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ORIGINAL PAPER

The Relationship Between Autistic Traits and Atypical Sensory Functioning in Neurotypical and ASD Adults: A Spectrum Approach

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Abstract Sensory processing atypicalities are a common feature in Autism Spectrum Disorders (ASD) and have previously been linked to a range of behaviours in individuals with ASD and atypical neurological development. More recently research has demonstrated a relationship between autistic traits in the neurotypical (NT) population and increased levels of atypical sensory behaviours. The aim of the present study is to extend previous research by examining specific patterns across aspects of autistic traits and sensory behaviours within both ASD and NT populations. The present study recruited 580 NT adults and 42 high-functioning ASD adults with a confirmed diagnosis to investigate the relationship between specific aspects of autistic traits and sensory processing using the subscales of the autism spectrum quotient (AQ) and adult/adolescent sensory profile (AASP). Results showed a significant relationship between all subscales except for attention to detail and imagination on the AQ and provided the first evidence that the strength and pattern of this relationship is identical between NT and ASD adults. These data also provided support for the broader autism phenotype, uncovering a clear progression of sensory atypicalities in line with an increase in autistic traits, regardless of diagnostic status, which has potential implications for the spectrum approach to ASD and how sensory behaviours across the whole of the neurotypical population are conceptualised.

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Introduction

Autism Spectrum Disorder (ASD) is a pervasive neurodevelopmental disorder based on a dyad of impairments in the domains of social communication and restricted/repetitive interests and behaviours (APA 2013). Whilst not specifically mentioned in previous diagnostic criteria (e.g. APA 2000), the most recent edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) has included atypical sensory behaviours within the criteria under the cluster of restricted, repetitive patterns of behaviour (APA 2013). Indeed, prior to their inclusion within the diagnostic criteria, sensory atypicalities were widely reported in ASD (e.g. Leekam et al. 2007) with original reports by Kanner (1943) and Asperger (1944/1991) noting abnormal responses to sensory stimulation (Minshew and Hobson 2008).

Atypical sensory behaviours have been noted in empirical studies (e.g. Marco et al. 2011) as well as autobiographical accounts (e.g. Grandin 1992) of ASD. These atypicalities affect an estimated 60–95 % of individuals with ASD (Kern et al. 2007; Crane et al. 2009) and can include atypical auditory processing, insensitivity to pain and atypical responses to visual and olfactory stimuli (Gerland 2003). Sensory atypicalities are apparent across the spectrum including Asperger syndrome (Dunn et al. 2002) and in childhood (Tomchek and Dunn 2007) through to adulthood (Crane et al. 2009), although there is some evidence to suggest that sensory atypicalities may decrease with age (Kern et al. 2006). There is an increasing consensus that such atypicalities are likely to have an impact on the development of a range of abilities including social and cognitive abilities due to an increased avoidance of social stimuli (Ben-Sasson et al. 2007).

An increasing proportion of the population is impacted by ASD, with the most recent CDC data estimating that as many as one in 68 individuals in the United States has an ASD (Christensen 2016). However, behaviours and cognitive styles that were once considered to be characteristic of this specific diagnostic group of individuals are now conceptualised as part of a broad range of individual differences that are distributed throughout the general population (Constantino and Todd 2003). Researchers and clinicians have increasingly embraced the idea that as a spectrum disorder, ASD lies on a continuum that extends into the neurotypical (NT) population. Thus, autistic traits are exhibited by NT individuals, albeit at lower levels of severity. Given this assertion, it is plausible to suggest that some of the behaviours observed in and reported by individuals with ASD may also be evident, to a lesser extent, in NT individuals who possess higher levels of autistic traits.

The Adult Autism Spectrum Quotient (AQ) (Baron-Cohen et al. 2001) has been utilised in numerous studies examining the effects of high levels of autistic traits on behaviours in the NT population. High scores on the AQ in NTs have been shown to be strongly related to higher levels of clumsiness (Moruzzi et al. 2011), lower relationship satisfaction in husbands (Pollmann et al. 2010) and even gender identity disorder in females (Jones et al. 2012). Higher levels of autistic traits in NT individuals have also been linked to cognitive performance including a reduced influence from lexical information during speech perception (Stewart and Ota 2008). Furthermore, atypical neurological development, including reduced left hemisphere dominance (Lindell and Withers 2008) and decreased white matter in the posterior superior temporal sulcus (STS) that is implicated in processing social stimuli (von dem Hagen et al. 2011), has been linked to increased autistic traits. These findings suggest that research examining NT individuals with a broad range of autistic traits is a fruitful way to increase our understanding of the ASD continuum.

Sensory atypicalities occur on a continuum. Traditionally theories of sensory processing have suggested hyper-responsiveness lies at one end, referring to the sensory channel being too open, hence there is too much stimulation for the brain to cope with. At the other end of the continuum is hypo-responsiveness where the sensory channel is too narrow, suggesting too little simulation is getting to the brain (Dunn 1997). More recently researchers have expanded this description to include two additional distinct behavior patterns: (1) sensory interests, repetitions and seeking behaviours and (2) enhanced perception (Baranek et al. 2014). Although these four categories are considered to be distinct patterns of sensory behaviours empirical studies (e.g. Baranek et al. 2006; Ben-Sasson et al. 2007, 2009) have demonstrated they coexist in a heterogeneous fashion that may underlie some of the heterogeneity seen in the presentation of ASD. In particular the co-occurrence of hyper- and hypo- responsiveness has been frequently reported in ASD (e.g. Baranek et al. 2006; Ben-Sasson et al. 2007) and are often associated with increased sensory seeking behaviours (Dunn 1997). Enhanced perception, on the other hand, may lead to hyper-responsiveness (Mottron et al. 2006) but is not necessarily co-occurring (Ausderau et al. 2014).

Recent studies have linked autistic traits in the neurotypical population to atypical sensory behaviours in various modalities including visual processing (Bayliss and Kritikos 2011; Sutherland and Crewther 2010) and speech perception (Stewart and Ota 2008) and atypical neurological responses to touch (Voos et al. 2013). In an fMRI study, Voos et al. (2013) found that NT individuals with high levels of autistic traits reported more of an aversion to social touch along with reduced activation of the right STS and the right orbital frontal cortex (OFC) during gentle touch. Voos et al. (2013) interpreted these findings as evidence for an association between autistic traits and a disruption in social brain function in NT individuals, which goes beyond the behavioural links demonstrated in previous research.

Four studies to date have specifically examined self-reported sensory functioning and autistic traits in NT individuals. Robertson and Simmons (2013) reported a strong correlation between autistic traits and atypical hypo- and hyper-sensory responsiveness [measured by the Glasgow Sensory Questionnaire (GSQ)] in a predominately NT adult population with two individuals (out of 270 recruited) self-reporting an ASD diagnosis. These findings were replicated by Horder, Wilson, Mendez and Murphy (2014) using the GSQ, the Adult/Adolescent Sensory Profile (AASP) and the Cardiff Anomalous Perception Scale (CAPS), with a similar relationship reported between autistic traits and sensory atypicalities, albeit with a lower significance level. This study contained NT participants and adults who had a self-reported ASD diagnosis, although diagnostic data was not confirmed. Takayama et al. (2014) also examined atypical sensory behaviours in a group of 64 adults with ASD and 70 NT adults during their validation of the Japanese version of the GSQ. They replicated Robertson and Simmons' (2013) and Horder et al. (2014) findings of a strong, positive correlation between self-reported sensory atypicalities and autistic traits in both the NT and ASD populations. Furthermore, their study extended previous findings reporting positive correlations between the subscales of the AQ and GSQ and total levels of sensory atypicalities and autistic traits respectively. Similarly, Tavassoli et al. (2014) demonstrated a positive correlation between autistic traits and self-reported sensory atypicalities in both NT and ASD adults on the Sensory Perception Quotient, a new measure of sensory perception they were validating. Further studies (e.g. Mayer and Heaton 2014; Mayer et al. 2014) have provided evidence of strong correlations between autistic traits and atypical sensory behaviours in both NT and ASD groups, however this was a side note within the background data screening.

The aim of the present study is to further the findings of Robertson and Simmons (2013) and Horder et al. (2014) by examining the relationship between specific aspects of the autistic trait profile and sensory behaviours with a direct analysis of the subscales of the AQ and AASP in a NT population and ASD individuals with an Autism Diagnostic Observation Schedule (ADOS) confirmed diagnosis. In order to extend Takayama et al.'s (2014) findings, the relationship between subscales of the AQ and AASP within each group will be statistically compared to examine whether a similar relationship between autistic traits and sensory behaviours exists in NT and ASD populations. Finally, the present study aimed to directly examine the broader autism phenotype (Constantino and Todd 2003) by splitting the neuortypical individuals into two groups, based on high and low levels of autistic traits, and comparing their autistic trait profiles and sensory behaviour profiles with those in the ASD group.

Methods

Participants

Neurotypical Participants

591 NT participants, 397 females and 194 males (Mean age = 23.56; SD = 8.73) were recruited from the general population through the student research participation scheme at the University of Roehampton or via Facebook and other social media sites. Participants either received research participation credit or were entered to win one of five £25 Amazon vouchers. Baron-Cohen et al. (2001) suggested that a score of 32+ is a useful cut off for distinguishing individuals who have clinically significant levels of autistic traits. Thus, in order to decrease the likelihood that typically developing participants may have clinically significant levels of autistic traits Baron-Cohen et al. (2001) suggested cut off score of 32+ was employed and those participants were removed from the analyses. In order to avoid the possibility of artificially influencing the results by removing participants with a higher level of autistic traits from the typically developing sample, analyses were conducting with and without these participants. Their removal did not impact the patterns or significance levels of the results reported in the next section. Thus, 580 typically developing participants, 392 females (67.6 %) and 188 males (32.4 %), were retained. The ages of the final sample ranged from 18 to 76 with a mean age of 23.49 (SD = 8.64).

ASD Participants

42 high-functioning adults with ASD, 14 females (33.3 %) and 28 males (66.6 %), participated. Their ages ranged from 19 to 61 with a mean age of 35.07 (SD = 12.38). The participants in the ASD group were part of a larger research project at the University of Roehampton, London, UK and as such received £8 per hour for their time. All of the ASD individuals who participated in this study had previously been diagnosed by clinicians in accordance the with *Diagnostic and Statistical Manual of Mental Disorders* [5th ed. (or equivalent]; American Psychiatric Association 2013). ASD participants' pre-existing diagnoses were confirmed by administering the ADOS (Lord et al. 2001).

In order to further characterise the ASD group the Weschler Abbreviated Scales of Intelligence (WASI) (Wechsler 1999) was used as a measure of intellectual and cognitive functioning. The WASI is made up of four subtests with Vocabulary and Similarities resulting in a verbal IQ score (VIQ), Block Design and Matrix Reasoning producing a performance IQ score (PIQ) and their combined scores generating an individual's full-scale IQ score (FSIQ). The FSIQ ranged from 78 to 134 (Mean = 110.21, SD = 16.25), VIQ ranged from 71 to 132 (Mean = 108.21, SD = 15.89) and PIQ ranged from 75 to 134 (Mean = 110.13, SD = 15.40).

Materials

Adult Autism Spectrum Quotient

In order to assess self-reported levels of autistic traits the Adult Autism Spectrum Quotient (AQ) (Baron-Cohen et al. 2001) was administered. The AQ is a 50 item questionnaire that examines five factors: Social Skills ("I would rather go to a library than a party"), Attention Switching ("I frequently get so absorbed in one thing that I lose sight of other things"), Attention to Detail ("I often notice small sounds when others do not"), Communication ("Other people frequently tell me that what I've said is impolite, even though I think it is polite") and Imagination ("When I'm reading a story, I find it difficult to work out the characters' intentions"). For each question participants were instructed to indicate the level to which they agreed with the statement: definitely agree, slightly agree, slightly disagree and definitely disagree. Participants received one point each time they reported autistic-like behaviour either mildly or strongly. The total possible score ranged from 0 to 50 with possible individual subscale scores ranging from 1 to 10. Within the AQ autistic-like behaviour is characterised by poor social, communication, or imagination skills, exceptional attention to detail and either poor attention switching or a strong focus of attention (Baron-Cohen et al. 2001).

Adult/Adolescent Sensory Profile

In order to obtain a measure of sensory behaviours the Adult/Adolescent Sensory Profile (AASP) (Brown and Dunn 2002) was administered. The AASP is a 60-item questionnaire that examines sensory functioning patterns across six sensory modalities including: taste/smell, movement, visual, touch, activity and auditory processing. Participants' raw scores across the six categories were used to derive their quadrant scores identified as: Low Registration ("I don't smell things that other people say they smell"), Sensation Seeking ("I like to wear colourful clothing"), Sensory Sensitivity ("I am distracted if there is a lot of noise around") and Sensation Avoiding ("I stay away from crowds"). The four quadrants of the AASP are based on Dunn's (1997) model of sensory functioning in which there are two neurological stimulation thresholds (high and low) and there are two self-regulation strategies (active and passive). Each quadrant represents a sensory functioning style characterised by one type of neurological stimulation threshold and one self-regulation strategy resulting in the following: Low Registration (high, passive), Sensation Seeking (high, active), Sensory Sensitivity (low, passive) and Sensation Avoiding (low, active). For each question participants were instructed to indicate whether the statement applied to them almost never, seldom, occasionally, frequently, or almost always. The total possible score ranged from 60 to 300 with possible individual quadrant scores ranging from 15 to 75. Higher scores within each quadrant represented increased sensory abnormalities. Participants' overall quadrant scores as well as their total score were obtained for analysis.

Procedure

Ethical approval for this study was obtained from the ethics committee at the University of Roehampton. Participants completed the study using Qualtrics, an online survey software. The questionnaires were administered in a randomised order to prevent testing fatigue and individual answers being influenced by the previous questionnaire. The order of questions within individual questionnaires remained faithful to the pen and paper versions to maintain validity. Qualtrics required participants to answer each question before moving on to the next page, thus there was no missing data for any individuals in this study. Participants who wished to abstain from particular questions withdrew themselves from the study and their incomplete data was not included in the dataset.

Results

Relationship Between Autistic Traits and Sensory Atypicalities

The means, standard deviations and ranges of the AQ total and subscale scores as well as the AASP total and subscale scores for the NT and ASD groups are presented in Table 1.

In order to examine the relationship between autistic traits and sensory functioning in high-functioning adults with ASD, bivariate correlations were conducted on the total and subscale scores for the AQ and sensory profile (Table 2). In general, the correlations demonstrated a significant positive correlation between autistic traits and sensory functioning in adults with ASD, with

Table 1 NT and ASD participant AQ and AASP means, SDs and ranges

	NT (N = 580)		ASD (N = 42)	
	Mean (SD)	Range	Mean (SD)	Range
AQ-total (0–50)	16.08 (5.53)	2–31	34.26 (7.34)	18–47
AQ-social skills (0–10)	1.94 (1.85)	0–9	6.24 (2.19)	2–10
AQ-attention switching (0–10)	4.64 (1.95)	0–10	7.63 (2.00)	3–10
AQ-attention to detail (0–10)	4.96 (2.18)	0–10	7.39 (1.69)	1–10
AQ-communication (0–10)	2.41 (1.74)	0–10	6.71 (2.44)	2–10
AQ-imagination (0–10)	2.14 (1.61)	0–8	6.34 (2.30)	2–10
AASP-total (60–300)	157.74 (20.93)	100–233	175.60 (23.46)	130–218
AASP-low registration (15–75)	35.35 (8.17)	17–59	40.95 (9.33)	24–62
AASP-sensation seeking (15–75)	47.02 (7.46)	28–69	41.83 (9.55)	16–63
AASP-sensory sensitivity (15–75)	38.40 (8.07)	17–61	46.19 (9.87)	22–62
AASP-sensation avoiding (15–75)	36.98 (7.84)	17–64	46.62 (8.34)	31–63

ASD autism spectrum disorders, *NT* neurotypical

Table 2 Bivariate and partial correlations between AQ and AASP

	Bivariate correlations						Partial correlations					
	AQ total	Social skills	Att. switch	Att. to detail	Comm.	Imag.	AQ total	Social skills	Att. switch	Att. to detail	Comm.	Imag.
ASD												
AASP-total	0.374*	0.373*	0.403**	0.018	0.351*	0.107	0.308*	0.318*	0.369*	−0.012	0.307*	0.038
Low registration	0.315*	0.422**	0.363*	−0.106	0.310*	0.043	0.309*	0.426**	0.355*	−0.100	0.312*	0.016
Sensation seeking	−0.473**	−0.488**	−0.196	−0.162	−0.433**	−0.307	−0.423**	−0.431**	−0.118	−0.182	−0.421**	−0.242
Sensory sensitivity	0.557***	0.515**	0.489**	0.098	0.514**	0.262	0.485**	0.438**	0.432**	0.085	0.481**	0.170
Sensation avoid	0.580***	0.533***	0.378*	0.236	0.534***	0.295	0.501***	0.455**	0.308*	0.219	0.498***	0.194
Neurotypical												
AASP-total	0.315***	0.185***	0.330***	0.112**	0.347***	−0.060	0.310***	0.179***	0.320***	0.094*	0.352***	−0.037
Low registration	0.234***	0.151***	0.223***	−0.026	0.386***	−0.025	0.226***	0.146***	0.204***	−0.048	0.392***	−0.001
Sensation seeking	−0.275***	−0.305***	−0.176***	−0.024	−0.108**	−0.209***	−0.270***	−0.302***	−0.175***	−0.015	−0.104**	−0.211***
Sensory sensitivity	0.355***	0.225***	0.371***	0.128**	0.298***	−0.002	0.353***	0.219***	0.368***	0.108**	0.304***	−0.024
Sensation avoid	0.495***	0.395***	0.437***	0.219**	0.320***	0.070	0.491***	0.393***	0.433***	0.204***	0.320***	0.085*

*p < .05; **p < .01; ***p < .001

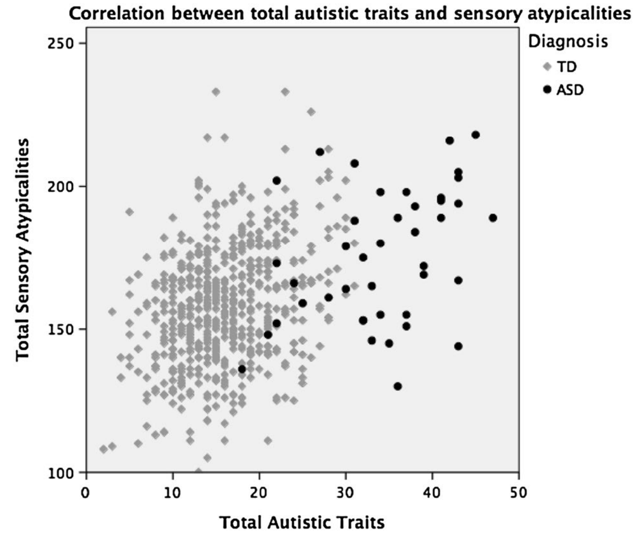

Fig. 1 Correlation between total autistic traits (measured by the AQ) and total sensory atypicalities (measured by the AASP)

higher levels of autistic traits related to higher levels of sensory functioning atypicalities. Notably, the AQ subscales of Attention to Detail and Imagination were not correlated with any AASP subscale scores or total level of atypical sensory behaviours. Thus, increased attention to detail and difficulties with imagination do not appear to be related to sensory functioning atypicalities. Additionally, the AASP subscale of Sensation Seeking was found to negatively correlate with AQ scores, suggesting that lower levels of autistic traits are related to higher levels of sensation seeking behaviours in high-functioning adults with ASD.

In order to examine the relationship between autistic traits and sensory functioning in NT adults, Pearson's bivariate correlations were conducted on the total and subscale scores for the AQ and sensory profile (Table 2). Similar patterns of correlations to those within the ASD group were found in the typically developing adults. In general, there were significant positive correlations between autistic traits and sensory functioning, demonstrating higher levels of autistic traits are related to higher levels of sensory functioning abnormalities within the NT population (Fig. 1). Notably, the AQ subscale of Attention to Detail was only correlated with AASP Total scores, Sensory Sensitivity and Sensation Avoiding, and the AQ subscale of Imagination was only correlated with the AASP subscales of Sensation Seeking and Sensation Avoiding. Thus, increased attention to detail and restricted imagination only appear to be related to some aspects of abnormal sensory functioning. Furthermore, the AASP subscale of Sensation Seeking was found to negatively correlate with AQ scores, suggesting that lower levels of autistic traits in the NT population are related to higher levels of sensation seeking behaviours, similar to the pattern seen in the ASD group.

Independent samples t-tests were conducted to examine the gender and age variables in the ASD and TD groups. Levene's test for equality of variances was found to be violated for the age variable, $F(1620) = 23.93$, $p < .001$, therefore a t-statistic not assuming homogeneity of variance was computed for this variable. Significant group differences were found between the two groups in participant age ($t(620) = 4.57$, $p < .001$) as well as gender ($\chi(1) = 19.09$, $p < .001$). The NT group was significantly younger and contained more females than the ASD group. Partial correlations were conducted to control for potential effects due to between group differences in age and gender. The pattern and strength of the correlations did not differ between the two sets of correlations, indicating that gender and age did not significantly impact the results.

To test for potential difference between the relationship between autistic traits and sensory functioning in adults with ASD and NT adults, the correlations were transformed into z-scores using Fisher's *r*-to-*z* transformation. For each correlation, z-scores based on the difference between the values for each of the two groups and the variance of the difference between the two scores were obtained and a two-tailed test of significance was conducted (Table 3). The positive correlation between levels of autistic traits on the social skills subscale of the AQ and sensory atypicalities on the Sensory Sensitivity subscale of the AASP was found to be significantly stronger in NT adults than in adults with ASD ($z = 2.06$, $p < .05$). Additionally, the negative correlation between levels of autistic traits on the Communication subscale of the AQ and sensory atypicalities on the Sensation Seeking subscale of the AASP was found to be significantly stronger in adults with ASD than in NT adults ($z = -2.15$, $p < .05$). There were no significant differences in any of the other correlations between AQ scores and AASP scores in the two groups. This suggests that there is a similar relationship between autistic traits and sensory abnormalities in high-functioning adults with ASD and NT adults.

Broader Autism Phenotype

In order to further address the assertion that autistic traits exist on a continuum throughout the typical population, a median split was used to divide the NT group into low AQ (scores between 0 and 15) and high AQ (scores between 16 and 31) groups and compared to the ASD group, which remained unchanged. The low AQ group consisted of 286 participants, 192 females (67.1 %) and 94 males (32.9 %), and the ages ranged from 18 to 71 with a mean age of 24.08 (SD = 9.01). Similarly, the high AQ group consisted of 294 participants, 200 females (68.0 %) and 94 males (32.0 %), and the ages ranged from 18 to 76 with a mean age of 22.91 (SD = 8.25).

A one-way ANOVA with Bonferroni corrected post-hoc tests was conducted to examine whether the gender and age variables differed between the three groups. Significant group differences were found in participant age ($F(2) = 34.17$, $p < .001$) as well as gender ($F(2) = 10.45$, $p < .001$). There was no significant difference between the high and low AQ groups on age ($p = .35$) or gender ($p = .99$), however both groups differed significantly from the ASD group on age and gender ($ps < 0.001$). The high and low AQ groups were significantly younger and contained more females than the ASD group. Therefore in all analyses below age and gender are entered as covariates. The means, standard deviations and ranges for AQ and AASP scores in the NT low AQ, NT high AQ, and ASD groups are reported in Table 4.

Significant group differences in the levels of autistic traits were found, when controlling for the effects of age and gender, on total AQ scores $F(2) = 842.94$, $p < .001$, partial $\eta^2 = 0.73$ as well as on the five factors of the AQ: Social Skills ($F(2) = 232.55$, $p < .001$, partial $\eta^2 = 0.43$), Attention Switching ($F(2) = 157.74$, $p < .001$, partial $\eta^2 = 0.34$), Attention to Detail ($F(2) = 103.67$, $p < .001$, partial $\eta^2 = 0.25$), Communication ($F(2) = 217.05$, $p < .001$, partial $\eta^2 = 0.41$) and Imagination ($F(2) = 152.36$, $p < .001$, partial $\eta^2 = 0.33$) (Fig. 2). Post hoc pairwise comparisons demonstrated that the ASD group scored significantly higher than both of the NT groups and the low AQ group scored significantly lower than the ASD and high AQ group on all

Table 3 Fischer's r-to-z analysis of AQ and AASP correlations in ASD and NT groups

	AQ total	Social skills	Att. switch	Att. to detail	Comm.	Imag.
AASP-total	Z = 0.40, p = .69	Z = 1.24, p = .22	Z = 0.51, p = .61	Z = −0.57, p = .57	Z = 0.03, p = .98	Z = 1.01, p = .31
Low registration	Z = 0.53, p = .60	Z = 1.80, p = .07	Z = 0.93, p = .35	Z = −0.49, p = .62	Z = −0.52, p = .60	Z = 0.41, p = .68
Sensation seeking	Z = −1.40, p = .16	Z = −1.32, p = .19	Z = −0.13, p = .90	Z = − 0.84, p = .40	Z = −2.15, p < .05*	Z = −0.64, p = .52
Sensory sensitivity	Z = 1.56, p = .12	Z = 2.06, p < .05*	Z = 0.88, p = .38	Z = −0.18, p = .86	Z = 1.58, p = .11	Z = 1.63, p = .10
Sensation avoid	Z = 0.72, p = .47	Z = 1.07, p = .28	Z = −0.43, p = .67	Z = 0.11, p = .91	Z = 1.60, p = .11	Z = 1.41, p = .16

*p < .05; **p < .01; ***p < .001

Table 4 Low AQ, high AQ and ASD participant AQ and AASP means, SDs and ranges

	NT low AQ N = 286		NT high AQ N = 294		ASD N = 42	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
AQ-total (0–50)	11.59 (2.80)	2–15	20.46 (3.73)	16–31	34.26 (7.34)	18–47
Social skills	0.94 (1.04)	0–4	2.92 (1.95)	1–9	6.24 (2.19)	2–10
Attention switching	3.63 (1.64)	0–8	5.61 (1.73)	0–10	7.63 (2.00)	3–10
Attention to detail	3.97 (2.07)	0–9	5.91 (1.84)	0–10	7.39 (1.69)	1–10
Communication	1.53 (1.20)	0–5	3.28 (1.63)	0–10	6.71 (2.44)	2–10
Imagination	1.55 (1.33)	0–7	2.72 (1.66)	0–8	6.34 (2.30)	2–10
AASP-tot (60–300)	153.14 (20.06)	100–233	162.23 (20.82)	111–233	175.60 (23.46)	130–218
Low registration	34.09 (7.52)	17–55	36.58 (8.60)	18–59	40.95 (9.33)	24–62
Sensation seeking	48.86 (7.30)	28–69	45.22 (7.18)	29–69	41.83 (9.55)	16–63
Sensory sensitivity	36.33 (7.61)	17–56	40.41 (8.00)	19–61	46.19 (9.87)	22–62
Sensation avoiding	33.86 (6.91)	17–62	40.01 (7.51)	22–64	46.62 (8.34)	31–63

ASD autism spectrum disorders, *NT* neurotypical

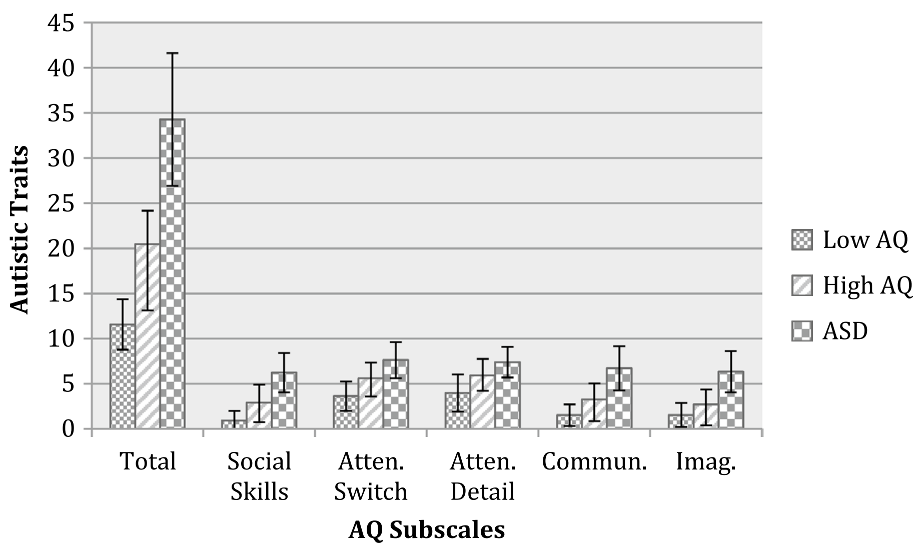

Fig. 2 Main effect of group on self-reported levels of autistic traits. Note: *Error bars* represent standard deviations

of the AQ subscales (all ps < 0.001, Bonferroni corrected). These analyses demonstrate that differences in overall levels of autistic traits are not distinguished by extreme differences on a particular aspect of autistic symptomatology (i.e. social skills) but rather are representative of a similar pattern across all AQ subscales. These finding further supports the broader autism phenotype.

In order to further explore the similarity of the patterns in Fig. 2, Pearson's bivariate correlations were carried out between the total score and five subscales of the AQ. When all of the groups are combined, strong positive correlations are seen between all facets of autistic traits measured by the AQ. However, when these same correlations were separately carried out on the ASD, high AQ and low AQ groups differences in the pattern and strength of these relationships emerged (Table 5). Most notably, both NT groups were characterised by a negative correlation between the Attention to Detail subscale and the Social Skills and Attention Switching subscales, whereas in the ASD group the correlation between these subscales was not significant. A similar discrepancy between the groups is also seen in the correlations between the Imagination subscale and the Attention Switching, Attention to Detail and Communication subscales.

The groups also differed significantly, when controlling for the effects of age and gender, on their Total Sensory Profile scores ($F(2) = 40.78$, $p < .001$, partial $\eta^2 = 0.12$) as well as their scores on all of the four quadrants, Low Registration ($F(2) = 26.10$, $p < .001$, partial $\eta^2 = 0.08$), Sensation Seeking ($F(2) = 96.80$, $p < .001$, partial $\eta^2 = 0.24$), Sensory

Table 5 Correlations between AQ subscales in low AQ, high AQ and ASD groups

	Total	Social skills	Attention switching	Attention to detail	Comm.	Imag.
All groups						
Total	1	0.797***	0.688***	0.532***	0.776***	0.654***
Social skills		1	0.501***	0.179***	0.629***	0.432***
Attention switching			1	0.206***	0.425***	0.239***
Attention to detail				1	0.207***	0.189***
Communication					1	0.402***
ASD						
Total	1	0.832***	0.718***	0.419**	0.800***	0.663***
Social skills		1	0.564***	0.082	0.687***	0.425**
Attention switching			1	0.303	0.377*	0.289
Attention to detail				1	0.186	0.081
Communication					1	0.401**
High AQ						
Total	1	0.638***	0.419***	0.155**	0.601***	0.250***
Social skills		1	0.208***	−0.259***	0.348***	−0.039
Attention switching			1	−0.151**	0.093	−0.252***
Attention to detail				1	−0.183**	−0.093***
Communication					1	−0.028
Low AQ						
Total	1	0.354***	0.473***	0.383***	0.392***	0.339***
Social skills		1	0.075	−0.264***	0.151*	0.155**
Attention switching			1	−0.142*	0.051	−0.080
Attention to detail				1	−0.213***	−0.174**
Communication					1	−0.064

*p < .05; **p < .01; ***p < .001

Sensitivity ($F(2)=26.91$, $p<.001$, partial $\eta^2=0.08$), and Sensation Avoiding ($F(2)=51.51$, $p<.001$, partial $\eta^2=0.14$) (Fig. 3). Post hoc pairwise comparisons demonstrated that the ASD group had significantly higher scores than both of the NT groups and the low AQ group had significantly lower scores than the ASD and high AQ groups (all ps < 0.001, Bonferroni corrected), on all but one subscale, indicating that the broader autism phenotype also applies to sensory abnormalities. Interestingly, the low AQ group reported significantly higher sensation seeking behaviours than the high AQ and ASD group (ps < 0.001, Bonferroni corrected) and the high AQ group also reported significantly higher sensation seeking behaviours than the ASD group ($p<.01$, Bonferroni corrected). Whilst this still supports the continuum approach, it also suggests that lower sensation seeking behaviours may be characteristic of individuals with increased autistic symptomatology.

Discussion

The present study provided the first evidence that the strength and pattern of the relationship between autistic traits and sensory functioning does not differ between NT and ASD adults, replicated findings that atypical sensory behaviours are present in both NT and ASD populations (Horder et al. 2014; Robertson and Simmons 2013; Takayama et al. 2014), and demonstrated that this relationship was present across all sensory quadrants and aspects of autistic traits. The present study also provided support for the broader autism phenotype, uncovering a clear progression of atypical sensory behaviours in line with an increase in autistic traits, regardless of diagnostic status.

An analysis of the relationship between subscales of the AQ and AASP in NT and ASD adults uncovered a general pattern of positive correlations between autistic traits and sensory functioning, with higher levels of autistic traits related to higher levels of sensory functioning atypicalities. However, the lack of significant correlations between the AQ subscales of Attention to Detail and Imagination and any AASP subscale scores or total level of sensory functioning atypicalities suggests that increased attention to detail and difficulties with imagination are not related to atypical sensory behaviours. Previous literature (e.g. Robertson and Simmons 2013) has linked sensory atypicalities in the visual and auditory domains to a local processing

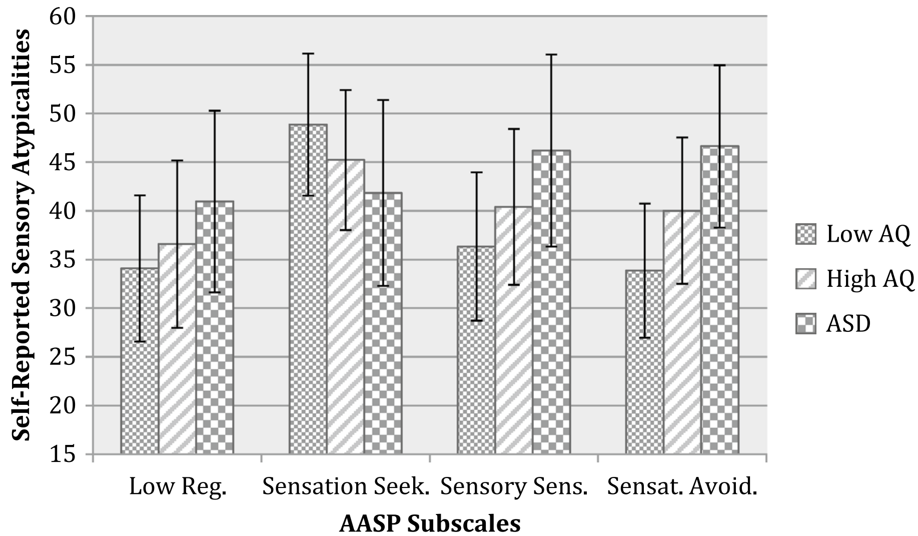

Fig. 3 Main effect of group levels of self-reported sensory abnormalities. Note: *Error bars* represent standard deviations

style as explained by the Weak Central Coherence (Happe and Frith 2006) and Enhanced Perceptual Functioning (Mottron et al. 2006) accounts of autism. Indeed, Mayer and Heaton (2014) found that increased perceptual disturbance when encoding and recalling speech in high-functioning adults with ASD was predicted by higher levels of sensory sensitivity measured by the AASP. However, the lack of significant correlations between autistic traits related to attention to detail and all aspects of self-reported sensory atypicalities in the present study suggests that although the local processing style often reported in ASD can occur alongside atypical sensory functioning, these aspects may well be independent of one another.

The broader autism phenotype analysis demonstrated a clear progression of atypical sensory behaviours in line with an increase in autistic traits, regardless of diagnostic status. Ruzich et al. (2015) performed a systematic review of 73 articles representing 6934 neurotypicals and 1963 matched individuals with ASD and uncovered overall NT and ASD mean self-reported autistic traits very similar (NT = 16.94, ASD = 35.19) to those reported in the present study. This provides further support for previous claims (e.g. Constantino and Todd 2003; Moruzzi et al. 2011; Stewart and Ota 2008; Voos et al. 2013) that autistic traits and some behaviours commonly associated with autism exist throughout the neurotypical population. Additionally the present study demonstrated that the broader autism phenotype was present across all core areas of autistic traits, with significantly more traits, in all five of the AQ subscales, appearing between NT adults with low and high autistic traits followed by high-functioning adults with ASD. Interestingly, a further analysis investigating the correlations between the different subscales of the AQ revealed a slightly different pattern of relationships amongst the facets of autistic traits across the ASD group and two NT groups, with differences even emerging between NT individuals categorised as having high or low levels of autistic traits. This tentative finding suggests that the interplay between various aspects of autistic symptomatology may be sensitive to particular thresholds of overall autistic traits or be representative of potential subgroups within the NT population. Further research is needed to explore the potentially different patterns of relationships between facets of autistic symptomatology within the broader autism phenotype.

The broader autism phenotype also held true within the sensory domain confirming previous results (Horder et al. 2014; Robertson and Simmons 2013) with total sensory functioning scores and across all four of the AASP subscales. Interestingly, although total self-reported atypical sensory behaviours and three of the subscales increased between neurotpical adults with low and high autistic traits followed by high-functioning adults with ASD, the AASP subscale of Sensation Seeking was found to decrease significantly across the same progression of groups. This suggests that lower levels of autistic traits are related to higher levels of sensation seeking behaviours in high-functioning adults with ASD, which is similar to previous reports suggesting that similar levels of sensation seeking behaviours exists in both NT and ASD adults (Mayer et al. 2014). Thus, although both hyper- and hypo- sensory sensitivity have been reported in ASD, it is plausible to suggest that hyper-responsiveness to sensory stimuli may be a more reliable way to distinguish between NT and ASD sensory functioning atypicalities. An increasingly hyper-responsiveness to sensory stimuli that coincides with increasing levels of autistic traits may also point to a distinguishing neurological processing style in which the sensory channel is too open, and too much stimulation for the brain to cope with is being received across one or more sensory modalities. Alternatively, the opposite relational profile between autistic traits and sensation seeking could further support Baranek et al.'s (2014) assertion that sensory interests, repetitions and seeking behaviours constitute a separate sensory behavioural pattern that is distinct from hypo and hyper- responsive behavioural patterns. Given the extent to which these distinct patterns have been shown to coexist (e.g. Dunn 1997; Liss et al. 2006) and the significant heterogeneity that has been reported it is plausible that autistic symptomatology is related to the interaction between sensation seeking behaviors and hyper/hypo responsiveness rather than the sensation seeking behaviours in isolation.

Taken together, the results from the present study along with Robertson and Simmons (2013), Horder et al. (2014), and Takayama et al. (2014) provide clear evidence that sensory functioning atypicalities exist throughout the neurotypical population and are not specific to ASD. Sensory information impacts all aspects of daily life, and the experience of an environment is influenced by sensory information in conscious and unconscious ways. Researchers, clinicians and therapists should take a global approach to inform how everyday environments (e.g. offices, classrooms and other public spaces) could be adapted to better accommodate the range of hyper or hypo-sensory sensitivity in seen individuals across the entire population.

A particular strength of the present study was the use of the ADOS module 4 (Lord et al. 2001) to confirm the diagnosis of all of the individuals within the ASD group alongside implementing a cut-off score of 32+ on the AQ, suggested by Baron-Cohen et al. (2001), within the NT group to avoid potential un-diagnosed cases of ASD. However, it is possible that excluding undiagnosed participants with AQ scores of 32+ did not account for all potentially undiagnosed individuals with ASD in the NT sample. Indeed some researchers (e.g. Woodbury-Smith et al. 2005) use a cut-off of 26+ and Gregory and Plaisted-Grant (2016) advise that a more conservative cut-off helps prevent against spurious effects in which undiagnosed individuals with ASD influence findings of an autistic-like profile in high-AQ groups. In the present study it was decided that adopting a more conservative AQ cut-off would create an unnecessary risk of artificially inflating potential differences between the NT and ASD groups based solely on excluding a range of AQ scores and thus impacting the ability to draw clear conclusions regarding the broader autism phenotype. The robust relationships between facets of autistic traits and sensory functioning uncovered in the present study both within the two distinct populations, and the high and low AQ groups in the neuotypical sample, strongly suggest that any potentially undiagnosed participants in the NT group did not have a spurious effect on the overall conclusions. Previous studies relied on a self-reported ASD diagnosis for placement within the ASD group (Horder et al. 2014) or included the full range of AQ scores but didn't distinguish between participants with and without an ASD diagnosis (Robertson and Simmons 2013). One limitation of the present study was the reliance on self-report measures to identify autistic trait and sensory functioning profiles. Whilst this is common practice in this area of research (e.g. Crane et al. 2009; Horder et al. 2014; Robertson and Simmons 2013) and has allowed a larger and more varied data set, future studies should seek to further address the findings of the present study utilizing behavioural and neuroimagining measures alongside the AQ and AASP. This type of experimental design would be particularly beneficial to address the questions that have arisen regarding the lack of relationship between sensory atypicalities and autistic traits in the area of attention to detail as well as whether hyper-responsiveness to sensory stimuli is a more reliable way than hypo-responsiveness to distinguish ASD from neurotypical processing styles.

The present study focused on adults and thus the conclusions cannot necessarily be generalised to NT and ASD children and adolescents. Indeed, some reports have suggested the sensory functioning may improve with age in individuals with ASD (Kern et al. 2006), whilst other studies have found similar levels of sensory atypicalities in children with ASD (Tomcheck and Dunn 2007) and adults (Crane et al. 2009). In the auditory modality, Mayer et al. (2014) proposed a relevant model that has implications for age-related changes in sensory functioning in individuals with ASD. They proposed that at a young age individuals with ASD allocate a substantial proportion of their attentional resources to the perceptual processing of speech, whereas the majority of NT individuals attentional resources are allocated to linguistic processing. As attentional resources increase with development, more processing becomes dedicated to linguistic aspects of speech in ASD, thus the distraction from sensory aspects of the auditory signal may decrease or have less of an impact.

The contradictory findings related to improvements in sensory functioning with age in ASD and the model proposed by Mayer et al. (2014) underscore the importance of future studies investigating the extent to which the conclusions drawn in the present study are also true of NT and ASD children and adolescents, or if as Kern et al. (2006) suggest, the relationship between autistic traits and sensory atypicalities would be even stronger in younger individuals. Such questions may provide insight into strength of local processing accounts of ASD at different developmental stages, as well as whether potential changes in the neurological processing of low-level stimuli are occurring with age in ASD. Additionally, further research into the interaction between sensory functioning and autistic traits may point to subgroups within the neurotypical population, independent of age. There is potential that these subgroups may be characterised by sensory functioning styles or the interaction between sensory functioning and autistic traits, which would have implications for conceptualisations of the broader autism phenotype.

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Author Contributions JLM conceived the study and design, coordinated the study and performed the measurement, performed the statistical analysis and drafted the manuscript.

Compliance with Ethical Standards

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the University or Roehampton, the British Psychological Society and the 1964 Helsinki declaration and its later amendments. Informed consent was obtained from all individual participants included in the study.

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