Relative importance of processing deficits in seven sensory modalities in predicting quantitative autistic traits in adults

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Research Article

Keywords: Broad autism phenotype, research domain criteria, dimensional perspective, central auditory processing disorder, pragmatic language deficits

Posted Date: May 18th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1642709/v1

Abstract

Background

Atypical sensory processing measured by self- or parent-report co-segregates with quantitative autistic traits (QAT) and has potential endophenotypic properties relevant to the mechanisms of autism. However, it is not known whether this association reflects a generalized sensory dysfunction or combinations of modality-specific mechanisms. Collinearity between QAT and modality-specific sensory scales limits the use of multiple regression to determine relative importance. Therefore, we combined a Bayesian variable selection method with dominance analysis to obtain a more nuanced understanding of potential modality-specific associations.

Methods

We recruited two independent cohorts of adults online to complete the Broad Autism Phenotype Questionnaire and the Glasgow Sensory Questionnaire (N = 592 in total). Subscale scores were derived for social, communicative, and rigid QAT and for the visual, auditory, tactile, olfactory, gustatory, proprioceptive, and vestibular sensory modalities. For each QAT, we performed a stochastic search variable selection (SSVS) procedure on the sensory modality subscales to test which sensory modalities predicted QAT while controlling for uncertainty in the other variables. Dominance analysis was then applied to the models identified by the SSVS to evaluate the relative importance of sensory modalities in predicting QAT.

Results

Only auditory scores reliably predicted all three QAT. The proprioceptive scale, which included motor and interoceptive deficits, specifically predicted communicative QAT. The tactile scale, which included touch sensitivity and atypical pain/temperature processing, specifically predicted social QAT.

Limitations:

The findings must be interpreted in light of limitations of the Glasgow Sensory Questionnaire. For example, associations between QAT and visual, olfactory, gustatory, or vestibular modalities might appear if measured in a different way. The study relied on self-report by anonymous participants, which precluded clinical evaluation of sensory difficulties. It is also important to note that the modalities found to lack associations with QAT are nevertheless known to be clinically significant in autism.

Conclusions

Auditory processing deficits, such as noise sensitivity, strongly predicted all QAT, whereas other sensory modalities did not. Thus, auditory processing could be further studied as a potential sensory endophenotype for autism. The results also indicate potential roles for tactile dysfunction in atypical social interaction and proprioceptive/motor dysfunction in pragmatic language.

Background

Atypical sensory processing is prevalent in autism spectrum conditions and often imposes great limitations on activities of daily living [1]. Like other quantitative autistic traits (QAT), sensory processing abnormalities measured by self- or informant-report are, to a large extent, genetically based [2, 3]. Self-reported sensory problems are positively correlated with QAT measured by the Autism Quotient (AQ) [4] or other measures of the broad autism phenotype, such as the Broad Autism Phenotype Questionnaire [5–9]. First-degree relatives of autistic children also showed elevated scores [10, 11], and twin studies found a genetic basis for the association between sensory sensitivity and QAT [3, 12].

Sensory perception is a broad construct comprising multiple modalities and levels of processing, and it is not presently clear whether deficits in autism are caused by some domain-general mechanism or heterogeneous combinations of domain-specific ones [13]. Subjective sensitivity often occurs in more than one sensory modality, supporting a more domain-general account. For example, autism has been associated with excitation/inhibition (E/I) imbalance, which may cause an increase in neural noise, stochastic resonance, or propagation of evoked signals outside sensory regions [14]. Another potential mechanism is related to predictive coding, which relies on learning about statistical properties of the sensory environment. For example, autistic people have been found to utilize predictions less efficiently, causing familiar stimuli to be processed as salient [15]. Modality-specific differences in sensory thresholds, discrimination, habituation, and other processes, have been reported in various studies, with heterogeneous results [13].

The relative contributions of different sensory modalities to autistic sensory symptoms are not known. Qualitative studies point towards the auditory modality as especially bothersome (e.g., [16, 17]), but elevated sensory symptoms are, on average, present across all modalities in autism [18]. Parents in multiplex ASD families showed higher auditory and visual scores on the Adult/Adolescent Sensory Profile compared to simplex families [19], possibly indicating a stronger genetic relationship between autism and these modalities. Several studies have also found bivariate correlations between QAT and modality-specific scores on sensory scales. Robertson and Simmons (2013) reported elevated scores on the Glasgow Sensory Questionnaire (GSQ) in all sensory domains in participants with high AQ [8], and the AQ score correlated linearly with all seven modality-specific subscales on the GSQ [9, 20]. Another study found that high AQ participants differed from low AQ participants on visual, auditory, tactile, and proprioceptive GSQ subscales but not on olfactory, gustatory, or vestibular subscales [21].

It is also not known whether autistic characteristics within specific areas (i.e., social reciprocity, communication/pragmatic language deficits, or restricted/repetitive behaviors) are differentially

correlated with sensory issues. When considering the total sensory scores rather than modality-specific ones, several studies have reported linear correlations for all specific QAT [7–9, 20, 21]. Auditory, tactile, and proprioceptive GSQ subscales showed bivariate correlations with social, communication, and rigid QAT, whereas other modalities had more variable relationships with specific traits [21]. Comparisons of genetic, biological, and behavioral contributions of specific sensory modalities to autistic traits are complicated by high collinearity between constructs [6, 8, 9].

One way of assessing the relative importance of intercorrelated predictor variables is dominance analysis (DA), which can provide information about the contribution of individual predictors to the total R^2 of a multiple regression model [22]. To evaluate the role of different modalities in predicting specific autistic traits, we combined DA with stochastic search variable selection (SSVS; [23]). We recruited two independent cohorts of adults to complete the GSQ and BAPQ (N = 252 + 268). SSVS was used to select the sensory modalities that most reliably predicted social, communicative, and rigid QAT, and DA was performed on the selected variables to assess their relative importance.

Methods

We used a dimensional approach consistent with the Research Diagnostic Criteria (RDoC) framework [24, 25]. This means that we used QAT and sensory constructs as disorder-relevant dimensional measures and tested associations trans-diagnostically using regression methods. Sensory measures that show strong correlations with QAT are considered to be particularly promising as potentially relevant clinical constructs.

Participants

We recruited two large community cohorts from the platform Prolific.co [26], using the built-in prescreening filters to control cohort composition without knowledge of the participants' identities. All individuals reported English as their first language and resided in Australia, Canada, Ireland, New Zealand, the United Kingdom, or the United States. Data collection for Cohort 1 was completed before starting recruitment for Cohort 2, and there was no overlap between the cohorts. Participants were reimbursed by Prolific for their participation. The study was exempt from ethical review according to Swedish regulations because participants were fully anonymous to the researchers, and no personal data were collected. Nevertheless, the study was designed according to the principles of the Declaration of Helsinki. Participants provided digital informed consent and could exit the study at any point by closing the browser window.

Cohort 1 was clinically enriched (40% autistic participants) as the data was collected as part of a different study (unpublished data) that relied on group comparisons between neurotypical and autistic adults. The approach ensured a broad distribution of QAT, with enough data in the highest ranges. Cohort 2 was recruited from the general population without any selection based on clinical variables, setting a Prolific filter to exclude participants who had been part of Cohort 1. This resulted in a cohort with 6%

autistic participants. Exclusion criteria were disclosed psychotic illnesses, primary sensory issues, brain injury and neurodegenerative disease, and failure to pass attention checks built into the questionnaires. Based on these criteria, we excluded 9 participants in Cohort 1 and 33 in Cohort 2. Demographic details are shown in **Table 1**.

Table 1

Demographic data

	Cohort 1 (N = 252)	Cohort 2 (N = 268)
Gender		
Woman	144	134
Man	87	126
Other	21	8
Age (years ± SD)	34.1 ± 11.6	37.6 ± 12.6
Country of residence		
United States of America	26 (10.3%)	81 (30.2%)
United Kingdom	199 (79%	150 (55.9%)
Australia	11 (4.4%)	9 (3.4%)
Canada	x	21 (7.8%)
Ireland	9 (3.5%)	4 (1.4%)
New Zealand	7 (2.8%)	3 (1.1%)
Education		
Years of schooling ± SD	16.5 ± 3.9	—
Parents' education		
Years of schooling ± SD	14.9 ± 4.7	—
Psychiatric conditions		
Obsessive/compulsive disorder	22 (8.7%)	27 (10.1%)
Developmental coordination disorder	20 (7.9%)	5 (1.9%)
Attention deficit disorder	16 (6.4%)	27 (10.1%)
Autism spectrum condition	101 (40.1%)	17 (6.3%)
Anxiety disorders	97 (38.4%)	140 (52.2%)
Mood disorders	77 (30.6%)	137 (51.1%)
Personality disorder	6 (2.3%)	19 (7.0%)

Materials

The Broad Autism Phenotype Questionnaire (BAPQ)

The BAPQ is a 36-item questionnaire developed to identify subclinical QAT in first-degree relatives of autistic children [6]. The QAT of the BAP include atypical social interaction, communication deficits and cognitive rigidity, measured by the subscales Aloof personality, Pragmatic language deficits, and Rigid personality, respectively. Each subscale consists of 12 items, and each item is rated on a six-point Likert scale. The scores are averaged to derive total and subscale scores ranging from 1 to 6. In the present study, the internal consistency was high for the total score and subscales (Cronbach's $\alpha > 0.85$; Table 2).

Glasgow Sensory Questionnaire (GSQ)

The GSQ was developed to measure sensory difficulties experienced by people with autism. The instrument contains 42 items covering all seven sensory modalities (vision, hearing, taste, smell, touch, proprioception, and vestibular; [8]). Items are scored on a 5-point Likert scale. We used the original modality-specific subscales (summed scores) for group comparison (non-autistic vs autistic) and correlations with the total BAPQ score. For the main analysis, which tested relationships between sensory modalities and specific QAT, we removed two items from the GSQ that overlapped too much with the Rigid subscale of the BAPQ. The removed items were "Do you like to listen to the same piece of music/part of a DVD over and over again?" (auditory subscale) and "Do you eat the same foods most of the time?" (gustatory subscale). For this analysis, subscale scores were averaged and ranged from 1 to 5.

Items on the GSQ can also be divided into hyper- and hyposensitivity scales, where items probing hyposensitivity include sensory seeking behaviors, non-responses to inputs, and difficulties deciphering inputs such as speech [8]. As previously reported [9], we found a strong positive correlation between the hyper- and hypo-sensitivity scores ($R^2 = 0.74$, $p < .001$), supporting the pooling of scores within modalities. In both cohorts, the internal consistency was high for the total GSQ (Cronbach's $\alpha = >.90$), whereas it was low to moderate for the subscales (Table 2), consistent with previous studies [21, 27].

Table 2
Cronbach's Alphas for subscales of the BAPQ and GSQ

Questionnaire/Subscale	N items	Cronbach's α (Cohort 1)	Cronbach's α (Cohort 2)
BAPQ	36	0.95	0.94
Aloof Personality	12	0.92	0.94
Pragmatic Language	12	0.85	0.85
Rigid Personality	12	0.90	0.91
GSQ	40	0.92	0.90
Visual	6	0.70	0.69
Auditory	5	0.70	0.68
Tactile	6	0.64	0.54
Olfactory	6	0.49	0.52
Gustatory	5	0.65	0.54
Proprioception	6	0.72	0.62
Vestibular	6	0.66	0.61

Note. The auditory and gustatory GSQ subscales contained 5 items due to the removal of items that overlapped with the rigid QAT construct 6 (see Methods for detail).

Demographic questions

Demographic questions included age, country of residence, psychiatric disorders and primary sensory deficits. The gender question had female and male options, as well as "non-binary" and "other/prefer not to say". The latter two options were pooled as a third gender and used as a dummy variable.

Statistical analysis

We tested for normal distributions using the Shapiro-Wilk tests. To explore which sensory modalities may be associated with higher QAT, we used SSVS [23]. SSVS is a Bayesian framework used for empirically driven variable selection [28]. The SVSS uses Markov chain Monte Carlo sampling to sample from a posterior distribution of the possible subsets of predictors to identify the best models. Predictors selected more frequently in the sampling receive higher marginal inclusion probabilities (MIPs) (0.0–1.0) [23, 28]. This approach selects predictors while controlling for uncertainty in other predictors included in the model, maximizing power, and minimizing false positives.

For each cohort, three analyses were performed using an online application that performs SSVS ([23]; https://ssvsforpsych.shinyapps.io/ssvsforpsych/). All analyses used the following SSVS specifications: prior inclusion probability α = 0.5 (indicating that each predictor has a 50/50 prior probability of being included in the model), 5,000 burn-in iterations to achieve convergence, and 20,000 total iterations. The seven modality-specific GSQ sub-scores, age and two dummy-coded gender variables (woman = 0) were entered as independent variables, with one of the QAT (aloof personality, pragmatic language, or rigid personality) as the dependent variable. To assess convergence and ensure that SSVS results were stable, we ran SSVS analyses twice and computed a Pearson's correlation between each variable's estimated MIPs. The obtained correlation exceeded R = .99 for all analyses.

The SSVS identifies the most robust predictors but does not test their relative importance. We, therefore, applied DA to each of the models returned by the SSVS using the procedure described in Braun et al. [22] and applied in White et al. [29]. We calculated general dominance weights by computing each predictor's averaged incremental validity across all possible subset regression models involving that predictor, over 1,000 Monte Carlo simulated runs [22, 30]. This method addresses the issue of sampling error variance that impacts individual instances of DA weights [22]. For a more straightforward interpretation of the predictors' relative importance, we divided each weight by the model R^2 creating standardized general dominance weights [31]. We did not correct for measurement error [22] because the low subscale reliabilities of the GSQ attenuated inter-variable correlations and made the correlation matrices non-positive definite [32].

Results

Replication of sensory differences in participants with high autistic traits

Cohort 1 was used to replicate previously observed sensory processing differences between autistic and non-autistic adults. The total GSQ and all modality subscales were significantly elevated in autistic participants, and there were significant bivariate correlations between the BAPQ and all GSQ scores (Table 3). BAPQ-GSQ correlations were significant also when autistic individuals were excluded (N = 151, data not shown).

Table 3
Replication of group differences and bivariate relationships (Cohort 1)

GSQ modality	Non-autistic (median ± SD)	Autistic (median ± SD)	Mann-Whitney test	Spearman correlation with BAPQ
Total scale	94 ± 17	114 ± 21	$U = 3130.0$, $p = 2.2\times10^{-15}$	$\rho = 0.583$, $p = 2.3\times10^{-24}$
Visual	13 ± 3.4	16 ± 4.1	$U = 4446.5$, $p = 1.9\times10^{-8}$	$\rho = 0.442$, $p = 1.7\times10^{-13}$
Auditory	18 ± 3.5	22 ± 4.0	$U = 3672.0$, $p = 2.7\times10^{-12}$	$\rho = 0.546$, $p = 5.3\times10^{-21}$
Tactile	12 ± 3.8	16 ± 4.2	$U = 4254.0$, $p = 2.5\times10^{-9}$	$\rho = 0.459$, $p = 1.5\times10^{-14}$
Olfactory	13 ± 2.8	15 ± 3.6	$U = 4938.5$, $p = 1.9\times10^{-6}$	$\rho = 0.329$, $p = 8.7\times10^{-8}$
Gustatory	13 ± 3.5	16 ± 3.6	$U = 4335.5$, $p = 5.9\times10^{-9}$	$\rho = 0.452$, $p = 4.3\times10^{-14}$
Proprioceptive	11 ± 3.0	15 ± 4.2	$U = 3050.5$, $p = 5.6\times10^{-16}$	$\rho = 0.519$, $p = 8.9\times10^{-19}$
Vestibular	12 ± 3.0	15 ± 4.3	$U = 4215.0$, $p = 1.6\times10^{-9}$	$\rho = 0.451$, $p = 5.0\times10^{-14}$

Note. BAPQ, Broad Autism Phenotype Questionnaire; GSQ, Glasgow Sensory Questionnaire.

Auditory and tactile differences dominate in predicting social QAT

When Aloof personality was used as the dependent variable, the SSVS found MIPs nearing 1.0 for the auditory modality in Cohort 1 and Cohort 2 (Fig. 1A). Tactile differences also reproducibly showed high MIP, whereas the male gender variable was only selected in Cohort 2 (Fig. 1A). Based on these results, the DA for Cohort 1 included auditory and tactile scores, and the DA for Cohort 2 additionally included male gender. General dominance was established for the auditory modality demonstrating the largest standardized averaged weight, highest averaged rank, and the largest proportion of times significantly different from zero in both analyses (**Table. 4**). The auditory and tactile predictors were significantly different from each other in 11% of runs in Cohort 1 and 60% of runs in Cohort 2. Male gender, when included, differed from the auditory predictor in 79% of runs and from the tactile predictor in 12% of runs (Fig. 1C).

Table 4
General Dominance Analysis Weight and Rank Values for predictors of Aloof personality in Cohort 1 and Cohort 2

	Cohort 1		Cohort 2	
Predictors	M [95% CI]	Sig	M [95% CI]	Sig
Weights				
Auditory	0.13 [0.07, 0.20]	96%	0.14 [0.07, 0.21]	99%
Tactile	0.10 [0.05, 0.17]	88%	0.05 [0.01, 0.10]	52%
Male	-	-	0.03 [0.00, 0.07]	16%
R2	0.23 [0.14, 0.33]		0.22 [0.13, 0.32]	
Ranks				
Auditory	1.28 [1.00, 2.00]		1.02 [1.00, 1.00]	
Tactile	1.72 [1.00, 2.00]		2.22 [2.00, 3.00]	
Male	-		2.80 [2.00, 3.03]	

Note. M = mean; CI = confidence interval; Sig = proportion of runs that the predictor was found to be significantly different from zero (i.e., the spurious predictor). The spurious predictor used to test for significant differences from zero was excluded from the table. Mean represents the average value across all simulated runs, and all values were based on 1000 simulated runs.

Auditory and proprioceptive differences dominate in predicting communicative QAT

Very high MIPs were seen for the auditory and proprioceptive modalities in the SSVS for Pragmatic language scores in both cohorts (Fig. 2A). In Cohort 2, the vestibular and tactile scores, as well as age and male gender, also exceeded our MIP cut-off of 0.5. DA of Cohort 1 showed general dominance of the proprioceptive modality, followed by the auditory modality (**Table. 5**), with the two modalities being significantly different from each other in 34% of runs. In Cohort 2, there was a more even dominance of the auditory and proprioceptive predictors (**Table. 5**), with significant differences in only 6.5% of runs (Fig. 2C). Vestibular and tactile scores explained intermediate proportions of variance (white bars in Fig. 2B) and differed from the auditory and proprioceptive modalities in 31–52% of runs (Fig. 2C). Age and gender were unimportant and differed from the sensory scores in most runs (Fig. 2B-C).

Table 5
General Dominance Analysis Weight and Rank Values for predictors of Pragmatic language in Cohort 1 and Cohort 2

	Cohort 1		Cohort 2	
Predictors	M [95% CI]	Sig	M [95% CI]	Sig
Weights				
Proprioception	0.25 [0.18, 0.33]	100%	0.13 [0.08, 0.18]	100%
Auditory	0.17 [0.10, 0.24]	100%	0.13 [0.08, 0.19]	100%
Vestibular	-	-	0.08 [0.05, 0.12]	99.40%
Tactile	-	-	0.07 [0.03, 0.12]	96.50%
Age	-	-	0.02 [0.00, 0.05]	22%
Male	-	-	0.01 [0.00, 0.03]	14%
R2	0.43 [0.33, 0.52]		0.45 [0.35, 0.56]	
Ranks				
Proprioception	1.08 [1.00, 2.00]		1.59 [1.00, 3.00]	
Auditory	1.92 [1.00, 2.00]		1.59 [1.00, 3.00]	
Vestibular	-		3.21 [2.00, 4.00]	
Tactile	-		3.64 [2.00, 5.00]	
Age	-		5.16 [4.00, 6.00]	
Male	-		6.02 [5.00, 7.00]	

Note. M = mean; CI = confidence interval; sig = proportion of runs that the predictor was found to be significantly different from zero (i.e., the spurious predictor). The spurious predictor used to test for significant differences from zero was excluded from the table. Mean represents the average value across all simulated runs, and all values were based on 1000 simulated runs.

Auditory differences dominate in predicting rigid QAT

When Rigid personality was used as the dependent variable for SSVS, only the auditory modality was selected in both cohorts. Age was additionally selected for Cohort 1, and the vestibular score was selected for Cohort 2 (**Table. 6**). The auditory modality showed general dominance in both Cohorts (**Table. 6**), although the vestibular modality explained almost as much variance as the auditory modality in Cohort 2. Auditory scores were significantly different from vestibular scores in 19% of runs (Fig. 3C). Age was unimportant and differed from the dominant predictor in 85% of cases (Fig. 3B-C).

Table 6
General Dominance Analysis Weight and Rank Values for predictors of Rigid personality in Cohort 1 and Cohort 2

	Cohort 1		**Cohort 2**	
Predictors	M [95% CI]	Sig	M [95% CI]	Sig
Weights				
Auditory	0.20 [0.11, 0.31]	100%	0.13 [0.06, 0.20]	98%
Age	0.04 [0.01, 0.10]	22%	-	-
Vestibular	-	-	0.09 [0.04, 0.15]	22%
R2	0.25 [0.15, 0.35]		0.22 [0.14, 0.32]	
Ranks				
Auditory	1.00 [1.00, 1.00]		1.20 [1.00, 2.00]	
Age	2.10 [2.00, 3.00]		-	
Vestibular	-	-	1.80 [1.00, 2.00]	
Note. M = mean; CI = confidence interval; sig = proportion of runs that the predictor was found to be significantly different from zero (i.e., the spurious predictor). The spurious predictor used to test for significant differences from zero was excluded from the table. Mean represents the average value across all simulated runs, and all values were based on 1000 simulated runs.				

Discussion

This study investigated modality-specific sensory difficulties and their relative importance in explaining variance in specific QAT in the adult population. High scores on the auditory modality subscale were strongly predictive of traits in all three domains, suggesting that it may be a robust endophenotype that co-segregates with the broad autism phenotype. In contrast, high tactile and proprioceptive scores specifically predicted social and communicative traits, respectively. The absence of associations for olfactory, gustatory, vestibular, and visual modalities must be interpreted in light of the moderate internal reliabilities for the GSQ subscales (Table 2). However, it might suggest that deficits in these modalities are inherited differently or are associated more specifically with autism as a diagnostic category rather than QAT.

The dominance of the auditory modality is consistent with the known presence of sound sensitivity in autistic populations and first-degree relatives [16, 17, 19], but it does not give any mechanistic explanation. The GSQ auditory subscale probes multiple auditory functions, including aversion to specific, loud, or unpredictable sounds, attraction to specific sounds, and difficulties with speech perception [8]. These difficulties are prevalent in autism but are likely to engage disparate mechanisms, such as auditory brainstem abnormalities, sensory gating deficits, disturbed central gain control, or

broader networks involved in emotional reactions to sounds. Subjective auditory sensitivity did not correspond to altered thresholds for detection or discrimination [33, 34], but the behavioral threshold for discomfort or startle is often lowered in autistic populations (reviewed in O'Connor, [35]). A meta-analysis of an extensive experimental literature on early auditory evoked activity recorded with electro- or magnetoencephalography found group differences in the earliest auditory responses reflecting processing in the primary and secondary auditory cortices [36]. Some aspects of speech perception, such as perception of speech in noise and attentional orienting to speech sounds, may be impaired in autistic individuals and might involve atypical hemispheric lateralization [37]. Specific questions about mechanisms and heritability can be addressed by combining neurophysiological measurements of responses to controlled stimuli and inclusion of first-degree relatives in the study design.

While this study did not address causal relationships between sensory symptoms and QAT, atypical auditory processing in early development may contribute to atypical development of higher-order functions impaired in autism. Auditory difficulties in adulthood may also have direct consequences on social, communicative, and rigid symptoms, e.g., by engaging behavioral homeostatic mechanisms such as rigid adherence to routines or social avoidance to avoid perceptual overload. Self-reported noise sensitivity to a wide range of environmental sounds is considered a stable personality trait and is a significant predictor of individual adverse reactions to sounds [38, 39]. Noise-sensitivity was also found to be correlated with the introversion dimension on the NEO Personality Inventory, which taps a similar construct to BAPQ's Aloof subscale [40, 41]. Similarly, extraversion on the Eysenck Personality Questionnaire was reported to be negatively correlated with noise annoyance [42, 43]. Thus, atypical auditory processing might be a transdiagnostic trait that contributes to disability rather than being specific to autism [44].

Atypical tactile processing was related to higher social QAT, which involves decreased social motivation and less enjoyment of social interactions. This is consistent with some studies exploring associations between social introversion and social touch. For example, self-reported aversion to social touch was found to correlate positively with total QAT [45–47], and parent-reported tactile hypersensitivity predicted an autism diagnosis in children [48]. Further, avoidance of social touch was negatively correlated with extraversion on a personality inventory [46]. The items on the tactile GSQ scale were designed to capture a range of deficits common in autism, ranging from atypical pain, temperature, and touch processing, to disliking haircuts, clothes labels, or hugs. While these items load onto the same latent factor, at least with moderate reliability, it seems unlikely that deficits in these domains are mediated by one mechanism. Tactile detection and discrimination thresholds might be altered in some autistic participants and might be related to E/I imbalances, but findings have been mixed [49–51]. An affective touch fMRI paradigm (slow versus fast stroke) found negative correlations between QAT and BOLD-responses in the superior temporal sulcus and orbitofrontal cortex, suggesting a role for CT-afferents and social brain networks [47]. Another potential mechanism is atypical autonomic reactivity, which was found in response to touch in autistic adults with normal tactile thresholds [49].

We found the proprioception subscale to be a stable and robust predictor of communication QAT across all analyses. It was the only modality-trait relationship that appeared to be as dominant as auditory dysfunction. The proprioception subscale of the GSQ comprises items concerning fine motor skills, interoceptive awareness, and perception of peri-personal space (e.g., standing too close to or too far away from someone), and thus probes a broader sensorimotor construct than its name suggests. Some of the items of the pragmatic subscale of the BAPQ either concern language production (e.g. “I find it hard to get my words out smoothly”/””, or “I speak too loudly or softly”) in addition to higher-order pragmatic language skills. Therefore, further studies should address whether the relationship is specific to motor function or reflects a broader association with higher language functions. In studies of infants, oral and fine motor skills have been found to predict later language capabilities [52–56], suggesting that basic motor development is a prerequisite for higher functions to develop. Our study preliminarily suggests that this association persists into adulthood. Consistent with this, a study on adults in a naturalistic conversation setting found that autistic participants demonstrated lower lexical diversity and produced fewer mouth movements [57]. On a higher cognitive level, a neural overlap was found between syntactic processes and tool use in the basal ganglia, as well as a bidirectional cross-domain transfer of learning between these two skills [58], raising the possibility of motor training to improve language development.

Limitations

The main limitation of this study is the potential shortcomings of the GSQ in measuring sensory symptoms. While the GSQ is suitable for capturing autism-relevant sensory differences as well as measuring these in the general population [8, 9, 27], the subscales contained only six items each and potentially include more than one neural construct. Thus, the results did shed light on the relative roles of sensory modalities in explaining the known correlation between QAT and total sensory scores, but they cannot be used to exclude sensory modalities from further research. Our use of anonymous adults precluded clinical characterization of sensory abnormalities, limiting generalizability beyond English-speaking adults with access to the Internet, who possess the cognitive resources to participate. The dimensional individual differences approach is suitable for this experimental design as it does not rely on formal diagnoses, but it excludes lower-functioning subpopulations of autistic people who may have different patterns of sensory problems. The study relied on self-report of sensory differences and QAT, which has uncertain correspondence to functions that can be measured objectively in the laboratory, such as detection thresholds, attentional reorienting to stimuli, or autonomic reactivity [33, 34, 49, 59].

Conclusions

We found that auditory processing deficits are robustly associated with all QAT domains, suggesting that auditory dysfunction may have endophenotypic properties. The finding adds to the current consensus that auditory dysfunction is highly clinically relevant and closely associated with autistic disorders and subclinical traits. Our study also suggests a novel differentiation of modality-trait associations, whereby

tactile dysfunction predicted atypical social interaction and proprioceptive-motor dysfunction predicted communicative QATs.

List Of Abbreviations

BAPQ: Broad Autism Phenotype Questionnaire; DA: Dominance analysis; GSQ: Glasgow Sensory Questionnaire; SSVS: stochastic search variable selection.

Declarations

Ethics approval and consent to participate. Swedish ethics regulations apply to only research that collects personal data that can be tied to a living person. Since the study only collected anonymous data and minimal demographic details, it was not evaluated by an ethics board. The study was designed in accordance with the Declaration of Helsinki. Participants provided digital informed consent and could exit the study without punishment.

Consent for publication. Not applicable.

Availability of data and materials. The datasets generated and analyzed during the current study (age, gender and subscale scores) are available in the Open Science Framework (OSF) repository (osf.io/a795u/). [Data will become public upon article acceptance.]

Competing interests. The authors declare that they have no competing interests.

Funding. The study was funded by a grant from the Swedish Research Council to KI (2018-02131).

Authors' contributions. PB collected data for Cohort 2, performed DA and SSVS and wrote the first draft. KI collected data for Cohort 1 and supervised the study. The authors co-wrote the paper, and both have approved the final manuscript.

Acknowledgements. We thank Maria Strömberg for her help with data collection for Cohort 1, and Erik Igelström (University of Glasgow) for statistical advice. Thanks also to Dr Joost Wiskerke at Linköping University for constructive feedback on the manuscript.

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Figures

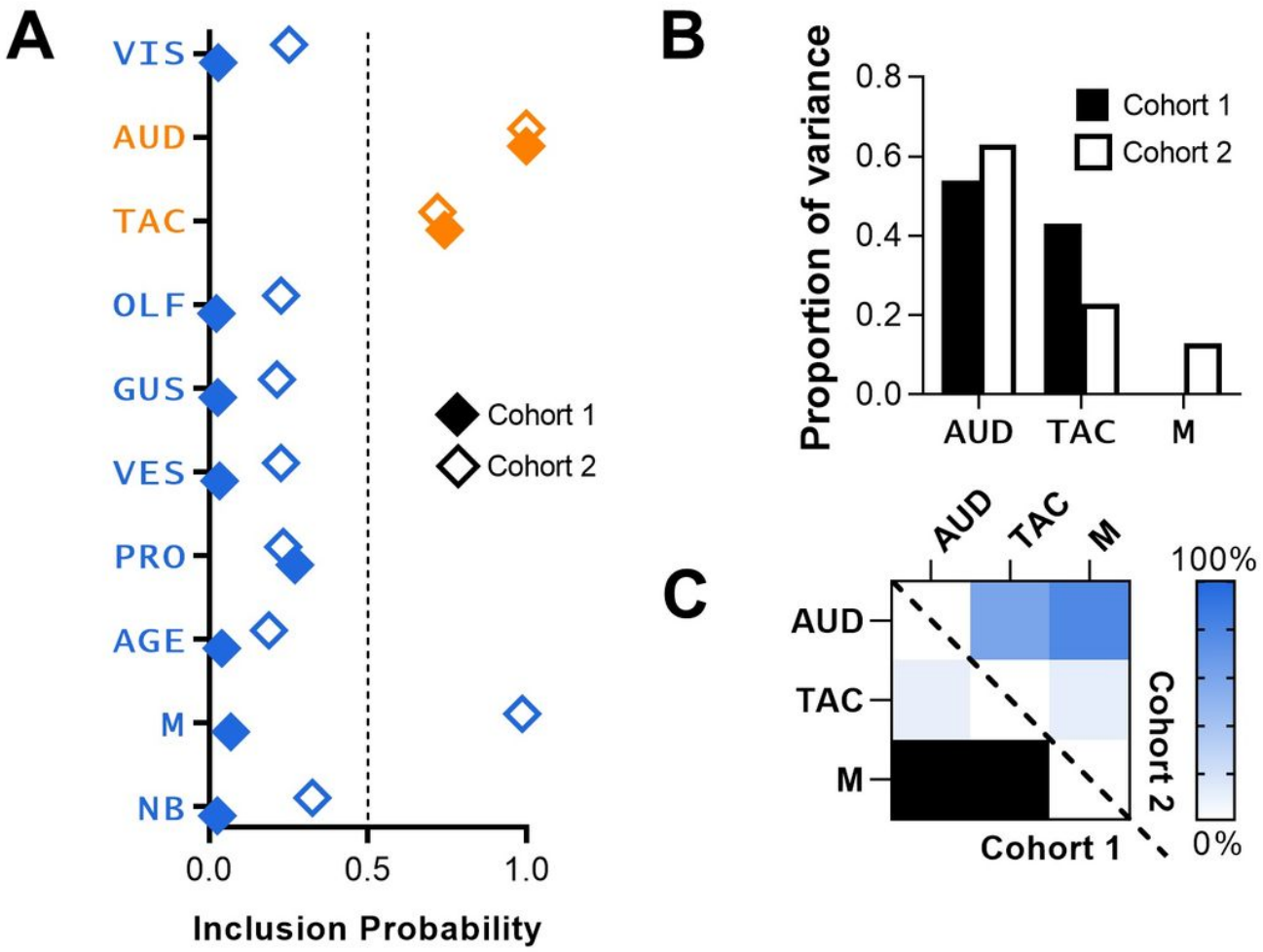

Figure 1

Aloof subscale of the BAPQ: Stochastic search variable selection and dominance analysis. A. Marginal inclusion probabilities for the sensory subscales and covariates for the two independent cohorts. Orange color highlight the predictors that exceeded the inclusion threshold of 0.5 in both cohorts. B. Relative proportions of variance explained by the predictors included in dominance analysis in the two independent cohorts. C. Illustration of the percentage of times that the pairs of predictors were significantly different from each other in the dominance analysis. Black squares indicate that the predictor was not included in the dominance analysis (see Methods for details). The lower triangle shows results for Cohort 1, and the upper triangle shows results for Cohort 2. Abbreviations: AUD, auditory; GUS, gustatory; M, male gender; NB, non-binary gender; OLF, olfactory; PRO, proprioceptive; TAC, tactile; VES, vestibular; VIS, visual.

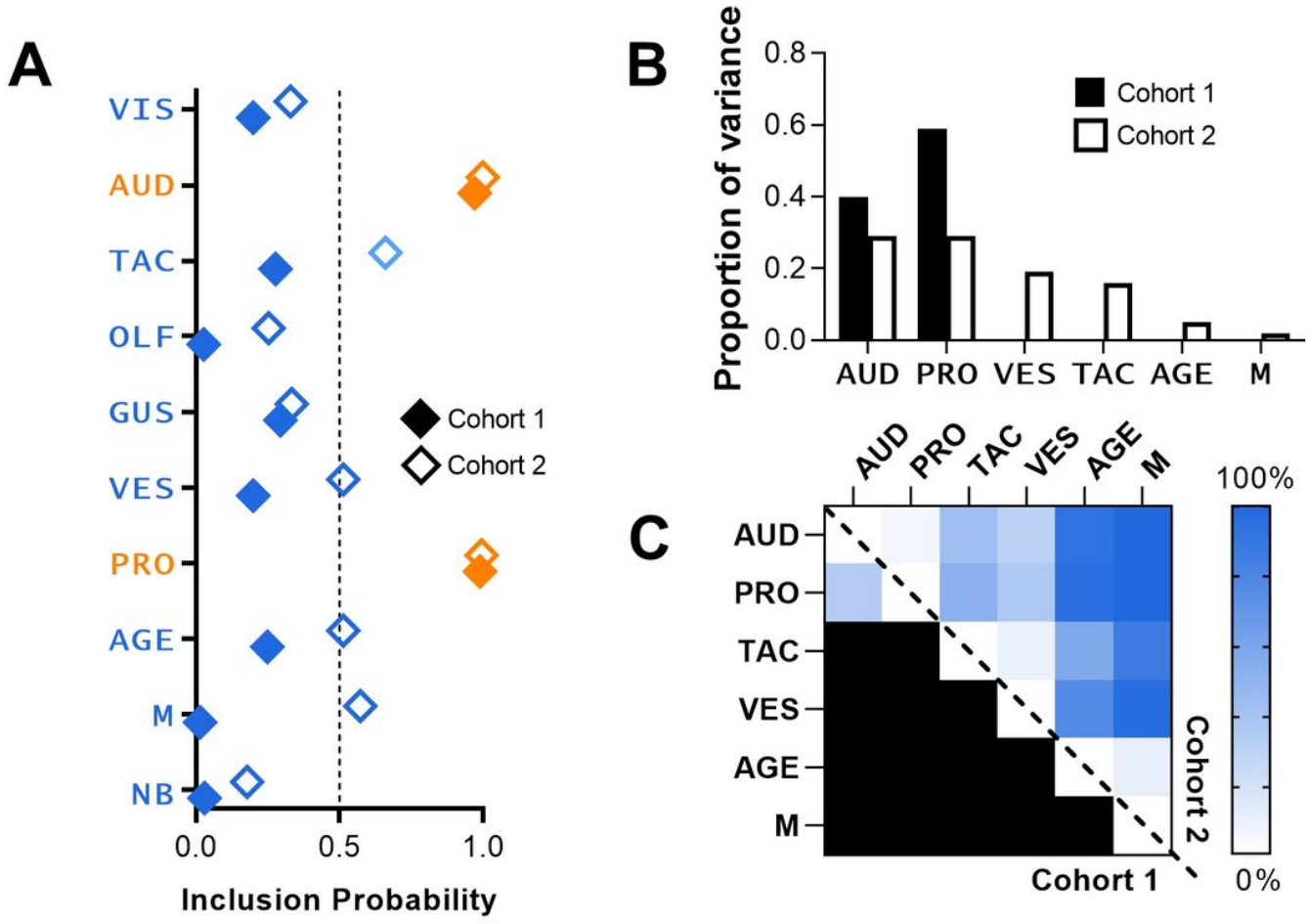

Figure 2

Pragmatic language subscale of the BAPQ: Stochastic search variable selection and dominance analysis. A. Marginal inclusion probabilities for the sensory subscales and covariates for the two independent cohorts. Orange color highlight the predictors that exceeded the inclusion threshold of 0.5 in both cohorts. B. Relative proportions of variance explained by the predictors included in dominance analysis in the two independent cohorts. C. Illustration of the percentage of times that the pairs of predictors were significantly different from each other in the dominance analysis. Black squares indicate that the predictor was not included in the dominance analysis (see Methods for details). The lower triangle shows results for Cohort 1, and the upper triangle shows results for Cohort 2. Abbreviations: AUD, auditory; GUS, gustatory; M, male gender; NB, non-binary gender; OLF, olfactory; PRO, proprioceptive; TAC, tactile; VES, vestibular; VIS, visual.

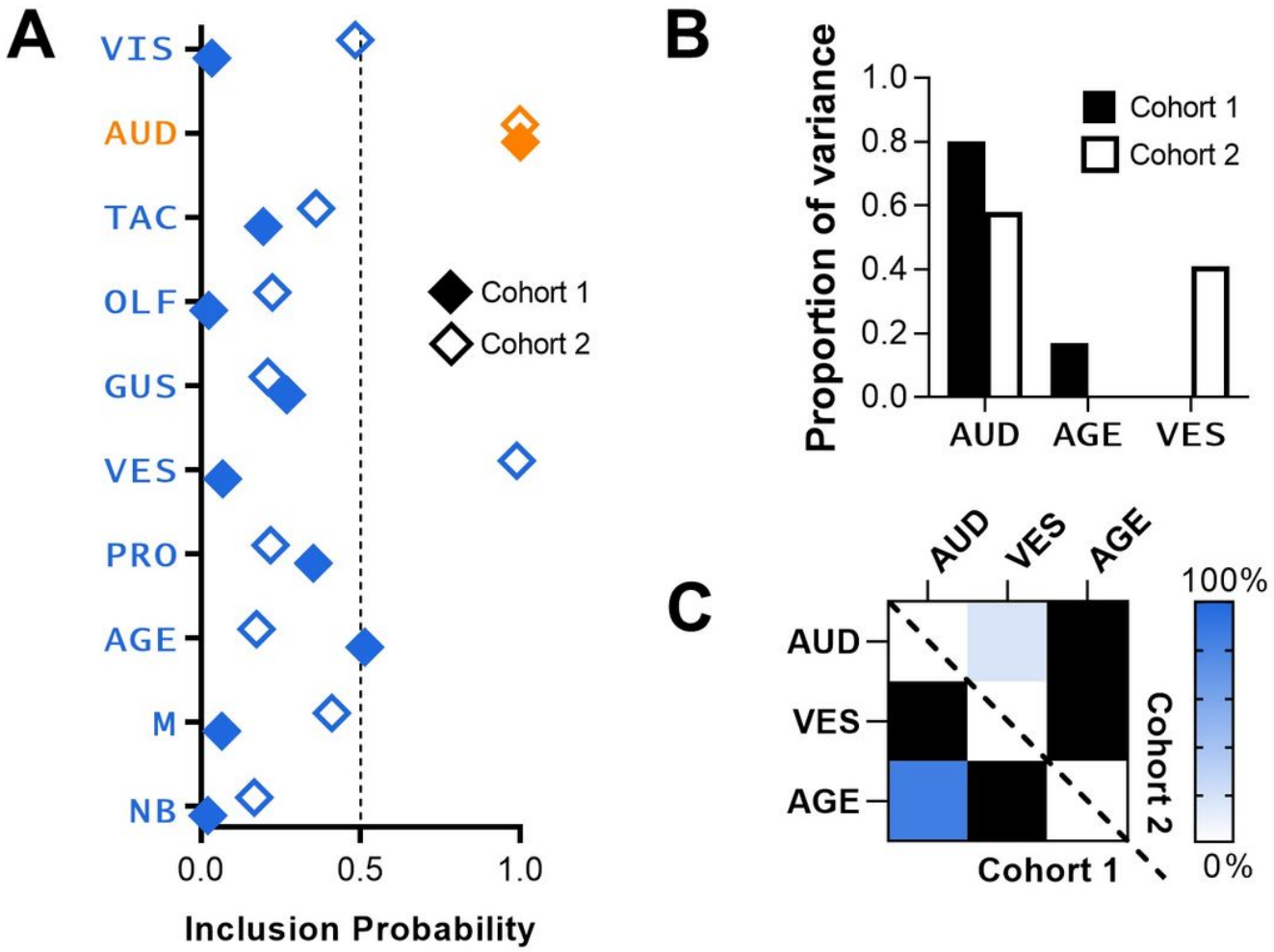

Figure 3

Rigid subscale of the BAPQ: Stochastic search variable selection and dominance analysis. A. Marginal inclusion probabilities for the sensory subscales and covariates for the two independent cohorts. Orange color highlight the predictors that exceeded the inclusion threshold of 0.5 in both cohorts. B. Relative proportions of variance explained by the predictors included in dominance analysis in the two independent cohorts. C. Illustration of the percentage of times that the pairs of predictors were significantly different from each other in the dominance analysis. Black squares indicate that the predictor was not included in the dominance analysis (see Methods for details). The lower triangle shows results for Cohort 1, and the upper triangle shows results for Cohort 2. Abbreviations: AUD, auditory; GUS, gustatory; M, male gender; NB, non-binary gender; OLF, olfactory; PRO, proprioceptive; TAC, tactile; VES, vestibular; VIS, visual.