for adult-like SiN task performance (e.g., Leibold & Buss, 2013; Nitttrouer & Boothroyd, 1990; Schafer et al., 2018). This difference might be more pronounced in children with ASC, potentially requiring even higher SNRs. To manage this, a 0 dB SNR based on participants' SRT data was chosen, aiming to prevent task disengagement due to challenging SNR conditions and mitigate potential confounding effects. Careful masker selection was also vital to avoid result confounding. Masker attributes, acoustical and linguistic, significantly impact listening effort. Complex maskers can lead to disengagement, particularly in children whose cognitive capacities are still developing (Johnson et al., 2014; Koelewijn et al., 2012; Ohlenforst et al., 2018; Wendt et al., 2017). Therefore, a basic steady-state noise masker was chosen to minimize potential disengagement, which was validated in our recent study (Xu et al., 2023).

Apparatus and Settings

The study utilized an eye-tracking system (Eyelink 1000, SR Research Ltd., Canada) with a 250 Hz sampling rate to record stable pupil diameter. Participants were seated in front of a display PC and an infrared camera that tracked eye and head movements. Adjustments were made for chair height and distance to the eye tracker, ensuring stable pupil response. Participants sat in a chinrest at a fixed distance from a 21-inch computer monitor (1920x1080, 144Hz, luminance 55 lx), while room lighting varied (60 ± 12 lx). Room illumination was individually adjusted to the median pupil size value of its dynamic range, reducing ceiling and floor effects in pupil dilation responses (Zekveld et al., 2014) to make the dilation independent of possible between-group differences in the tonic pupil size (Anderson and Colombo, 2009).

Stimulus presentation was controlled using MATLAB and PsychToolbox on a display PC. Test stimuli were delivered through a sound card and presented by loudspeakers situated in a double-walled, acoustically treated room with background noise below 25 dBA. The speech signal from the MHINT-C was presented via a loudspeaker located at 0° azimuth, while the masker was via a loudspeaker sited at 180° azimuth. Both loudspeakers were set at head level at a distance of one meter from the participant. The primary experimenter sat in front of the host PC to keep track of the pupillary state and record verbal responses while a trained research assistant was seated behind the rear loudspeaker to record simultaneously as a reliability check. An illustration of setting details is provided in Figure 1.

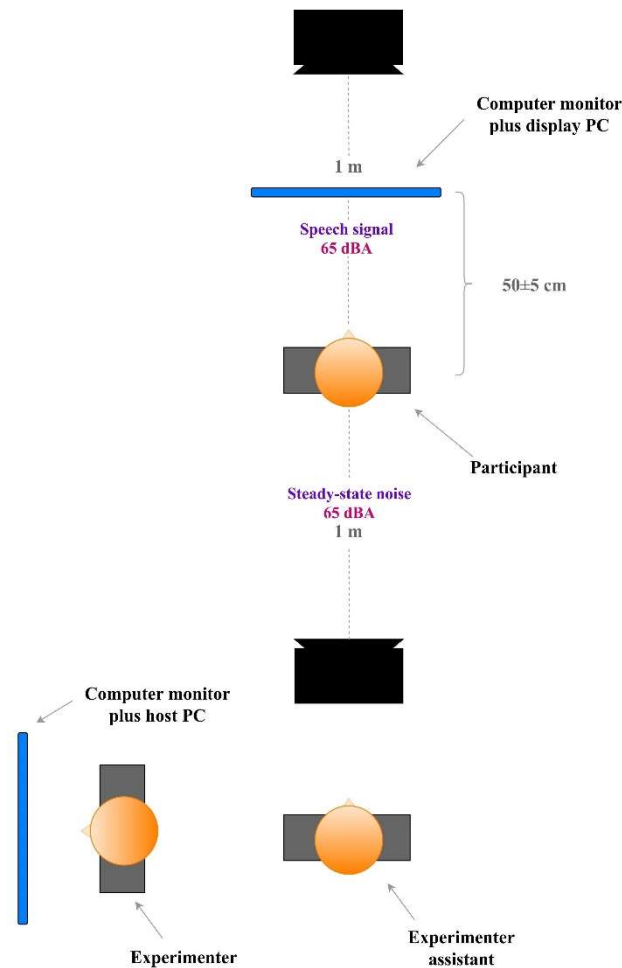


Figure 1. Diagram for the spatial setup.

Procedure

Participants had two lab visits: one for screening and recruitment, and another for experiments. During the first visit, all children underwent pre-recruitment assessments, including intelligence tests and pure tone audiometry. For the ASC group, guardians completed questionnaires about their children's medical history and familiarity with MHINT-C words.

In the second visit, participants completed pupillometric tests in randomized sequences to counterbalance order effects. Before starting, the eye gaze position was validated and calibrated using a 9-point grid. A training block of 10 trials familiarized participants with the procedure and setup. Each treatment level had 10 trials. Masker noise began 3 seconds before sentence onset and ended 3 seconds after sentence offset. A black fixation dot (15x15 pixels) was displayed at the center or midpoints of the screen's sides to sustain younger participants' attention. Participants were guided to gaze at the dot, repeat the sentence after noise cessation, and click 'next' or tap the space bar to continue. Assistance was given as needed. A 5-second pause followed each trial to return pupil size to baseline. NT group measurement took about 30 minutes, and ASC group measurement took around 50 minutes, with 10-minute breaks in between. See Figure 2 for a detailed event sequence.

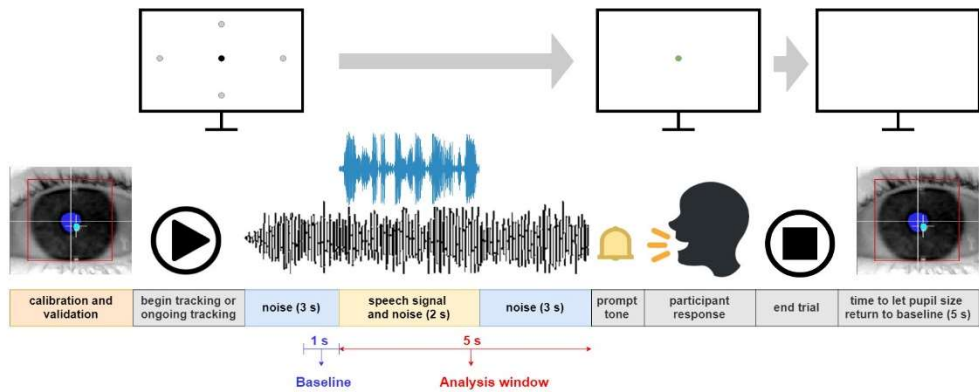


Figure 2. Illustration of trial design during the pupillometric measurement.

Statistical Analyses

Data preprocessing and statistical analyses were conducted using R version 4.2.2 (R Core Team, 2022). Raw accuracy data, expressed as percent correct scores, were transformed into rationalized arcsine units (RAU; Studebaker et al., 1995) due to non-normal distribution. Pupil data were preprocessed using the *gazeR* package (Geller et al., 2020). Mean pupil dilations and standard deviations were calculated for traces from 3 seconds before speech onset to noise offset. Pupil diameters below three standard deviations were treated as eye blinks, and rectified by linear interpolation. Trials with over 25% eye-blink duration, artifacts, or missing data were removed. Incorrect behavioral responses were excluded to eliminate confounding. A 5-second moving average filter smoothed remaining trials, and baseline pupil size was subtracted to control for arousal-related size variation.

Peak dilation was the maximum within 5 seconds from speech onset to prompt tone onset. Peak latency was relative to sentence onset. Linear mixed-effects models (LMMs) analyzed performance and pupillometric measures (peak dilation and latency), considering participants' variability and dependencies. LMMs were created using *lmerTest* (Kuznetsova et al., 2017), guided by AIC (Akaike information criterion), and inspected for normality and homoscedasticity. Interaction terms were tested using *emmeans* or *emtrends* (Bonferroni/Kenward-Roger adjusted) from the *emmeans* package (Lenth, 2020).

Generalized additive mixed models (GAMMs) were used to analyze holistic pupillary changes over time. GAMMs accounted for temporal effects more accurately. Data were down-sampled to 50 Hz without additional smoothing. *mgcv* and *itsadug* packages were used for GAMMs. A backward stepwise selection based on visual inspection and summary statistics fitted parsimonious models. AIC assessed model strength. The goodness-of-fit was assessed with *acf_resid* and *acf_plot* functions. The scaled-t family transformed residuals to normality. The final GAMM included a *Group* effect and a *Group*×*Condition* interaction, estimating nonlinear regression lines for each *Group* level. Random smooth for *Time* and *Event* accounted for non-linear random variances. This term compensated for participants' reduced attention and increased pupil size during the experiment (Boswijk et al., 2020).

Results

Speech Recognition Accuracy

Table 2 displays descriptive statistics and the LMM results for accuracy data (in RAU). A Type III ANOVA on the LMM with Satterthwaite's method revealed significant main effects of *Condition* [$F(1,40) = 90.23, p < 0.0001, \eta^2p = 0.69$] and *Group* [$F(1,40) = 24.49, p < 0.0001, \eta^2p = 0.38$], along with a significant interaction between them [$F(1,40) = 34.68, p < 0.0001, \eta^2p = 0.46$]. Post-hoc pairwise comparisons revealed significant accuracy differences between groups in noisy conditions (estimate_{NT-ASC} = 2.12, SE = 0.33, $t = 6.36, p < 0.0001$), indicating reduced accuracy in the ASC group

when exposed to noise. Conversely, no significant group difference emerged in quiet conditions ($p = 0.33$). Specifically, noise significantly compromised accuracy for ASC participants ($\text{estimate}_{\text{Quiet-Noise}} = 2.20$, $\text{SE} = 0.19$, $t = 11.44$, $p < 0.0001$), while showing negligible impact on NT participants ($p = 0.12$).

Table 2. Descriptive statistics of the accuracy (in RAU) and a summary of the LMM for the effects of Condition and Group on the accuracy. (RAU=rationalized arcsine units; LMM=linear mixed-effects models; SD= standard deviation; ASC=autism spectrum condition; NT=neurotypical).

Sentence recognition accuracy (in RAU)					
mean±SD _{ASC-Noise}	6.83±1.27	mean±SD _{NT-Noise}	9.17±1.20		
mean±SD _{ASC-Quiet}	9.03±0.94	mean±SD _{NT-Quiet}	9.68±0.82		
Formula code: Accuracy ~ Group + Condition + Group:Condition + (1 Subject)					
<i>Fixed effects</i>	<i>Estimate</i>	<i>SE</i>	<i>95% CI</i>	<i>t value</i>	<i>p value</i>
<i>(Intercept)</i>	9.68	0.24	9.19 – 10.18	39.19	<0.001
<i>Group: ASC</i>	-0.65	0.33	-1.32 – 0.01	-1.95	0.054
<i>Condition: Noise</i>	-0.52	0.21	-0.94 – -0.09	-2.44	0.017
<i>Group: ASC × Condition: Noise</i>	-1.68	0.29	-2.25 – -1.11	-5.89	<0.001
ICC	0.63				
<i>N</i> _{subject}	42				
Observations	84				
Marginal R ² / Conditional R ²	0.52/ 0.83				

Pupillometric Measures

Figure 3 illustrates peak dilation (left panel) and peak latency (right panel) statistics across the four experimental levels. Meanwhile, Tables 3 and 4 summarize LMM results for peak dilation and peak latency, respectively.

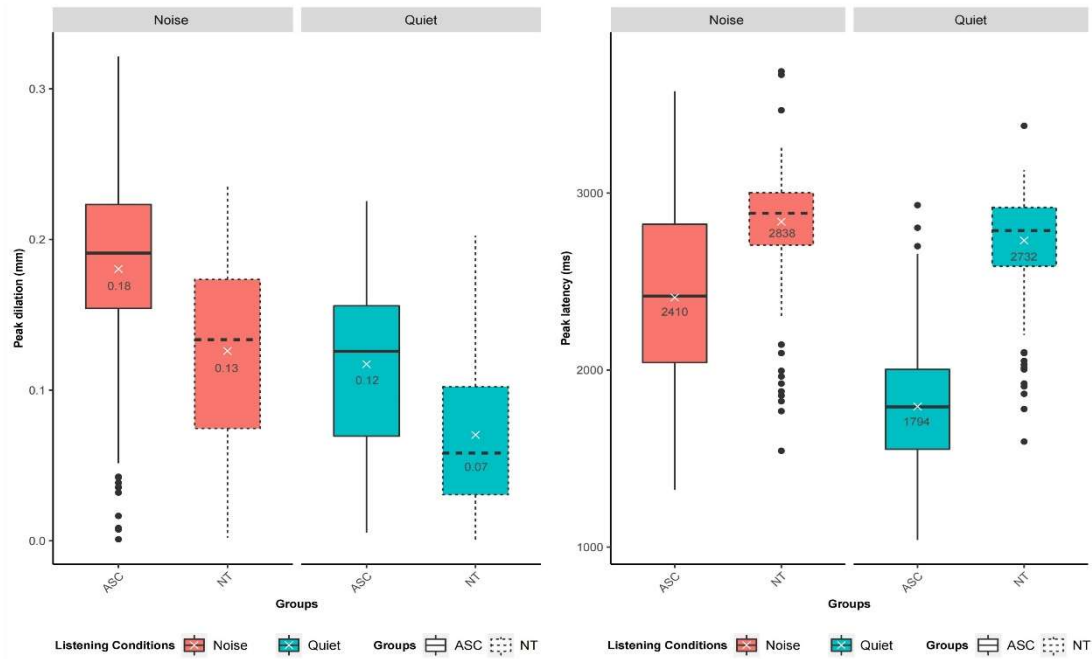


Figure 3. Visual representation of peak dilation and peak latency statistics as a function of Group (ASC vs. NT) and Condition (Quiet vs. Noise). (ASC=autism spectrum condition; NT=neurotypical).

Table 3. Summary of the LMM for the effects of *Condition* (Quiet vs. Noise) and *Group* (ASC vs. NT) on the peak dilation.

Formula code: Peak Dilation ~ Group + Condition + IQ + Group: Condition + Condition:IQ + (1 Subject) + (1 Trial)					
Peak dilation (mm)					
Fixed effects	Estimate	SE	95% CI	t value	p value
(Intercept)	0.28	0.08	0.11 – 0.34	3.30	0.001
Group: ASC	0.08	0.02	0.04 – 0.12	3.85	<0.001
Condition: Noise	-0.10	0.07	-0.14 – 0.05	-1.30	0.20
IQ	-0.001	0.0007	0.002 – 0.0002	-1.64	0.10
Group: ASC × Condition: Noise	0.04	0.02	0.008 – 0.08	2.38	0.02
Condition: Noise × IQ	0.002	0.0006	0.0005 – 0.003	2.82	0.005
ICC	0.15				
N _{subject}	42				
N _{trial}	10				
Observations	774				

Marginal R^2 / Conditional R^2 0.33/ 0.43

Table 4. Summary of the LMM for the effects of *Condition* (Quiet vs. Noise) and *Group* (ASC vs. NT) on the peak latency.

Formula code: Peak Latency ~ Group + Condition + Group: Condition + Condition: IQ + (1|Subject) + (1|Trial)

Peak latency (ms)					
Fixed effects	Estimate	SE	95% CI	t value	p value
(Intercept)	2686.32	226.86	2240.97 – 3131.66	11.84	<0.001
Group: ASC	-936.85	51.87	-1038.67 – -835.03	-18.06	<0.001
Condition: Noise	-493.52	254.30	-992.72 – 5.69	-1.94	0.053
Group: ASC × Condition: Noise	578.20	58.09	464.17 – 692.24	9.95	<0.001
Condition: Noise × IQ	5.37	1.88	1.68 – 9.06	2.86	0.004
Condition: Quiet × IQ	0.47	1.86	-3.19 – 4.13	0.25	0.801
ICC	0.07				
N _{subject}	42				
N _{trial}	10				
Observations	774				
Marginal R^2 / Conditional R^2	0.56/ 0.60				

LMM for peak dilation revealed a significant *Group* main effect [$F(1, 37.47) = 29.80, p < 0.001, \eta^2p = 0.44$]. However, *Condition* ($p=0.28$) and *IQ* ($p=0.67$) had no significant main effects. Notably, significant interactions emerged: *Group*×*Condition* [$F(1, 726.88) = 5.68, p<0.05, \eta^2p = 0.001$] and *Condition*×*IQ* [$F(1, 724.58) = 7.96, p<0.01, \eta^2p = 0.01$]. The post hoc tests for the first interaction showed significant between-group differences in both quiet (estimate_{NT-ASC}= -0.08, SE = 0.02, $t = -3.85, p < 0.01$) and noisy conditions (estimate_{NT-ASC}= -0.12, SE = 0.02, $t = -5.94, p < 0.0001$). Surprisingly, the ASC group's noise-related peak dilation resembled the NT group's in quiet ($p = 1.00$). Both groups exhibited greater peak dilation in noise compared to quiet (ASC: estimate_{Quiet-Noise}= -0.14, SE = 0.01, $t = -12.21, p < 0.0001$; NT: estimate_{Quiet-Noise}= -0.10, SE = 0.01, $t = -7.73, p < 0.0001$). Regarding the second interaction, post-hoc analysis revealed an estimated marginal trend for *IQ* in quiet at -0.001 [SE = 0.0007, 95% CI = (-0.002, 0.0002), $t = -1.64, p = 0.11$], and 0.0006 in noise [SE = 0.0007, 95% CI = (-0.0008, 0.002), $t = 0.86, p = 0.39$]. A significant difference between these trends was confirmed [estimate_{Quiet-Noise} = -0.002, SE = 0.0006, $t = -2.82, p < 0.01$]. These findings suggest higher *IQ* is associated with reduced effort in quiet settings, while effort amplifies in noisy conditions.

Moreover, LMM for the peak latency revealed a significant *Group* main effect [$F(1, 39.34) = 226.34, p < 0.0001, \eta^2p = 0.85$], indicating substantial peak latency differences between groups. ASC participants displayed approximately 936.85 ms shorter peak latency than NT participants ($p < 0.001$). While the *Condition* did not have a significant effect ($p = 0.39$), the *Group*×*Condition* interaction was

highly significant [$F(1, 732.52) = 99.07, p < 0.0001, \eta^2p = 0.12$], indicating an intricate interplay between these factors. Post hoc analysis unveiled that in quiet, NT's peak latency exceeded ASC's ($\text{estimate}_{\text{NT-ASC}} = 936.8, \text{SE} = 51.9, t = 18.06, p < 0.0001$). Comparing both groups in noise, NT also had longer peak latency ($\text{estimate}_{\text{NT-ASC}} = 358.6, \text{SE} = 52.0, t = 6.89, p < 0.0001$). ASC consistently exhibited shorter peak latencies regardless of listening conditions. NT's peak latency did not significantly differ between conditions ($p = 0.82$). Conversely, ASC's peak latency significantly increased from quiet to noise ($\text{estimate}_{\text{Quiet-Noise}} = -638.3, \text{SE} = 37.1, t = -17.21, p < 0.0001$), underlining group distinctions in auditory processing and broader cognitive mechanisms. For the second interaction, the modulatory effect of *IQ* on the *Condition*'s impact on peak latency was evident [$F(2, 74.28) = 4.46, p < 0.05, \eta^2p = 0.11$]. Post-hoc trend analysis showed a differential impact of *IQ* on peak latency across listening conditions. For the quiet condition, the relationship between *IQ* and peak latency was negligible, as evidenced by a slope of 0.47 ($p = 0.80$). In contrast, noisy conditions showed a strong positive association with a slope of 5.37 [$\text{SE} = 1.88, 95\% \text{ CI } (1.63, 9.12), t = 2.86, p < 0.01$]. A direct trend comparison confirmed a significantly stronger *IQ*-peak latency effect in noise than in quiet ($\text{estimate}_{\text{Quiet-Noise}} = -4.9, \text{SE} = 2.1, t = -2.34, p < 0.05$), implying higher *IQ* individuals may have prolonged peak latencies in challenging auditory environments.

Pupillary Time Course Analysis

The final GAMM captured 60.60% of deviance, signifying its robust ability to model pupil response variation over time. Table 5 outlines the GAMM output. A significant main effect of *Condition* emerged: Participants generally demonstrated greater pupil dilation—reflecting heightened listening effort—in noise compared to quiet over the 5-second analysis window. The main effect of *Group* did not show statistical significance; however, the *Group*×*Condition* interaction was significant. This interaction was explored through post hoc testing using the *emmeans* function and detailed visualization via *plot_smooth* and *plot_diff* functions.

Table 5. Output of the GAMM for the effects of *Group* (ASC vs. NT) and *Condition* (Quiet vs. Noise) on the time course of pupil dilation.

Formula code: Pupil Dilation ~ Group + Condition:Group + s(Time, Condition) + s(Time, Group) + s(Time, Event, bs = "fs")				
Parametric coefficients	Estimate	SE	t-value	Pr(> t)
(Intercept)	-0.0007	0.0007	-1.03	0.30
Group: ASC	0.0009	0.001	0.77	0.44
Condition: Noise	0.003	0.001	3.42	<0.001
Group: ASC × Condition: Noise	-0.004	0.002	-2.51	0.01
Smooth terms	Edf	Ref.df	F-value	p-value
s (Time, Condition: Noise)	13.25	14.44	1.91	0.01
s (Time, Condition: Quiet)	15.35	16.40	4.87	<0.0001
s (Time, Group: ASC)	13.79	15.04	2.21	0.003
s (Time, Group: NT)	7.16	8.03	0.35	0.95
s (Time, Event)	3567.15	4199.00	49.97	<0.0001

¹ SE: standard error; Edf: estimated degree of freedom; Ref.df: reference degree of freedom.

Table 6 shows that after *Bonferroni correction*, NT's mean estimate surpassed ASC's across listening conditions. Notably, NT's mean dilation increased in noise relative to quiet, while ASC's showed no substantial difference. Figure 4 displays estimated effects across experimental levels, revealing ASC's heightened variability in pupil size throughout analyses. About 1000 ms post sentence onset, both groups exhibited a pupil size decrease from baseline, more pronounced in ASC. Pupil diameters then surged, peaking near speech end (around 1500 ms to 2500 ms). Intriguingly, autistic children displayed a more pronounced peak dilation and shorter latency than NT peers, aligning with prior LMM findings. Figure 5 illustrates estimated pupil response disparities over time for four contrasts: noisy minus quiet conditions in ASC (Figure 5A), noisy minus quiet conditions in NT (Figure 5B), ASC minus NT in noisy conditions (Figure 5C), and ASC minus NT in quiet conditions (Figure 5D). Notable differences between noisy and quiet conditions appeared during the first half of the 3-second retention interval. Over an approximate 1200-ms window centered around the sentence end (2000 ms), ASC exhibited significantly larger pupil dilation compared to NT, with the reverse pattern outside this window.

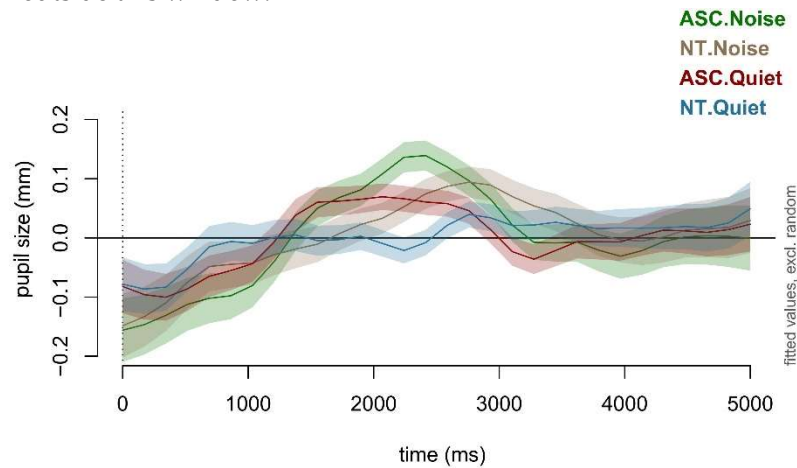


Figure 4. Diagram of change in mean pupil size (in millimeters) over time (in milliseconds) from speech onset, with a 95%CI shaded. (ASC=autism spectrum condition; NT=neurotypical).

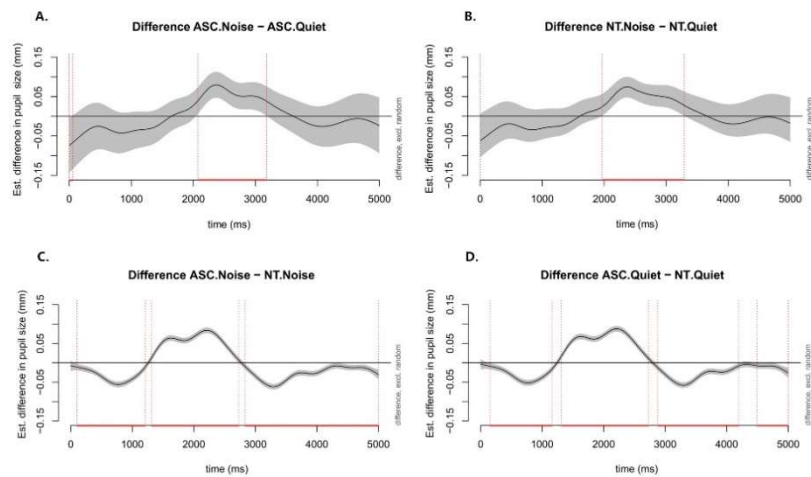


Figure 5. Schematic of estimated difference in pupil size (in millimeters) over time (in milliseconds) across four contrasts: (A) Noisy vs. Quiet in ASC, (B) Noisy vs. Quiet in NT, (C) ASC vs. NT in Noisy, and (D) ASC vs. NT in Quiet. (ASC=autism spectrum condition; NT=neurotypical).

Table 6. Post-hoc analysis for the *Group × Condition* interaction in the first GAMM (only research-related contrasts included).

<i>Pairwise contrasts</i>	<i>Estimate</i>	<i>SE</i>	<i>t value</i>	<i>p value</i>
NT Quiet - ASC Quiet	0.072	0.017	4.27	0.0001
NT Noise - ASC Noise	0.075	0.017	4.51	<0.0001
NT Noise – NT Quiet	0.05	0.004	13.08	<0.0001
ASC Noise – ASC Quiet	0.022	0.017	1.31	1.0000

Discussion

This study aimed to investigate the impact of background noise on the cognitive demands of speech perception in children with ASC compared to NT children. We utilized the relatively new pupillometry approach, demonstrating that online pupillary dilation responses can effectively reflect the cognitive workload and listening effort during SiN perception in both ASC and NT children.

Effects of Noise

The results largely confirmed our first hypothesis that demanding auditory conditions, exemplified by background noise, would heighten the cognitive resources required for listening tasks, producing increased peak dilation, prolonged peak latency, and elevated mean dilation in both groups when exposed to noisy environments. This aligns with previous research suggesting that the presence of competing auditory stimuli, such as noise, challenges cognitive systems, leading to increased demands on auditory tasks (Peelle, 2018). It is especially salient in educational settings, where students, particularly those in the early stages of auditory development, grapple with comprehending instructions amidst diverse background disturbances over extended durations.

While the challenges of processing speech in noise are notably pronounced in the ASC group, this should not be regarded as an exclusive, distinct deficit solely associated with autism. Instead, it can be understood as a broader cognitive challenge that impacts a wide range of young individuals (including NT children), albeit to varying degrees, which resonates with the principles of the neurodiversity movement (Chawner & Owen, 2022). Thus, implementing acoustic enhancements in all learning spaces or introducing interventions tailored to enhance speech processing amidst auditory complexities could prove advantageous.

The effects of noise on listening effort exhibited variability based on children's cognitive capacities, irrespective of their neurodevelopmental profiles. Higher IQ individuals showed increased effort in noise, seen in larger peak dilations and longer peak latencies, with less effect in quiet. This relates to cognitive spare capacity in terms of extra resources beyond task needs. Higher cognitive capacity allocates more resources for processing speech in noise, ensuring comprehension. In quiet, cognitive resources are unstrained, yielding reduced effort. When faced with background noise, individuals with higher cognitive capacities draw upon their cognitive reserves to surmount the barriers introduced by the noise. Their surplus cognitive resources enable them to allocate more effort towards task completion, leading to increased listening effort (Peelle, 2018). Additionally, individuals with greater cognitive resources often hold higher performance expectations and exhibit more motivation to engage in cognitively taxing tasks (Ackerman & Heggstad, 1997). They are also inclined to employ intricate top-down processing strategies, leveraging their cognitive resources to counteract degraded auditory input and meet heightened task demands (Rönnberg et al., 2013).

Between-Group Differences in Listening Effort

The data strongly supported our second hypothesis that the ASC group's listening effort patterns would deviate from those of the NT comparison group. The ASC group consistently exhibited larger peak dilations compared to their NT counterparts in comparable listening contexts. Strikingly, even

under quiet conditions, the ASC group displayed peak dilations akin to those observed in NT participants exposed to noisy conditions. This divergence persisted despite similar recognition accuracy between the ASC and NT groups. These findings suggest that ASC children may need to heighten their cognitive involvement to achieve accuracy levels comparable to their NT peers, potentially to overcome underlying speech processing challenges.

Notably, the distinct speech processing patterns observed in the ASC population are well-documented. Individuals with ASC often grapple with difficulties in analyzing and manipulating phonetic and phonological speech components (Kjelgaard & Tager-Flusberg, 2001). Furthermore, they frequently exhibit reduced sensitivity to vocal cues (Fan & Cheng, 2014; Gervais et al., 2004), manifest unique speech discrimination and transcription patterns (Huang et al., 2018; Russo et al., 2009), and display altered perception of linguistic and emotional prosody (Zhang et al., 2021).

However, the data also revealed an intriguing contrast. Despite the ASC group's larger peak dilation, they showcased significantly shorter peak latencies and reduced mean dilations compared to the NT group when exposed to similar listening conditions. These patterns suggest that the ASC group might engage fewer cognitive resources, leaning towards more rapid and automated auditory processing mechanisms to address auditory input and task demands. This perspective aligns with the reduced average IQ scores of the ASC cohort compared to the NT group, indicating diminished cognitive resources available to sustain prolonged processing.

The larger mean dilation observed in the NT group resonates with the 'effort hypothesis' – individuals with higher cognitive abilities allocate more resources to tasks, leading to augmented performance and increased processing loads (van der Meer et al., 2010; Zekveld et al., 2011). Alternatively, the resource allocation hypothesis (Goldknopf, 2013) posits that resources in autism, especially in cases with pronounced sensory symptoms, could be more constrained compared to typical cognition. Such a constraint might result in an intense and disproportionate allocation of resources across modalities, processing stages, and cognitive functions. This could explain the ASC group's larger peak dilation and shorter peak latency, indicative of intensive engagement with early speech processing stages. However, sustaining such high engagement over time might strain their limited resources, potentially elucidating the reduced mean pupil dilation observed in the ASC group compared to NT individuals. This resource competition could be accentuated in noisy conditions, as evidenced by the ASC group's rapid decline in pupil size post-peak compared to quiet conditions. Furthermore, difficulties in modulating arousal and attention, or different arousal mechanisms during auditory processing (e.g., Orekhova & Stroganova, 2014; Zhao et al., 2022), could also contribute. The ASC group might experience heightened arousal upon initial exposure to speech stimuli, potentially explaining their larger peak dilations and shorter peak latencies compared to NT peers.

It is also plausible that ASC individuals might use unique auditory strategies, prioritizing local details over global context (Happé & Frith, 2006). This focus could explain their larger peak dilation. However, challenges in integrating auditory information, especially in noise, could result in their smaller mean dilation, suggesting less holistic integration than NT children, which is consistent with what Alcántara et al. (2004) reported.

Interplay between Noise and Subject Group

The results partly support our third hypothesis that proposed an interaction between the subject group and listening conditions, indicating that discerning speech amidst noise posed greater listening effort and difficulty for children with ASC compared to their NT peers. Both groups displayed increased peak dilations in noise compared to quiet, yet the ASC group consistently exhibited significantly larger peak dilations. Furthermore, noise led to longer peak latencies and decreased recognition accuracy among ASC participants, while NT participants showed no significant effect.

Several factors may account for these response patterns. Firstly, individuals with ASC struggle with selective attention and filtering out irrelevant information (Keehn et al., 2013), which noise exacerbates, contributing to their longer latencies and reduced accuracy. Deficits in rapid auditory processing and atypical activation in auditory regions (Brock et al., 2002; Gandal et al., 2010)

compromise their auditory stream segregation, a crucial ability to perceptually organize and differentiate overlapping sound sources into coherent auditory streams in complex acoustic settings, which may further compound their cognitive load in noise. Secondly, a key finding lies in the distinct mean dilation response in noise: While both cohorts exhibited increased mean dilation in noise, the ASC group's increase was more subdued compared to the NT group, whose noise-quiet contrast reached statistical significance. The ASC group's relatively restrained increase reflected their constrained cognitive resources, which may inhibit their ability to mobilize additional resources in demanding auditory contexts (Goldknopf, 2013). Conversely, NT's robust cognitive reserve helps manage noise, enabling them to manage the heightened processing demands of challenging auditory conditions effectively. Thirdly, altered auditory cortex connectivity in autism might affect their auditory processing in noisy settings. Typical brain development features a well-integrated auditory cortex connected to various brain regions, facilitating comprehensive auditory information processing. However, in individuals with ASC, this connectivity is often disrupted, especially between the auditory cortex and regions pivotal for attention, cognitive control, and multisensory integration (Keehn et al., 2013). Such connectivity challenges in ASC can further limit resource allocation and integration, leading to diminished neural synchronization and cognitive saturation (Mamashli et al., 2017), possibly resulting in subdued dilation compared to NT peers in noisy environments.

Limitations

This study has several limitations. First, pupillometry results are subject to multiple confounding factors. Emotional arousal and personality characteristics can influence pupil dilation, as indicated by Bradley et al. (2008) and Lyall and Jarvikivi (2021). Additionally, motivation significantly affects listening effort, especially in noisy conditions (Carolan et al., 2022). This complexity in the context of sensory issues in autism may strongly influence listening effort. Shields et al. (2022) discuss challenges in measuring listening effort, revealing no consensus on the best method. Integrating physiological markers like galvanic skin response or heart rate variability may offer a more comprehensive understanding (Madsen & Parra, 2022). Second, the interventions that the participants underwent would conceivably influence the outcomes. For instance, music training or therapy can influence SiN perception (Benitez-Barrera et al., 2022; Dubinsky et al., 2019), but the impact on ASC remains controversial (Marquez-Garcia et al., 2021). Third, both sample size and diversity are vital, given the heterogeneity of the ASC population (Hand et al., 2017). Larger, more diverse samples could strengthen the statistical power of the study. Our sample included a demographic bias towards middle-class families from major cities. Socioeconomic status impacts language and auditory skills (Fernald et al., 2013; Ursache & Noble, 2016), and its effects on SiN processing require further study. While excluding co-occurring disorders helps data analysis and interpretation, it also limits the findings' applicability (Simonoff et al., 2008). Lastly, our controlled stimulus design aids data consistency but may miss real-world complexity. Steady-state noise oversimplifies real-world auditory scenes (Bronkhorst, 2015). Fixed SNR levels also do not mirror real-world variability (Best et al., 2016). Ecologically valid scenarios and stimuli using technologies like virtual reality can better replicate authentic auditory challenges (Zhang et al. 2022).

Conclusions

The current study represents an initial exploration using pupillometry to gain insights into how school-age children with ASC process auditory information in noise. Compared to their NT peers, the ASC group showed clear differences in accuracy and pupillary responses. They exhibited more prominent peak dilation and extended peak latencies in noisy conditions, whereas the NT group's variations were subtler. These patterns underscore heightened listening effort in ASC and suggest potential differences in cognitive resource allocation. The disparities in mean pupil dilation between conditions also hint at diverse cognitive resource availability and utilization. These results underscore pupillometry's value as a feasible measure of cognitive load, particularly in autism

research, which has implications for the development or assessment of improved auditory settings or tailored assistive technologies for children with ASC.

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