scientific reports

OPEN

# Auditory environments influence the link between Autistic traits and quality of life

R. Poulsen[1]✉, D. W. Tan[2,3,4], P. F. Sowman[5,6], D. McAlpine[1] & E. Pellicano[2,7]

**Autistic people often report a heightened sensitivity to sound. Yet, research into Autistic people's auditory environments and their impacts on quality of life is limited. We conducted an online survey to understand how auditory environments influence the relationships between Autistic traits and impacts on quality of life (iQoL) due to sound sensitivity. We also sought to determine strategies that Autistic people use to navigate auditory sensitivities in daily life.**

**296 Autistic adults (58.4% women, 15.9% men, 24.3% non-binary +) aged 18–71 years completed the survey comprising a questionnaire with bespoke items measuring auditory experiences in different environments (e.g., noisy vs. quiet) and measures of Autistic traits and iQoL. Our path analyses revealed a significant indirect effect of aversive auditory environments on the relationships between all domains of Autistic traits and iQoL. Notably, the association between non-verbal social communication trait and iQoL was fully mediated by all forms of auditory environments. Additionally, most (n = 217, 73.5%) Autistic participants reported using earplugs and headphones to manage their sound environments in everyday life. Our study demonstrates that many aspects of auditory environments—beyond noise alone—can negatively impact Autistic people's QoL. Addressing barriers created by auditory environments through accommodations should improve QoL for Autistic people.**

**Keywords** Autism, Auditory, Quality of life, Autistic traits, Auditory environments, Co-production

Deriving meaning from the world requires processing extensive sensory information to generate embodied and immersive phenomenological experiences. These experiences can hold a range of positive or negative valences, shaping our perceptions, beliefs, thoughts, and actions.

Autism is a neurodivergent condition, characterized by differences in communication and social interaction, repetitive behaviours and focused interests. Additionally, since the introduction of the DSM-5 in 2013, sensory differences have been explicitly recognised as a core characteristic of autism[1]. Compared to the general population, "Autistic" people (we have also chosen to capitalize the word Autistic to indicate a proper adjective, which reflects its status as a robust and valued identity and shared community, similar to the Deaf community[2]) consistently report heightened sensivity to sound. This heightened sensitivity can generate unique challenges and needs for Autistic people as they navigate their everyday environments[3,4]. However, growing evidence suggests that differences in auditory experiences between Autistic and non-Autistic people extend beyond reported hyper-responsivity to sound or reduced sound tolerance to encompass a wide range of perceptual phenomena, including expanded access to auditory information[5], heightened perception to pitch[6], difficulties dealing with speech in background noise[7,8], and taking longer to adapt to auditory environments[9]. These differences are likely related to increased sensitivity to sound[8,10,11].

Emerging evidence suggests that differences in sound perception and processing between Autistic and non-Autistic people extend beyond the auditory domain to influence cognition[12], including social[13–15] and non-social traits[16–18]. For example, altered auditory processing in Autistic people has been shown to negatively affect non-verbal social communication abilities, such as discerning speech in noisy settings and interpreting nuanced or complex auditory social cues[8,19,20]. Further, some Autistic people may engage (consciously or subconsciously) in camouflaging or masking behaviors to manage perceived hostile auditory environments, including adapting

[1]Department of Linguistics, Faculty of Medicine, Health and Human Sciences, Macquarie University, 16 University Avenue, Macquarie Park, NSW 2109, Australia. [2]Macquarie School of Education, Macquarie University, Macquarie Park, Australia. [3]Health & Wellbeing Research Centre, Lifespan, Macquarie University, Macquarie Park, Australia. [4]School of Psychological Science, University of Western Australia, Perth, Australia. [5]School of Clinical Sciences, Auckland University of Technology, Auckland, Aotearoa, New Zealand. [6]School of Psychological Sciences, Macquarie University, Macquarie Park, Australia. [7]Department of Clinical, Educational and Health Psychology, University College London, London, UK. ✉email: bec.poulsen@mq.edu.au

or masking their natural responses to auditory stimuli[21,22]. These behaviors are particularly evident in social situations, where Autistic individuals may attempt to conform to presumed neurotypical norms or manage sensory overload[21–23].

Auditory environments (AE's) may also influence non-social Autistic traits. Cognitive flexibility—the ability to switch between tasks—may become more difficult due to variability and uncertainty in the auditory environment[24]. Self-regulating repetitive behaviors could, therefore, serve as a response to manage auditory sensitivities, improving one's ability to navigate cognitively-taxing demands from the environment[16]. Finally, the relationship between auditory processing and other sensory modalities may increase the propensity for sensory overload by increasing cognitive demands, leading to sensory meltdown or shutdown[25–27]. Shutdowns and meltdowns are adaptive responses to overwhelming sensory input and often arise when self-regulation strategies are no longer sufficient[28,29]. These increased cognitive demands may, in turn, contribute to short- and long-term avoidance of certain situations or increased reliance on self-regulatory mechanisms to manage (overwhelming) sensory input.

The impact of auditory processing challenges on the everyday lives of Autistic people's may be far-reaching[5], with ubiquitous environmental landscapes such as busy streets, crowded public spaces, and work or educational settings rendered overwhelming due to the cacophony of sounds[30–35]. Further, emerging evidence suggests that such experiences are not fixed but can fluctuate based on context[36,37], transforming sensory discomfort from inconvenience into a significant barrier that can impede participation in education and employment and opportunities for social interaction[38,39]. The consequence of this can be to lower the extent to which Autistic people access a wide range of community spaces and generation of short- and long-term sensory distress[27,34,40]. Consequently, these challenges can limit experiences of autonomy and self-determination essential for even the most basic quality of life (QoL)[2]. Despite this growing body of evidence, however, the impact of AEs on everyday QoL for Autistic people remains largely unexplored.

Here, we sought to address this gap. Our aims were threefold. We first investigated the relationships between Autistic traits, auditory sensory experiences, and the iQoL due to sound sensitivity. We then examined the mediating effects of different types of AEs on the relationship between Autistic traits and the iQoL due to sound sensitivity. Finally, we sought to understand strategies or technologies Autistic people use to support their auditory sensitivities or auditory well-being.

To achieve these aims, Autistic adults completed several questionnaires, including an assessment of Autistic traits—the Comprehensive Autistic Trait Inventory (CATI)[41,42]; a bespoke Auditory Environments (AEs) questionnaire tapping the perceived experience of different types of environmental noise, listening environments with single or multiple talkers, and the effects of auditory phenomena such as adapting to environments, reverberation, and sound directionality; and the Multidimensional Inventory of Sound Tolerance (MIST-A)[43], which includes a subscale to measure the impact of acoustic environments and events on QoL relating to sound sensitivity (iQoL). We also asked participants to indicate technologies or strategies they used to navigate AEs that positively impact QoL.

We hypothesized that Autistic people with higher levels of social and non-social Autistic traits report more frequent negative auditory experiences from differing AEs and that these experiences affect QoL. We also hypothesized that specific AEs significantly mediate the association between Autistic traits and iQoL.

## Methods
### Participants
A total of 484 people attempted the survey. Following best practices for online surveys[44], those who completed less than 80% of the survey (n = 188; 38.8%) were excluded from the analysis to ensure the quality and reliability of the data. Data from the remaining 296 participants, aged 18 to 72 years (M = 37.84, SD = 11.4), were included for analysis (see Table 1). Of these participants, 173 (58.4%) identified as women, 47 (15.9%) as men, 58 (19.6%) as non-binary, and 14 (4.7%) stated other gender identities (including agender, demi-gender woman, gender diverse, gender apathetic, gender queer, gender fluid, and male). Four people (1.4%) preferred not to disclose.

Of the 296 participants, 201 people (67%) reported having received a clinical diagnosis of an autism spectrum condition (M age of diagnosis = 32.3 years, SD = 14.4, range = 2–67), while 84 people (28.4%) self-identified as Autistic. In the survey, participants were asked whether they had received a formal autism diagnosis from a qualified healthcare professional (e.g., psychologist, psychiatrist). Those who indicated a clinical diagnosis provided further information on their specific diagnosis—that is, whether they were diagnosed with autism spectrum disorder, Asperger syndrome, or pervasive developmental disorder (not otherwise specified). Eleven participants (3.7%) identified as Autistic but preferred not to disclose whether they self-identified or were clinically diagnosed and, therefore, were included in the sample. Participants were specifically asked whether they had been diagnosed with any co-occurring conditions by a healthcare professional (e.g., psychologist, psychiatrist). Most participants (n = 240; 81.1%) reported having at least one co-occurring condition (see Table 2), most commonly anxiety (n = 185; 62.5%), depression (n = 152; 53.4%), Attention Deficit Hyperactivity Disorder (ADHD; n = 111; 37.5%) and Post Traumatic Stress Disorder (PTSD; n = 64; 21.6%).

In the current study, we intentionally recruited and included both clinically diagnosed and self-identified Autistic participants. The inclusion of self-identified Autistic people is supported by growing recognition that access to clinical diagnosis is often limited due to systemic barriers such as gender biases, socioeconomic factors, and restricted access to diagnostic services[45–47]. The CATI has been included in the current study as a measure of Autistic traits, rather than a diagnostic screening tool, a methodology recommended by the CATI authors[41,42]. To support the merging of both clinically and self-identified groups, we conducted group comparisons and found no meaningful differences between Autistic participant groups (see Supplementary Table 1; Cohen's d = − 0.02 to − 0.39). Furthermore, we compared our samples to existing studies[41,42] and found that both groups were within the range observed in Autistic populations. While individual variability exists, this distribution

| | N | % |
|---|---|---|
| Age (years) | | |
| Under 25 | 44 | 14.9 |
| 26–32 | 67 | 22.6 |
| 33–39 | 57 | 19.3 |
| 40–46 | 58 | 19.6 |
| 47–53 | 40 | 13.5 |
| 54–60 | 20 | 6.8 |
| 61 and over | 10 | 3.4 |
| Sex at birth | | |
| Male | 56 | 18.9 |
| Female | 229 | 77.4 |
| Prefer not to say | 11 | 3.7 |
| Gender | | |
| Man | 47 | 15.9 |
| Woman | 173 | 58.4 |
| Non-binary | 58 | 19.6 |
| Different gender identity | 14 | 4.7 |
| Prefer not to say | 4 | 1.4 |
| Ethnicity | | |
| White | 264 | 83.0 |
| Hispanic | 12 | 4.1 |
| Asian | 12 | 4.1 |
| Māori or Indigenous New Zealander | 5 | 1.7 |
| Middle Eastern or South African | 4 | 1.4 |
| African American/black | 3 | 1.0 |
| Native American | 3 | 0.9 |
| Australian Aboriginal and/or Torres Strait Islander | 1 | 0.3 |
| Other (included Indian, Italian, Filipino, Romani, Australian) | 14 | 4.7 |

**Table 1**. Participant demographic Information.

| | N | % |
|---|---|---|
| Autism diagnosis | | |
| Clinical | 201 | 67.9 |
| Self-identify | 84 | 28.4 |
| Prefer not to say | 11 | 3.7 |
| Condition* | | |
| Anxiety | 185 | 62.5 |
| Depression | 152 | 53.4 |
| Attention deficit hyperactivity disorder (ADHD) | 111 | 37.5 |
| Post-traumatic stress disorder (PTSD) | 64 | 21.6 |
| Obsessive compulsive disorder (OCD) | 27 | 9.1 |
| Eating disorder | 27 | 9.1 |
| Bipolar disorder | 16 | 5.4 |
| Borderline personality disorder | 8 | 2.7 |
| Substance abuse disorder | 8 | 2.7 |
| Tourette syndrome | 8 | 2.7 |
| Dissociative disorder | 4 | 1.4 |
| Schizophrenia | 3 | 1 |
| Other (includes Irlen syndrome, dyslexia, gender dysphoria, unspecified trauma, social phobia, agoraphobia) | 32 | 10.8 |

**Table 2**. Autism Diagnosis Type and Co-occuring Conditions. *Participants could select multiple conditions; hence, the total percentage for co-occurring conditions is greater than 100%

strongly suggests that both groups are comparable in their level of Autistic traits, justifying their inclusion as a single group for analysis[41].

## Procedure

Ethics approval for this study was granted by the Macquarie University Human Research Ethics Committee (Ref 52023563048250). All research was performed in accordance with relevant guidelines/regulations[48]. All participants provided informed written consent. Survey data were collected over three months in a secure online hosting service, REDCap[49,50]. The research team provided any necessary accommodations for participants to complete the survey in an adapted way that suited their individual needs, such as completing the survey offline or with the support of a caregiver. The survey was designed to ensure that participants could provide feedback throughout. Participants (Autistic adults aged 18 + years, anywhere in the world) were recruited through snowball convenience sampling[51] and leveraging existing networks and community organizations using online platforms and word-of-mouth.

## Measures

*Comprehensive autistic traits inventory (CATI)*

The CATI is a self-report questionnaire designed to assess Autistic traits in adults in the general population[41,42]. We chose this measure over traditional measures (e.g., Autism-spectrum Quotient) as it is one of few psychometrically validated measures to include sensory features. It consists of 42 statements related to six trait dimensions associated with autism: (1) *Social Interactions*, (2) *Social Communication*, (3) *Social Camouflage*, (4) *Self-Regulating Repetitive Behaviors*, (5) *Cognitive Flexibility*, and (6) *Sensory Sensitivity*. Each subscale includes seven statements and asks participants to rate the extent to which they agree on a 5-point Likert scale, ranging from '1' (definitely disagree) to '5' (definitely agree). The total CATI score is calculated by summing all items' scores (ranging from 42 to 210). It captures the subjective experiences of an individual related to these traits, with higher scores reflecting a stronger endorsement of the described experiences or a more frequent use of described strategies. An initial validation study showed that CATI has excellent internal consistency for total-scale scores (Cronbach's $\alpha = 0.95$) with good internal consistency for subscales (all Cronbach's $\alpha s > 0.81$), superior predictive ability for classifying autism (Youden's Index of CATI = 0.62 vs Autism-spectrum Quotient = 0.59), and demonstrated measurement invariance for sex[41]. In the current sample, the internal consistency was high for total-scale ($\alpha = 0.896$) and good for individual subscales ($\alpha = 0.734 – 0.831$; see Table S1).

*Auditory environments (AEs) survey*

The AE survey was specially designed to capture experiences of AEs across various contexts. It includes 15 items about the experience of auditory environments, including sound tolerance to noisy and quiet environments, single and multiple speakers, environments with reverberation, sound directionality and the ease or difficulty of getting used to auditory environments. Participants were asked to rate how much they agreed with the statements on a 5-point Likert scale, ranging from '1' (definitely disagree) to '5' (definitely agree). Table S2 shows the items and participants' mean score of each item.

To reduce the dimensionality of the AE instrument, we performed an exploratory factor analysis on the 15 items using Principal Component Analysis with Oblimin Varimax rotation. Kaiser Normalization, including the Kaiser–Meyer–Olkin (KMO) criterion, guided the determination of the optimal number of retained factors by assessing their ability to explain variance in the data. Factors with an eigenvalue greater than one were selected, and items with factor loadings greater than 0.40 were retained. This analysis extracted four factors, and all 15 items were retained for analysis (see Table S3). This factor structure explained 50.8% of the variance. Factor scores for each participant were computed using the regression method in SPSS which assigns weights to responses to each survey item according to their respective factor loadings, sums these to produce a score for each factor, and then adjusts the weights to account for the varying number of items in each factor.

The four factors were *Adverse* AEs, *Tolerable* AEs, *Adapting to* AEs, and *Complex* AEs. The first factor, *Adverse* AEs, included six items primarily related to experiences in noisy environments. *Tolerable* AEs included three items related to auditory environments that respondents scored low (less than 2) on the 5-point Likert scale, meaning they disagreed with the item statement (See Table S2). *Adapting* AEs included two items describing the ease of getting used to an environment. *Complex* AEs included four items describing scenarios with multiple sound sources (e.g., 2 + speakers) or included the perceptual component of an auditory scene (e.g., reverb or sound direction). These four factors were used in the subsequent data analysis. The Cronbach's α for the four factors are 0.66, 0.62, 0.70 and 0.24, respectively. While all four factors show reasonable to poor internal consistency, particularly the fourth factor, it is important to note that this measure is bespoke and of an exploratory nature rather than a confirmatory validation. The poor internal consistency of the fourth factor may indicate weak inter-relatedness between items, possibly due to the varied nature of the AEs the items captured and variability in the impact of these items on different individuals, possibly explaining the heterogeneity in this population[52]. Nevertheless, we included factor four in our analysis due to its theoretical and experiential relevance and the unique insights it provides on the more unexplored aspects of auditory environment experiences, such as reverberation, directionality and multiple speakers in different environments. This measure aims to identify potential patterns and relationships that may inform future research into the complexities and subtleties of the heterogeneous population under investigation.

*Quality of Life on sound sensitivity measure*

We used a subscale of the Multidimensional Inventory of Sound Tolerance (MIST-A)[43], a measure of sound tolerance sensitivity, to determine the impact of sound sensitivity on QoL. The iQoL subscale consists of eight items asking participants how sound sensitivity affects their daily QoL, including their ability to undertake everyday tasks, participate in social and community life, and their well-being and relationships. Respondents indicated how much sound sensitivity affects QoL on each item on a 5-point Likert scale, ranging from '0' (not at all) to '4' (very much). Based on Williams et al.'s recommendation[43], the normalized mean score was calculated to represent the average response per question (normalized total mean = 2.28, SD = 0.86). The higher the total QoL score, the more QoL is negatively impacted by sound sensitivity. In the current sample, the internal consistency for the iQoL was excellent (Cronbach's $\alpha = 0.92$).

*Auditory devices and technologies*

As part of our bespoke survey, we also asked people to state which, if any, hearing/listening devices or technologies they used as well as the duration they use these devices on an average day. We did this to understand how Autistic adults employ technologies in everyday life to reduce barriers created by auditory environments. We also asked how long people employ these technologies in a day, with tick box answers ranging from under 30 min to over 16 h.

## Data screening

SPSS (Version 29.0.0) was used for analysis. Data were cleaned and screened before formal analysis. Preliminary analyses of the CATI subscores and the QoL measure identified five univariate outliers based on $z$-scores between ± 3.29[53]. This small percentage of outliers (1.69%) is within the acceptable range (usually 1–2%)[54] suggesting that the outliers are unlikely to influence our findings[55–57], hence these data points were retained. Multivariate outliers were assessed using Mahalanobis distance, with the results compared to a critical value from the chi-square distribution for all variables at a significance level of $p < 0.001$, as recommended by Becker and Gather[58]. The identified outliers represented approximately 2.4% of the sample which is well within the acceptable range of 5–10%[56,59]. Therefore, the responses of all 296 participants were retained for analyses. Normality was checked for all CATI variables and the iQoL variables; all variables showed acceptable skewness (between -2 and 2) and kurtosis (between − 7 and 7)[60]. Finally, the normally distributed residuals, homoscedasticity, and multicollinearity assumptions were tested. The residuals were normally distributed, and the assumption of homoscedasticity was satisfied. Multicollinearity was evaluated to be within the acceptable range, with variance inflation factor values well below 10 and tolerance values above 0.1[61].

*Community involvement statement*

The research team, led by an Autistic researcher, worked with an Autistic steering committee throughout this project[62,63]. Four Autistic people (researchers and non-researchers) who ranged in age, life experiences, and perceived support needs were brought together from the outset of the project to advise on the critical aspects of the project, meeting several times online to make decisions about the research questions, survey design, accessibility assessments, as well as participant recruitment. They had particular input on language use, survey length, and tools used within the survey, including the decision to use the CATI (rather than other existing Autistic trait measures). Autistic advisors were remunerated for their time and expertise.

## Data analysis

To test the hypothesis that Autistic people with higher levels of social and non-social Autistic traits report more-frequent negative auditory environment experiences and that these experiences negatively impact QoL, we conducted correlational analyses between the CATI subscores, Auditory Environment (AE) factor scores and iQoL due to sound sensitivity measure. To test the hypothesis that specific AE experiences demonstrate a significant mediating effect on the association between Autistic traits and iQoL, we examined whether AE influence the relationships between Autistic traits and iQoL, by performing a parallel mediation analysis using Model 4 in PROCESS v4.2 macro for SPSS[64]. This model tests the direct effects of the AE factors on the relationship between each Autistic trait and iQoL and determines whether any iQOL indirectly influenced by individual AE factors (see Fig. 1 for conceptual model). The analysis used percentile bootstrapping with 5000 resamples at 95% upper and lower confidence intervals. Non-significant pathways in the model are indicated by confidence intervals overlapping with zero.

Finally, we report whether Autistic people use devices or technologies to support their auditory sensitivities or to enhance their daily auditory wellbeing, along with their self-assessed frequency and duration of use.

# Results

## Correlation analyses with CATI, AE and iQoL

We first sought to understand the broad relationships between CATI scores and AE factors measures with the negative impact of quality of life (iQoL) due to sound sensitivity. Specifically, we determined significant correlations between CATI subscores and AE factors negatively impacting QoL, and found two AE factors to be significantly correlated with iQoL. *Adverse* AE were most strongly correlated with iQoL scores ($r = 0.423$, $p < 0.001$) as were *Adapting to* AEs ($r = 0.26$, $p < 0.001$). Further, as predicted, there were significant relationships between CATI trait subscores and the iQoL score, including *Social Interactions* ($r = 0.239$, $p < 0.001$), *Communication* ($r = 0.139$, $p < 0.05$), and *Cognitive Flexibility* ($r = 0.245$, $p < 0.001$). *Self-Regulatory Repetitive Behaviors* ($r = 0.260$, $p < 0.001$) were also positively correlated with the negative iQoL due to sound sensitivity. See Table 3 for all correlations.

We next identified any significant relationships between AE factors and Autistic trait scores from the CATI. *Adverse* AEs were significantly correlated with the social interaction subscale scores from the CATI ($r = 0.178$, $p < 0.01$), as well as camouflage ($r = 0.291$, $p < 0.001$), cognitive flexibility ($r = 0.216$, $p < 0.001$), and repetitive behaviors ($r = 0.327$, $p < 0.001$), whilst *Tolerable* AEs were positively correlated with communication ($r = 0.154$, $p < 0.01$) and *Adapting to* AEs with social interactions ($r = 0.185$, $p < 0.01$). *Adapting to* AEs was positively correlated with communication ($r = 0.179$, $p < 0.01$) and social interactions ($r = 0.225$, $p < 0.01$), and *Complex*

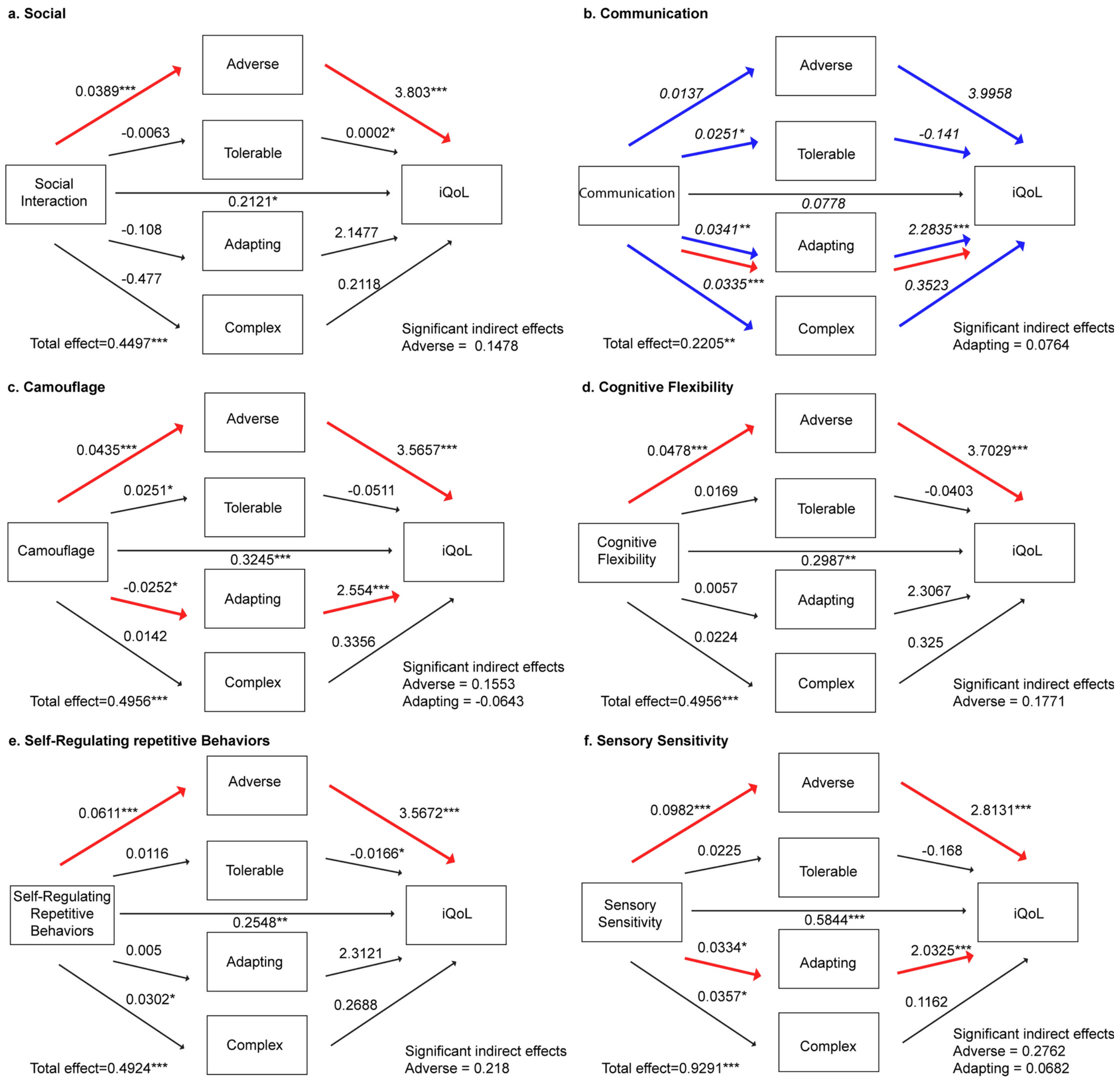


**Fig. 1**. Path analysis model for each of the CATI subscores (**a**) social interaction, (**b**) communication, (**c**) camouflage, (**d**) cognitive flexibility, (**e**) self-regulating repetitive behaviors, and (**f**) sensory sensitivities. Red paths indicate significant indirect effects. Blue paths indicate full mediation model. Black paths indicate non-significant effects. Values indicate effect co-efficient. *p < 0.05, **p < 0.01, ***p < 0.001.

AEs were positively correlated with social interactions (r = 0.225, $p < 0.01$) and social camouflage (r = 0.254, $p < 0.001$), indicative of efforts to manage behavior in social contexts. The sensory sensitivity CATI subscore was moderately significantly correlated with *Adverse* AEs (r = 0.400, $p < 0.001$), less, but still significantly, correlated with *Tolerable* AEs (r = 0.145, $p < 0.05$), but not significantly correlated with *Adapting* and *Complex* AEs. These outcomes likely reflect that the CATI subscore for sensory sensitivity encompasses all sensory modalities but only one auditory-specific item—addressing strong reactions to loud noises. The sensory sensitivity subscore is less relevant to the *Adapting* or *Complex* AE factors, as both encapsulate more varied and complex auditory environment experiences than the broader CATI measure.

## AEs as mediators of the relationships between Autistic traits and iQoL

As Autistic trait from the CATI subscores were all correlated to iQoL, we next explored the influence of AEs on these relationships. To investigate whether and to what extent AE factors mediate the relationship between Autistic traits and iQoL, we tested six models, one model for each of the six subscores of the CATI (*Social Interaction*, *Communication*, *Camouflaging*, *Cognitive Flexibility*, *Self-Regulating Repetitive Behaviors*, and

| CATI subscores | Co-efficient | Auditory environment factors | | | | Impact on QoL |
|---|---|---|---|---|---|---|
| | | Adverse | Tolerable | Adapting | Complex | |
| Social | | **0.178**** | 0.081 | **0.185**** | 0.225** | 0.239*** |
| Communication | | 0.09 | **0.154**** | **0.179**** | 0.208** | **0.139*** |
| Camouflage | | 0.291*** | 0.095 | -0.099 | 0.029 | 0.254*** |
| Cognitive Flexibility | | 0.216*** | 0.092 | 0.018 | 0.103 | 0.245*** |
| Self-Reg Rep Behaviors | | 0.327*** | 0.105 | 0.009 | **0.131*** | 0.260*** |
| Sensory Sensitivities | | 0.400*** | **0.145*** | 0.105 | 0.114 | 0.442*** |
| Impact on QoL | | 0.423*** | 0.018 | 0.268*** | 0.1 | |

**Table 3**. Spearmans correlations of Autistic Traits, AE Factors and Impacts to iQoL. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ A subsequent Bonferroni analysis ($\alpha = 0.00142$) identified correlations that would not remain significant, which are highlighted in bold. Given the exploratory nature of this study, all non-corrected correlations were retained.

| Technology or device used | N | % |
|---|---|---|
| Insert earplugs | 132 | 44.6 |
| Noise-cancelling headphones | 130 | 43.9 |
| Over-ear headphones without noise cancellation | 83 | 28 |
| Sound generator (e.g., white, or pink noise machine) | 41 | 13.9 |
| Hearing Aid | 11 | 3.7 |
| Combination device (hearing aid and sound generator, in the same device) | 1 | 0.3 |
| None | 79 | 26.7 |

| Duration | Frequency | % |
|---|---|---|
| < 30 min | 45 | 22.06 |
| 30 min–2 h | 70 | 34.31 |
| 2–4 h | 36 | 17.64 |
| 4–8 h | 33 | 16.18 |
| 8–12 h | 10 | 4.9 |
| 12–16 h | 3 | 1.47 |
| 16 + hours | 7 | 3.43 |

**Table 4**. Technologies used in daily life (n = 293, 99% responded). Participants could select multiple devices, hence, the total percentage is over 100%. Duration devices and technologies used in a typical day used specifically to block out or reduce noise (n = 204, 70.6% responded).

*Sensory Sensitivity*) as independent variables, iQoL as the dependent variable, and the four AE factors as parallel mediators. Of the six models, full mediation was observed in one model whereby the relationship between the *Communication* trait subscore and iQoL scores was mediated by all four AE factors. We also observed a significant indirect effect through the *Adapting* factor (B = 0.0341, CI = [0.0144, 0.0538]; see Fig. 1b and Table S4). All told, the *Communication* trait model accounted for 27.7% of the variance in iQoL scores, $F(1, 284) = 6.8$, $p = 0.0094$.

In the remaining five models, we observed significant indirect effects of the factor *Adverse* AEs, suggesting partial mediating effects in the relationship between iQoL scores and each of the remaining five CATI sub-scores (see Fig. 1a,c–f). Additionally, significant indirect effects of the factor *Adapting to* AEs were observed in two models involving *Camouflaging* and *Sensory Sensitivities*, indicating *Adapting to* AEs has a partial mediating effects on iQoL (see Fig. 1c and f). Overall, the data demonstrate that *Adverse* and *Adapting to* AEs significantly mediate the relationship between CATI traits and iQoL, highlighting the complex interplay between auditory sensitivity and Autistic traits in determining QoL outcomes due to sound sensitivities.

## Strategies to improve auditory experience in everyday life

Finally, to better understand how Autistic people navigate their daily auditory environments, we asked participants what strategies or technologies they use and, on average, how long they use them per day. Most participants (n = 204; 68.9%) reported using some device to reduce any negative impacts of external sounds. Many respondents reported using earplugs (n = 123, 44.6%) and noise-cancelling headphones were used more often (n = 130, 43.9%) than headphones without noise cancellation (n = 83, 28%). Hearing amplification (e.g., white noise generator) rather than noise suppression/cancellation was reported to be used by less than 3% of respondents, and approximately one-quarter of participants reported using no sound technologies at all (see Table 4). When asked how much a participant uses ear protection on an average day, responses ranged from under 30 min (n = 45, 15.2%) to over 16 h (n = 7, 2.4%), with the most common duration of reported use being between 30 min to 4 h (M = 1.66 h, SD 1.47, Table 3).

## Discussion

We investigated how Autistic traits relate to everyday auditory environment experiences across different contexts and how these experiences may negatively impact quality of life (iQoL) in individuals with sound sensitivities associated with autism. Our data demonstrate that Autistic people who report a greater impact on their QoL of their sound sensitivities experience significantly more challenges in *Adverse* AEs[11,34] and greater difficulties in adapting to their AEs. From path analyses, our data also demonstrate that *Adverse* AEs and the ability to adapt to these environments significantly mediate the relationships between different domains of Autistic traits (quantified from the CATI) and the negative iQoL experienced by Autistic people.

Our data support the hypothesis that higher levels of Autistic traits are associated with more negative auditory environment experiences and a greater impact on QoL due to sound sensitivities. All six CATI subscores were, to varying degrees, significantly correlated with iQoL scores. Specifically, Autistic participants who reported greater social and communication difficulties, more frequent use of camouflaging strategies and self-regulatory repetitive behaviors, and greater cognitive inflexibility also reported experiencing a more profound impact on QoL due to sound sensitivities[34,65–67].

Correlation analyses revealed that Autistic people who experience more challenges in *Adverse* AEs and have greater difficulties *Adapting to* these environments also experience greater negative iQoL. The association between *Adverse* AEs and iQoL is consistent with previous studies where Autistic people reported preferring quiet environments relative to noisy[68]. Notably, the factor *Adverse* AEs included items related to noisy environments inducing feelings of tiredness, anxiety, and difficulties with concentration, as well as seemingly insignificant sounds in quiet environments[11,17,19]. On the other hand, *Adapting to* AEs included items describing whether it is easy to "get used" to, or adapt to, an auditory environment if it is familiar or enjoyable, which overall, respondents scored low (that is, disagreed with the item). Exposure to noisy environments over time negatively impacted iQoL due to sound sensitivity, consistent with previous reports[69–71].

Nevertheless, we found that experiences around *Tolerable* AEs and *Complex* AEs were not significantly correlated with iQoL. The null relationship between *Tolerable* AEs and iQoL is apparent given these auditory environments are reportedly manageable among our participants. The non-significant relationship between *Complex* AEs and iQoL is, however, unexpected; notwithstanding participants reporting considerable difficulty with these auditory tasks associated with *Complex* AEs (see S1 for individual item results). The *Complex* AE factor encompasses items such as the ease or difficulty in following conversations with two or more people in both quiet and noisy environments, detecting the direction of sounds, and managing environments with reverberation. A possible explanation for this null finding is that while these challenges are recognized, they may not be as pervasive or consistently impactful as those captured by the *Adverse* and *Adapting to* AE factors, both of which involve more salient experiences such as coping with noisy environments and getting used to them over time. Difficulties represented within the items in the *Complex* AE factor might occur in more specific or context-dependent situations, that, whilst challenging, may not dominate daily life to the extent that they significantly impair overall QoL[72]. The impact of more nuanced complexities of contextual auditory attention and cognitive demands are little investigated[34]. While research into multi-speaker environments has been previously explored[35,73,74], these studies have not specifically examined the influence of background noise in shaping multi-speaker communication challenges.

In analyzing the relationship between the different domains of Autistic traits in the CATI and AE measures, we found that different aspects of Autistic traits were related to each of the four types of AE. Autistic people who reported greater difficulties in *Adverse* AEs had higher Autistic traits scores across all CATI subscores except that of *Communication*. The significant correlations suggest that *Adverse* auditory conditions may exacerbate difficulties in *Social Interaction, Cognitive Flexibility, Sensory Sensitivities* and greater use of *Camouflaging* and *Self-Regulatory Repetitive Behaviors*. Additionally, more significant challenges in auditory environments generally tolerated by Autistic people (i.e. the items in *Tolerable* AEs) were associated with greater *Communication* difficulties and *Sensory Sensitivities*. This suggests that Autistic participants with heightened sensory sensitivities may still struggle to cope with auditory environments that other Autistic people usually tolerate. While *Communication* trait scores were unrelated to difficulties around *Adverse* AEs, they were significantly associated with *Tolerable* ones. Further, *Communication* traits in the CATI subscale include challenges in reading non-verbal cues, understanding figurative language, and comprehending unspoken social rules. The lack of correlation between the *Adverse* AE factor and *Communication* may reflect the focus of the *Adverse* AE items on auditory experiences like tiredness, anxiety, or difficulty concentrating, rather than auditory environments with a social or communicative component, which are better captured by the *Complex* AE factor through its multi-speaker scenario items. Considering the visual component of social communication, it is possible that it may not be the noise level alone that challenges these largely non-verbal visually-driven aspects of communication but rather the complexity and amount of information that needs to be processed in different auditory environments in combination with parsing visual information in a social context[15,75].

Autistic participants who reported greater difficulties in *Adapting to* their AEs tended to report more challenges around social interaction and communication, possibly because *Adapting to* auditory stimuli over time might increase cognitive and emotional load, leaving fewer resources available for navigating social interactions[18,31,76,77]. This heightened sensory sensitivity could exacerbate feelings of overwhelm or anxiety in social situations and increased difficulties communicating[67,78]. Additionally, the need to manage or avoid overwhelming auditory environments might limit opportunities for social engagement, further hindering social and communicative development[29,79]. Finally, participants who experienced greater difficulties in *Complex* AEs also reported greater social and communication difficulties and more frequent use of *Self-Regulatory*

*Repetitive Behaviors*. In this study, the factor *Complex* AEs includes items that include situations with multiple sound sources. These correlations suggest Autistic people with greater *Social Interaction* and (non-verbal) *Communication* difficulties may find these complex AEs more challenging and employ more self-regulatory repetitive behaviors to cope. Together, correlational analyses underscore the complexity of auditory processing in Autistic people, supporting the view that the interaction between auditory environment experiences, Autistic traits, and iQoL is multifaceted, with different auditory environments impacting various aspects of Autistic traits beyond the sensory domain[80].

We hypothesised that specific AEs significantly mediate the associations between Autistic traits and iQoL. Of the six parallel mediation analyses we conducted, one model revealed that the relationship between the communication difficulties and iQoL was fully mediated by all four AE factors: *Adverse*, *Tolerable*, *Adapting to*, and *Complex* AEs, with the *Adapting to* AE factor representing the key mediator. While *Adverse* AEs alone did not fully explain communication difficulties, *Adverse* AEs, alongside *Tolerable*, *Adapting to*, and *Complex* AEs, play a significant role in exerting a significant negative impact on the association between communication difficulties and QoL[81–83].

The factor *Adapting to* AEs had a statistically significant indirect effect on the association between *Communication* difficulties and iQoL, suggesting that cognitive demands required to adapt continuously and process changing auditory stimuli can heighten challenges in interpreting non-verbal cues and social complexity[82]. Sensory sensitivities can significantly impact social communication and well-being[67,78,84]. However, more complex aspects of this relationship went unexplored beyond simply stating the heterogeneity of sensory experiences across the Autistic population[31,66,85]. A more holistic approach to supporting auditory sensitivities in environments using personal strategies and environmental modification[33,34,86,87] would acknowledge the potential for complex interactions between Autistic experiences and their combined influence on iQoL.

The factor *Adverse* AEs, mainly characterized by items describing noisy environments, was a key mediator for all five Autistic traits, as measured by the CATI. This partial mediation suggests that *Adverse* AEs can exacerbate challenges in areas where Autistic people may need to exert more cognitive effort, which could deleteriously affect QoL[18]. For the *Social Interaction* trait, which includes preferences and challenges related to engaging in social activities, AEs perceived as aversive can heighten difficulties with neuronormative social interactions and potentially increase the stress associated with such situations, a concept previously reported in the literature[13,19,34]. The *Cognitive Flexibility* subscore, which involves preferences for routine and discomfort with change or unpredictability, is further strained under aversive auditory conditions, making it more difficult for Autistic people to cope with unexpected disruptions, which has not previously been reported. *Self-Regulatory Repetitive Behaviors*, often used to manage external input and stress, are also influenced by enduring aversive noisy environments, leading to increased reliance on these behaviors to manage negative iQoL due to sound sensitivity. A relationship between auditory environment experiences and repetitive behaviors has been reported in the literature[16]. However, the impact of aversive environments on self-regulatory repetitive behaviors has not been previously shown.

The auditory factor, *Adapting to* AEs, which involves the ability to adjust to various sound environments over time, also plays a significant mediating role. This factor significantly influences the relationship between Autistic traits and negatively impacts QoL due to sound sensitivity, specifically *Social Interactions, Communication* and *Cognitive Flexibility*. The difficulties around being exposed to inaccessible and often perceivably hostile sensory environments for long periods have been researched, showing that Autistic people express this as a major barrier to participation[8,34,88–90]. Regarding *Social Interactions*, the need to *Adapt to* AEs can highlight difficulties in navigating neuronormative social situations over time, making social occasions or public spaces stressful and increasing social avoidance. *Cognitive Flexibility* is also impacted by the need to *Adapt to* AEs, leading to heightened rigidity and discomfort with dealing with change within an environment over time[8,13,19,31,84,91]. Previous literature shows that hostile sensory environments can negatively affect non-social Autistic traits such as *Cognitive Flexibility*, *Self-Regulating Repetitive Behaviors* and *Sensory Sensitivity* (including other sensory modalities)[92–96]. These findings underscore the need to design auditory environments that reduce stress and cognitive load for Autistic people in diverse settings.

A negative indirect effect was observed between the *Camouflage* subscore and negative iQoL due to sound sensitivity through the *Adapting to* AE factor. Autistic people have reported camouflaging taking a high cognitive load to maintain[21,22,97,98], suggesting that the challenges faced in camouflaging behaviors are amplified and become more difficult to maintain in auditory settings over time. As outlined in the DSM, Autistic people have a hyperresponsivity to sound[1]. Still, here we show it is much more complex than a simple descriptor of hypersensitivity or decreased sound tolerance.

Overall, these results underscore the intricate and dynamic relationship between the broader Autistic profile and the iQoL of Autistic people and how the different types of auditory environments can impact them. These findings reaffirm the importance of recognizing and respecting the unique sensory experiences of Autistic people, particularly, in this instance, those with sound sensitivities[32,65,66,99]. By acknowledging that auditory processing differences and sensory differences are more broadly a core aspect of the Autistic experience, we can better understand the challenges faced and the strategies employed by Autistic people to navigate their environments. It is, therefore, essential to create supportive and accommodating auditory environments that reduce the negative impacts of sound sensitivities. Such enabling environments should significantly enhance the opportunities for Autistic people to flourish[2].

Finally, we asked about technologies people use in daily life to mitigate sound sensitivities. Our findings revealed that approximately 75% of participants reported using some noise-cancelling device, including earplugs and over- and in-ear noise-cancelling headphones. The use of these devices has been previously shown to increase access and reduce barriers to desired participation at home and in the community, as well as reducing stress or anxiety around potentially under-supported sound sensitivities[8,100–102]. Using these devices can, in turn, allow a person to personalize their auditory environment and reduce the potential adverse effects of high amplitudes in an environment, including those causing hearing loss[103,104]. These devices can often also increase speech-in-noise intelligibility[105], thus enhancing communication ability and desired social participation. Nevertheless, over 40% of our participants reported using these devices for more than two hours a day (including 3.4% who use them for more than 16 h). Further studies are therefore warranted to investigate the potential long-term implications of auditory devices over long durations, particularly if users are listening to music or not (or audio that potentially causes ear damage over time)[106].

This study has several limitations. Although hearing is not different across genders, this study included a high proportion of Autistic people who were assigned as female at birth. Additionally, this study was conducted online. Despite offering alternative survey completion methods, all participants opted for online participation. This approach may have limited our participant pool, potentially excluding individuals from marginalized communities or low socio-economic backgrounds, thus affecting the demographic representation in our study. Future research should replicate this study by targeting such populations by surveying in person or via other accessible means. A final limitation was the psychometric construct of the auditory environments measure, with the low internal consistency of the fourth factor. This measure was bespoke and exploratory and included auditory environmental experiences of Autistic people reported previously in the literature. Future research should build on the current study to expand and refine this measure further.

Future research should explore auditory experiences longitudinally to understand how these experiences wax and wane over time and also seek to determine the effectiveness of particular supports or accommodations (including technologies). In this study we chose not to compare sex or gender. Although there may be sex differences across specific sensory processing domains in the general population[8], in the current study, the dependent variable of interest is the impact of sound sensitivities on the quality of life which has been shown to be consistent across sex and genders, which reflects previous research regarding gender and sound sensitivities[107]. Future research could further specifically explore potential sex- or gender-based differences in this relationship. Future research could also expand on our work on sound environment complexity. Such approaches should extend beyond the traditional understanding of auditory sensitivity to encompass secondary sound sources such as surface reflections, reverberation and environments with multiple sound sources, and the impact of exposure over time. Our findings also warrant further exploration into how other sensory modalities, beyond auditory processing, may influence the lives of Autistic people. Future research could investigate similar mediating effects in other sensory domains, providing a more comprehensive understanding of the sensory experiences in autism. Such studies would be instrumental in developing targeted supports that address the specific sensory needs and challenges faced by Autistic people.

Our work builds on the current literature to reveal a more multidimensional understanding of the challenges of auditory environments beyond just loudness or noise. This study provides novel insights into how the experience of auditory environments affect the QoL for Autistic adults, due to sound sensitivities. Results from this study enhance the understanding of the relationship between auditory environments and QoL for Autistic people, emphasizing the substantial impact of sound sensitivities. It is not just noise that affects QoL, but rather the complexity and variability of auditory information in an environment. The impact extends beyond auditory processing alone, particularly affecting non-verbal communication. Our findings highlight the significant impact of sound beyond simple sensitivity, underscoring the importance of creating supportive and accessible spaces for Autistic people. Autistic people often rely on noise-suppressing technologies to manage noise; however, support must also include thoughtful tailoring of auditory environments in public, educational, and community settings. The results of this study could inform practical approaches to making auditory environments more accessible, potentially improving the QoL for Autistic individuals who experience sound sensitivity and auditory processing differences.

## Data availability

Data is available upon request, by contacting Dr Rebecca Poulsen bec.poulsen@mq.edu.au.

Received: 20 December 2024; Accepted: 13 March 2025
Published online: 27 March 2025

## References

1. Amercian Psychiatric Association. *Diagnostic and Statistical Manual of Mental Disorders (DSM)*. (APA, 2013).
2. Pellicano, E. & Heyworth, M. The foundations of autistic flourishing. *Curr. Psychiatry Rep.* **25**(9), 419–427 (2023).
3. Ide, M., Yaguchi, A., Atsumi, T., Yasu, K. & Wada, M. Hypersensitivity as extraordinary high temporal processing in individuals with autism-spectrum disorders. *Brain Nerve* **69**(11), 1281–1289 (2017).
4. Williams, Z. J., Suzman, E. & Woynaroski, T. G. Prevalence of decreased sound tolerance (hyperacusis) in individuals with autism spectrum disorder: A meta-analysis. *Ear Hear.* **42**(5), 1137–1150 (2021).
5. Brinkert, J. & Remington, A. Making sense of the perceptual capacities in autistic and non-autistic adults. *Autism* **24**(7), 1795–1804 (2020).
6. Bonnel, A. et al. Enhanced pure-tone pitch discrimination among persons with autism but not Asperger syndrome. *Neuropsychologia* **48**(9), 2465–2475 (2010).
7. Caniato, M., Zaniboni, L., Marzi, A. & Gasparella, A. Evaluation of the main sensitivity drivers in relation to indoor comfort for individuals with autism spectrum disorder Part 1: Investigation methodology and general results. *Energy Rep.* **8**, 1907–1920 (2022).
8. Ruiz Callejo, D. & Boets, B. A systematic review on speech-in-noise perception in autism. *Neurosci. Biobehav. Rev.* **1**, 105406 (2023).
9. Millin, R. et al. Reduced auditory cortical adaptation in autism spectrum disorder. *ELife* **7**, e36493 (2018).
10. Gomes, E., Rotta, N. T., Pedroso, F. S., Sleifer, P. & Danesi, M. C. Auditory hypersensitivity in children and teenagers with autistic spectrum disorder. *Arq. Neuropsiquiatr.* **62**(3B), 797–801 (2004).

11. Kuiper, M. W. M., Verhoeven, E. W. M. & Geurts, H. M. Stop making noise! Auditory sensitivity in adults with an autism spectrum disorder diagnosis: physiological habituation and subjective detection thresholds. *J. Autism Dev. Disord.* **49**(5), 2116–2128 (2019).
12. Aykan, S., Gürses, E., Tokgöz-Yılmaz, S. & Kalaycıoğlu, C. Auditory processing differences correlate with autistic traits in males. *Front. Hum. Neurosci.* **14**, 584704 (2020).
13. Chang, K.-Y. et al. The relationships between the auditory behavioral characteristic and the sociality of children with autism spectrum disorder. *J. Korean Soc. Sens. Integr. Ther.* **12**(2), 1–12 (2014).
14. Haskins, A. J. et al. Reduced social attention in autism is magnified by perceptual load in naturalistic environments. *Autism Res.* **15**(12), 2310–2323 (2022).
15. Honisch, J. J., Mane, P., Golan, O. & Chakrabarti, B. Keeping in time with social and non-social stimuli: Synchronisation with auditory, visual, and audio-visual cues. *Sci. Rep.* **11**(1), 8805 (2021).
16. Kargas, N., López, B., Reddy, V. & Morris, P. The relationship between auditory processing and restricted, repetitive behaviors in adults with autism spectrum disorders. *J. Autism Dev. Disord.* **45**(3), 658–668 (2015).
17. Normansell-Mossa, K. M. et al. Sensory sensitivity and intolerance of uncertainty influence anxiety in autistic adults. *Front. Psychol.* **12**, 1753 (2021).
18. Poulsen, R., Williams, Z., Dwyer, P., Pellicano, L., Sowman, P. F. & McAlpine, D. How auditory processing influences the Autistic profile: A review. *Autism Res.* (2024).
19. Hernandez, L. M. et al. Social attention in autism: Neural sensitivity to speech over background noise predicts encoding of social information. *Front. Psychiatry* **11**, 343 (2020).
20. Schelinski, S., Tabas, A. & von Kriegstein, K. Altered processing of communication signals in the subcortical auditory sensory pathway in autism. *PsyArXiv* (2020).
21. Pearson, A. & Rose, K. A conceptual analysis of autistic masking: Understanding the narrative of stigma and the illusion of choice. *Autism Adulthood* **3**(1), 52–60 (2021).
22. Pearson, A. & Rose, K. *Autistic Masking: Understanding Identity Management and the Role of Stigma*. (Pavilion Publishing, 2023).
23. Miller, D., Rees, J. & Pearson, A. "Masking Is Life": Experiences of masking in autistic and nonautistic adults. *Autism Adulthood* **3**(4), 330–338 (2021).
24. Lau, B. Y. et al. Anxiety in young people with autism spectrum disorder: Common and autism-related anxiety experiences and their associations with individual characteristics. *Autism* **24**(5), 1111–1126 (2020).
25. Hames, E. C. et al. Visual, auditory, and cross modal sensory processing in adults with autism: An EEG power and BOLD fMRI investigation. *Front. Hum. Neurosci.* **10**, 167 (2016).
26. Opoku-Baah, C. et al. Visual influences on auditory behavioral, neural, and perceptual processes: A review. *JARO* (2021).
27. Wada, M. et al. Qualitative and quantitative analysis of self-reported sensory issues in individuals with neurodevelopmental disorders. *Front. Psychiatry* **14**, 1077542 (2023).
28. Montaque, I., Dallos, R. & McKenzie, B. "It feels like something difficult is coming back to haunt me": An exploration of 'meltdowns' associated with autistic spectrum disorder from a parental perspective. *Clin. Child Psychol. Psychiatry* **23**(1), 125–139 (2017).
29. Phung, J., Penner, M., Pirlot, C. & Welch, C. What I wish you knew: Insights on burnout, inertia, meltdown, and shutdown from autistic youth. *Front. Psychol.* **12**, 741421 (2021).
30. Buckley, E., Pellicano, E. & Remington, A. Higher levels of autistic traits associated with lower levels of self-efficacy and wellbeing for performing arts professionals. *PLoS ONE* **16**(2), e0246423 (2021).
31. Gonçalves, A. M. & Monteiro, P. Autism spectrum disorder and auditory sensory alterations: A systematic review on the integrity of cognitive and neuronal functions related to auditory processing. *J. Neural Transm.* **130**(3), 325–408 (2023).
32. Howard, P. L. & Sedgewick, F. 'Anything but the phone!': Communication mode preferences in the autism community. (2021).
33. Johnson, T. D. & Joshi, A. Dark clouds or silver linings? A stigma threat perspective on the implications of an autism diagnosis for workplace well-being. *J. Appl. Psychol.* **101**(3), 430–449 (2016).
34. MacLennan, K. et al. "It is a big spider web of things": Sensory experiences of autistic adults in public spaces. *Autism Adulthood* (2022).
35. Newman, R. S., Kirby, L. A., Von Holzen, K. & Redcay, E. Read my lips! Perception of speech in noise by preschool children with autism and the impact of watching the speaker's face. *J. Neurodev. Disord.* **13**(1), 4 (2021).
36. Cary, E. et al. Brain signatures of early and late neural measures of auditory habituation and discrimination in autism and their relationship to autistic traits and sensory overresponsivity. *J. Autism Dev. Disord.* **54**, 1344–1356 (2023).
37. Orekhova, E. V. & Stroganova, T. A. Arousal and attention re-orienting in autism spectrum disorders: evidence from auditory event-related potentials. *Front. Hum. Neurosci.* **8**, 34 (2014).
38. Cunningham, M. 'This school is 100% not autistic friendly!' Listening to the voices of primary-aged autistic children to understand what an autistic friendly primary school should be like. *Int. J. Inclusive Educ.* **1**, 1–15 (2020).
39. de Vries, B. Autism and the right to a hypersensitivity-friendly workspace. *Public Health Ethics* **14**(3), 281–287 (2021).
40. Timms, S., Lodhi, S., Bruce, J. & Stapleton, E. Auditory symptoms and autistic spectrum disorder: A scoping review and recommendations for future research. *J. Otol.* **17**, 239–246 (2022).
41. English, M. C. W. et al. The comprehensive autistic trait inventory (CATI): Development and validation of a new measure of autistic traits in the general population. *Mol. Autism* **12**(1), 37 (2021).
42. English M. et al. Psychometric evaluation of the Comprehensive Autistic Trait Inventory (CATI) in autistic and non-autistic adults. (2024).
43. Williams, Z., Cascio, C. & Woynaroski, T. *Multidimensional Inventory of Sound Tolerance in Adults (MIST-A)*. (2021).
44. Dillman, D. A., Smyth, J. D. & Christian, L. M. *Internet, Phone, Mail, and Mixed Mode Surveys: The Tailored Design Method* 4th edn. (Wiley, 2014).
45. Ardeleanu, K. et al. Self-identification of autism: Why some autistic adults lack a clinical diagnosis and why this matters for inclusion. *Autism* **136**, 23613241 (2024).
46. Botha, M., Dibb, B. & Frost, D. M. "Autism is me": An investigation of how autistic individuals make sense of autism and stigma. *Disabil. Soc.* **1**, 1–27 (2020).
47. Kapp, S., Gillespie-Lynch, K., Sherman, L. & Hutman, T. Deficit, difference, or both? Autism and neurodiversity. *Dev. Psychol.* **49**(1), 59–71 (2013).
48. WMA. *The World Medical Association-WMA Declaration of Helsinki – Ethical Principles for Medical Research Involving Human Participants*. (2024).
49. Harris, P. A. et al. Research electronic data capture (REDCap)—A metadata-driven methodology and workflow process for providing translational research informatics support. *J. Biomed. Inform.* **42**(2), 377–381 (2009).
50. Harris, P. A. et al. The REDCap consortium: Building an international community of software platform partners. *J. Biomed. Inform.* **95**, 103208 (2019).
51. Heckathorn, D. D. Snowball versus respondent-driven sampling. *Sociol. Methodol.* **41**(1), 355–366 (2011).
52. Tavakol, M. & Dennick, R. Making sense of Cronbach's alpha. *Int. J. Med. Educ.* **2**, 53–55 (2011).
53. Leys, C., Ley, C., Klein, O., Bernard, P. & Licata, L. Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median. *J. Exp. Soc. Psychol.* **49**(4), 764–766 (2013).
54. Barnett, V. & Lewis, T. *Outliers in Statistical Data* 3rd edn. (Wiley, 1994).

55. Gnanadesikan, R. & Kettenring, J. R. Robust estimates, residuals, and outlier detection with multiresponse data. *Biometrics* **28**(1), 81–124 (1972).
56. Hampel, F. R., Ronchetti, E. M., Rousseeuw, P. J. & Stahel, W. A. *Robust Statistics: The Approach Based on Influence Functions* (Wiley, 1986).
57. *International Handbook of Survey Methodology*. (Routledge, 2008).
58. Becker, C. & Gather, U. The masking breakdown point of multivariate outlier identification rules. *J. Am. Stat. Assoc.* **94**(447), 947–955 (1999).
59. Becker, C. G. & Becker, T. Repellent guidance of regenerating optic axons by chondroitin sulfate glycosaminoglycans in zebrafish. *J. Neurosci.* **22**(3), 842–853 (2002).
60. Byrne, B. M. *Structural Equation Modelling with AMOS: Basic Concepts, Applications and Programming* 2nd edn. (Routledge, 2010).
61. Field, A. *Discovering Statistics Using IBM SPSS Statistics* 4th edn. (SAGE Publications, 2013).
62. Poulsen, R., Brownlow, C., Lawson, W. & Pellicano, E. Meaningful research for autistic people? Ask autistics!. *Autism* **26**(1), 3–5 (2022).
63. Tan, D. Reporting community involvement in autism research: Findings from the journal. *Autism* (2024).
64. Hayes, A. F. *Introduction to Mediation, Moderation, and Conditional Process Analysis: A Regression-Based Approach* (Guilford Publications, 2022).
65. Bellamy, R. et al. The effect of ambient sounds on decision-making and heart rate variability in autism. *Autism* **25**(8), 2209–2222 (2021).
66. Lin, L.-Y. & Huang, P.-C. Quality of life and its related factors for adults with autism spectrum disorder. *Disabil. Rehabil.* **41**(8), 896–903 (2019).
67. Strömberg, M., Liman, L., Bang, P. & Igelström, K. Experiences of sensory overload and communication barriers by autistic adults in health care settings. *Autism Adulthood* **4**(1), 66–75 (2022).
68. Pellicano, E. Sensory symptoms in autism: A blooming, buzzing confusion?. *Child Dev. Perspect.* **7**(3), 143–148 (2013).
69. Arnold, S. R. et al. Towards the measurement of autistic burnout. *Autism* **136**, 23613221 (2023).
70. Higgins, J. M., Arnold, S. R., Weise, J., Pellicano, E. & Trollor, J. N. Defining autistic burnout through experts by lived experience: Grounded Delphi method investigating #AutisticBurnout. *Autism* **25**(8), 2356–2369 (2021).
71. Hudac, C. M. et al. Early enhanced processing and delayed habituation to deviance sounds in autism spectrum disorder. *Brain Cogn.* **123**, 110–119 (2018).
72. Waldron, D. A., Coyle, C. & Kramer, J. Aging on the autism spectrum: Self-care practices and reported impact on well-being. *J. Autism Dev. Disord.* **52**(8), 3512–3522 (2022).
73. Alispahic, S., Pellicano, E., Cutler, A. & Antoniou, M. Multiple talker processing in autistic adult listeners. *Sci. Rep.* **14**(1), 14698 (2024).
74. Lau, B. K.et al. The impact of cognitive ability on multitalker speech perception in neurodivergent individuals. (2022).
75. Feldman, J. I. et al. Audiovisual multisensory integration in individuals with autism spectrum disorder: A systematic review and meta-analysis. *Neurosci. Biobehav. Rev.* **95**, 220–234 (2018).
76. Robertson, C. E. & Baron-Cohen, S. Sensory perception in autism. *Nat. Rev. Neurosci.* **18**(11), 671–684 (2017).
77. Williams, D. M. & Happé, F. What did I say? Versus what did I think? Attributing false beliefs to self amongst children with and without autism. *J. Autism Dev. Disord.* **39**(6), 865–873 (2009).
78. Chen Y. et al. “Utterly overwhelming”—a mixed-methods exploration of sensory processing differences and mental health experiences in middle-aged and older autistic adults. *Autism Adulthood* (2024).
79. Harricharan, S., McKinnon, M. C., Lanius, R. A. How processing of sensory information from the internal and external worlds shape the perception and engagement with the world in the aftermath of trauma: Implications for PTSD. *Front. Neurosci.* **15** (2021).
80. Bang, P. & Igelström, K. Modality-specific associations between sensory differences and autistic traits. *Autism* **27**(7), 2158–2172 (2023).
81. Ainsworth, K., Ostrolenk, A., Irion, C. & Bertone, A. Reduced multisensory facilitation exists at different periods of development in autism. *Cortex* **134**, 195–206 (2021).
82. Baum Miller, S. H. & Wallace, MT. Multisensory processing differences in individuals with autism spectrum disorder. In *Multisensory Processes*, 243–272 (2019).
83. Beker, S., Foxe, J. J. & Molholm, S. Ripe for solution: Delayed development of multisensory processing in autism and its remediation. *Neurosci. Biobehav. Rev.* **84**, 182–192 (2018).
84. Green, S. A., Hernandez, L. M., Bowman, H. C., Bookheimer, S. Y. & Dapretto, M. Sensory over-responsivity and social cognition in ASD: Effects of aversive sensory stimuli and attentional modulation on neural responses to social cues. *Dev. Cogn. Neurosci.* **29**, 127–139 (2018).
85. O’Connor, K. Auditory processing in autism spectrum disorder: A review. *Neurosci. Biobehav. Rev.* **36**(2), 836–854 (2012).
86. Bagatell, N., Chan, D. V., Syu, Y.-C., Lamarche, E. M. & Klinger, L. G. Sensory processing and community participation in autistic adults. *Front. Psychol.* **13**, 876127 (2022).
87. Pellicano, E. & den Houting, J. Annual research review: Shifting from ‘normal science’ to neurodiversity in autism science. *J. Child Psychol. Psychiatry* (2021).
88. Gelbar, N. W., Smith, I. & Reichow, B. Systematic review of articles describing experience and supports of individuals with autism enrolled in college and university programs. *J. Autism Dev. Disord.* **44**(10), 2593–2601 (2014).
89. Livingston, L. A., Shah, P. & Happé, F. Compensatory strategies below the behavioural surface in autism: A qualitative study. *Lancet Psychiatry* **6**(9), 766–777 (2019).
90. Pfeiffer, B., Erb, S. R. & Slugg, L. Impact of noise-attenuating headphones on participation in the home, community, and school for children with autism spectrum disorder. *Phys. Occup. Ther. Pediatr.* **39**(1), 1–17 (2019).
91. Kapp, S. K. Social support, well-being, and quality of life among individuals on the autism spectrum. *Pediatrics* **141**(Supplement 4), S362–S368 (2018).
92. Boyd, B. A. et al. Sensory features and repetitive behaviors in children with autism and developmental delays. *Autism Res.* **3**(2), 78–87 (2010).
93. Glod, M., Riby, D. M., Honey, E. & Rodgers, J. Sensory atypicalities in dyads of children with autism spectrum disorder (ASD) and their parents. *Autism Res.* **10**(3), 531–538 (2017).
94. Jaffey, S. & Ashwin, C. Exploring antecedents and outcomes of restricted and repetitive behaviours in autistic children: A thematic analysis of teacher interviews. *Res. Autism Spectr. Disord.* **97**, 102021 (2022).
95. Joyce, C., Honey, E., Leekam, S. R., Barrett, S. L. & Rodgers, J. Anxiety, intolerance of uncertainty and restricted and repetitive behaviour: insights directly from young people with ASD. *J. Autism Dev. Disord.* **47**(12), 3789–3802 (2017).
96. Moore, H. L. et al. The mediating effects of alexithymia, intolerance of uncertainty, and anxiety on the relationship between sensory processing differences and restricted and repetitive behaviours in autistic adults. *J Autism Dev Disord* (2021).
97. Bradley, L., Shaw, R., Baron-Cohen, S. & Cassidy, S. Autistic adults’ experiences of camouflaging and its perceived impact on mental health. *Autism Adulthood* **3**(4), 320–329 (2021).
98. Hull, L. et al. “Putting on my best normal”: Social camouflaging in adults with autism spectrum conditions. *J. Autism Dev. Disord.* **47**(8), 2519–2534 (2017).

99. Jaswal, V. K. & Akhtar, N. Supporting autistic flourishing. *Behav. Brain Sci.* **42**, 25 (2019).
100. Danesh, A. A., Howery, S., Aazh, H., Kaf, W. & Eshraghi, A. A. Hyperacusis in autism spectrum disorders. *Audiol. Res.* **11**(4), 547–556 (2021).
101. Fodstad, J. C., Kerswill, S. A., Kirsch, A. C., Lagges, A. & Schmidt, J. Assessment and treatment of noise hypersensitivity in a teenager with autism spectrum disorder: A case study. *J. Autism Dev. Disord.* **51**(6), 1811–1822 (2021).
102. Ikuta, N. et al. Effectiveness of earmuffs and noise-cancelling headphones for coping with hyper-reactivity to auditory stimuli in children with autism spectrum disorder: A preliminary study. *Hong Kong J. Occup. Ther.* **28**(1), 24–32 (2016).
103. Hoshina, T., Fujiyama, D., Koike, T. & Ikeda, K. Effects of an active noise control technology applied to earphones on preferred listening levels in noisy environments. *J. Audiol. Otol.* **26**(3), 122–129 (2022).
104. Seol, H.-Y. et al. Influence of the noise-canceling technology on how we hear sounds. *Healthcare* **10**(8), 1449 (2022).
105. Mueller, B. J., Liebl, A., Herget, N., Kohler, D. & Leistner, P. Using active noise-cancelling headphones in open-plan offices: No influence on cognitive performance but improvement of perceived privacy and acoustic environment. *Front. Built Environ.* **8**, 1–10 (2022).
106. Neville, F., Sedgewick, F., McClean, S., White, J. & Bray, I. Reacting, retreating, regulating, and reconnecting: How autistic adults in the United Kingdom use time alone for well-being. *Autism Adulthood* (2024).
107. Musumano, L. B. et al. Hyperacusis: Focus on gender differences: A systematic review. *Life* **13**(10), 2092 (2023).


## Acknowledgements

We are extremely grateful to all our participants who took our online survey. We thank our Autistic advisory group. We thank Dr Zachary Williams and Dr Michael English for their support and assistance with the use of the MIST-A and the CATI tools. We also acknowledge Romaric Bourveret and Jayde Cahir for administrative and research support, and Yvonne Tran for advice on analysis methodology.


## Author contributions
RP: Conceptualization, Methodology, Investigation, Formal Analysis, Data Curation, Writing—Original Draft, Review and Editing, Visualization, Project Administration. DT: Analysis, Writing—Review and Editing. PS: Writing—Review and Editing, Supervision, Funding Acquisition. DM: Writing—Review and Editing, Supervision, Funding Acquisition. EP: Methodology, Writing—Review and Editing, Supervision, Funding Aquisition.

## Funding

RP, LP, PS, and DM are funded through the Simons Foundation SFARI Grant RFA-873809. D.T. was supported by a Macquarie University Research Fellowship (MQRF0001113). The study's funders had no role in the study design, data collection, data analysis, data interpretation, or writing of this manuscript.


## Declarations

## Competing interests
The authors declare no competing interests.

## Additional information
**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-94585-y.


**Correspondence** and requests for materials should be addressed to R.P.