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The link between interoceptive processing and anxiety in children diagnosed with autism spectrum disorder: Extending adult findings into a developmental sample

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ABSTRACT

Anxiety is a major associated feature of autism spectrum disorders. The incidence of anxiety symptoms in this population has been associated with altered interoceptive processing. Here, we investigated whether recent findings of impaired interoceptive accuracy (quantified using heartbeat detection tasks) and exaggerated interoceptive sensibility (subjective sensitivity to internal sensations on self-report questionnaires) in autistic adults, can be extended into a school-age sample of children and adolescents (n = 75). Half the sample had a verified diagnosis of an Autism Spectrum Disorder (ASD) and half were IQ- and age-matched children and adolescents without ASD. The discrepancy between an individual's score on these two facets of interoception (interoceptive accuracy and interoceptive sensibility), conceptualized as an interoceptive trait prediction error, was previously found to predict anxiety symptoms in autistic adults. We replicated the finding of reduced interoceptive accuracy in autistic participants, but did not find exaggerated interoceptive sensibility relative to non-autistic participants. Nonetheless, the positive association between anxiety and interoceptive trait prediction error was replicated. However, in this sample, the best predictor of anxiety symptoms was interoceptive sensibility. Finally, we observed lower metacognitive accuracy for interoception in autistic children and adolescents, relative to their non-autistic counterparts. Despite their reduced interoceptive accuracy on the heartbeat tracking task and comparable accuracy on the heartbeat discrimination task, the autistic group reported higher confidence than the typical group in the discrimination task. Findings are consistent with theories of ASD as a disorder of interoceptive processing, but highlight the importance of validating cognitive models of developmental conditions within developmental populations.

1. Introduction

The term interoception refers to the detection of the physiological state of the body (Ceunen, Vlaeyen, & Van Dist, 2016 for review; Sherrington, 1948). Interoception is now thought to encompass sensations from inside the body (e.g., relating to cardiac and respiratory functions or digestion) and also sensations from outside the body that are important for homeostatic regulation (e.g., temperature, itch, pain and pleasure from sensual touch) (Craig, 2002). Garfinkel and colleagues (Garfinkel & Critchley, 2013; Garfinkel, Seth, Barrett, Suzuki, & Critchley, 2015; Garfinkel et al., 2016) have recently proposed that there are three dissociable dimensions to interoception: (1) interoceptive accuracy, (2) interoceptive sensibility, and (3) interoceptive awareness. Interoceptive accuracy, measured using the traditional heartbeat detection tasks (e.g., Schandry, 1981; Whitehead, Drescher, Heiman, & Blackwell, 1977) reflects 'objective' interoceptive accuracy (Critchley, Wiens, Rotshtein, Ohman & Dolan, 2004; Dunn, Stefanovitch, Evans, & Dalgleish, 2010; Katkin, Reed, & Deroo, 1983; Pollatos, Traut-Mattausch, Schroeder, & Schandry, 2007; Schandry, 1981; Whitehead et al., 1977). Interoceptive sensibility, measured using self-report questionnaires (e.g., Porges, 1993) measures how aware an individual thinks they are of their internal bodily signals, that is, their 'subjective' belief in their access to interoceptive information. Interoceptive awareness, defined as an individual's metacognitive awareness for interoceptive signals, is measured by asking for a confidence judgement on accuracy after each heartbeat detection trial

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(Garfinkel et al., 2015). Here, the term "metacognitive" is used to denote the monitoring of performance on the task, where higher confidence on accurate judgements indicates good metacognitive awareness.

While atypical sensory processing symptoms in autism have been well-researched in the exteroceptive domain (e.g. Crane, Goddard, & Pring, 2009; Kern et al., 2006; Lane, Young, Baker, & Angley, 2010) and despite the fact that autism has also been theoretically linked to impaired interoceptive processing (Quattrocki & Friston, 2014), little work has been done in the interoceptive domain. Only four published reports are known to date (Garfinkel et al., 2016; Mash, Schauder, Cochran, Park, & Cascio, 2017; Schauder, Mash, Bryant & Cascio, 2015; Shah, Hall, Catmur, & Bird, 2016). Garfinkel et al. (2016) recently reported reduced interoceptive accuracy in autistic relative to typical adults. The picture in children, however, appears more complex, with one report of no overall group differences (Schauder et al., 2015) and another study suggesting that the developmental pattern may be different in autistic children (at least in those with an IQ of less than 115), such that interoceptive accuracy increases with age in typically developing children, but decreases with age in autistic children (Mash et al., 2017). Interoceptive accuracy is related to empathy (Fukusima, Terasaw & Umeda, 2011) and emotion processing (Barrett, 2004; Wiens, 2005), which can be affected in autism (American Psychiatric Association, 2013). The insula, found to be involved in interoceptive processing (Critchley et al., 2004; Simmons et al., 2013; Zaki, Davis, & Ochsner, 2012), is hypo-activated and reduced in functional connectivity in autistic adolescents and young adults (Ebisch et al., 2011). Further, it has been proposed that developing an understanding of others requires accurate representation of the self's interoceptive states (Fotopoulou & Tsakiris, 2017; Ondobaka, Kilner & Friston, 2015).

Altered interoceptive processing has also been found in individuals with anxiety and depression (Ehlers, 1993; Paulus & Stein, 2006), conditions which have high co-occurrence with autism (Paulus & Stein, 2010). Indeed, anxiety-related concerns are among the most common problems presented by autistic children and adolescents in the clinic (Ghaziuddin, 2002) and empirically, a number of studies have identified higher rates of anxiety disorders and symptoms in autistic children than typically developing children (Gadow, DeVincent, Pomeroy, & Azizian, 2004; Kim, Szatmari, Bryson, Streiner, & Wilson, 2000; Muris, Sterrneman, Merchelbach, Holdrinet, & Meesters, 1998; Simonoff et al., 2008; Sukhodolsky et al., 2008; Weisbrot, Gadow, DeVincent, & Pomeroy, 2005). Of the previous investigations of interoceptive abilities in autistic individuals to date, only one included a measure of anxiety. Garfinkel et al. (2016) investigated the performance of twenty autistic adults on each of the three interoceptive dimensions they delineated, compared to twenty typical adults of similar age and gender. In addition to reduced interoceptive accuracy, they found elevated interoceptive sensibility in autistic, relative to typically developing, participants. No group differences were found in interoceptive awareness. The authors conceptualized the difference between interoceptive sensibility and interoceptive accuracy as an interoceptive trait prediction error. They found that this difference was greater in the autistic than the typical adults, and that it was predictive of anxiety symptoms; that is, the greater the prediction error, the more elevated the anxiety levels, providing a novel explanation for the elevated anxiety levels seen in autism.

Consistent with this interpretation, Schmitz, Blechert, Krämer, Asbrand, and Tuschen-Caffier (2012) proposed that individuals who are more prone to anxiety also show an altered interoceptive trait prediction signal. This discrepancy between observed and expected body states triggers the symptoms of anxious affect, worrisome rumination and avoidance behaviors. Yet, the experimental literature on the role of interoception in anxiety has been mixed, and different dimensions of interoception have not been thoroughly investigated. Enhanced interoceptive accuracy has been reported to be over-represented amongst anxiety patients (Dunn et al., 2010; Pollatos et al., 2007). However, other studies show no relationship between interoceptive accuracy and anxiety (Antony et al., 1995; Barsky, Cleary, Sarnie, & Ruskin, 1994; Ehlers, Margraf, Roth, Taylor, & Birbaumer, 1988) or the reverse relationship, with higher anxiety symptoms in those with weaker interoceptive accuracy (De Pascalis, Alberti, & Pandolfo, 1984). It is unclear what is behind these divergent findings, although it is likely that low sample sizes and different measurement protocols play some role.

Understanding the nature of anxiety symptoms in autism has been identified as an area that is under-researched and urgently needed for the development of appropriate treatment and intervention (Lord et al., 2005). Given the nature of autism as a developmental condition and the extremely high rates of anxiety in this population, a greater understanding of the genesis and time course of the relationship between interoception and anxiety can arguably be gained by studying their interaction as early as possible. To this end, we sought to replicate and extend Garfinkel et al.'s (2016) study with a younger sample of school-age autistic children and adolescents and a comparison group of age- and IQ-matched typically developing children and adolescents. This design allowed us to investigate whether interoceptive dimensions are a critical predictor of anxiety symptoms during development. Based on Garfinkel et al.'s previous (2016) findings with an adult sample, we hypothesized that 1) autism will be associated with impaired interoceptive accuracy, that is, reduced performance on behavioral tests of interoception; 2) autistic participants will display enhanced interoceptive sensibility, that is, their subjective belief about their interoceptive aptitude will be higher, compared to typically-developing children; and 3) across both groups, the discrepancy between interoceptive accuracy and interoceptive sensibility, the interoceptive trait prediction error, would be predictive of anxiety symptoms.

2. Methods and materials

2.1. Participants

A total of 75 children and adolescents aged between 6 and 18 years were recruited from community contacts in London and the South East of England. Forty-five were reported by parents to be typically developing, with no ongoing or historic neurological or psychological conditions. Thirty were reported by parents to have received an independent clinical diagnosis of an autism spectrum disorder, according to DSM-IV and ICD-10 criteria (DSM-IV-TR, 2000; ICD-10, 1993). These children were also assessed using the Autism Diagnostic Observation Schedule – 2nd edition (ADOS; Lord et al., 2012) (see Table 1 for scores) and the parent-report Social Communication Questionnaire. Ethical approval was granted by the local Ethics Board at University College London (Approval number: FPS 456) and all procedures were conducted in accordance with the Declaration of Helsinki. Parents of all children provided written informed consent for them to take part and the children gave their assent.

For the between-groups analysis (see below), the sample of 30 autistic children and adolescents were matched to a group of 30 typically developing children and adolescents in terms of chronological age [$t(58) = 0.843$, $p = 0.403$], full-scale IQ [$t(49.771) = 0.982$, $p = 0.331$], performance IQ [$t(58) = 0.224$, $p = 0.823$], and verbal IQ [$t(50.339) = 1.373$, $p = 0.176$] (see Table 1 for full participant characteristics).

2.2. Stimuli and procedure

Interoceptive accuracy was gauged by the participants' ability to detect their own heartbeats using a heartbeat tracking task (Schandry, 1981) and a heartbeat discrimination task (Katkin et al., 1983; Whitehead et al., 1977). For the heartbeat tracking task, participants' heartbeats were monitored via a pulse oximeter with the sensor mounting attached to their index finger. Participants were required to count their heartbeats during six randomized time windows of varying

Table 1
Participant characteristics.

Variable	Autistic children (n = 30) (all analyses)			Typical children in Between-Groups Analysis (n = 30)			Typical children in Analysis of Individual Differences (n = 45)		
Sex (male:female)*	25:5			16:14			23:22		
	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD
Age	6.3–18	12.5	2.88	6–17.20	11.86	3.03	6–17.2	11.26	3.16
IQ	80–132	100.83	15.43	85–124	104.13	10.02	85–139	108.38	11.38
Verbal	62–132	99.73	17.74	86–128	104.13	10.02	86–142	108.67	12.94
Performance	72–158	102.47	19.63	80–137	103.47	14.50	80–152	109.18	15.91
Anxiety	42–80	57.65	9.05	30–64	50.44	9.19	30–66	50.56	9.38
SCQ*	10–41	22.90	8.68	0–9	3.60	3.07	0–10	3.32	3.28
ADOS-2	1–10	5.50	2.47						

Notes: ADOS-2–Autism Diagnostic Observation Schedule – 2nd edition (Lord et al., 2012). Scores reflect calibrated severity scores. Higher scores are indicative of greater autism severity. Verbal, Performance and Full-Scale IQ scores were derived from the Wechsler Abbreviated Scales of Intelligence – 2nd edition (WASI-II; Wechsler, 2011). Anxiety scores, measured using the Spence Children's Anxiety Scale (Spence, 1998), reflect t-scores which were calculated for a subsample of the participants (n = 56 out of 75) within the validated age range. Asterisk indicates significant difference at $p < 0.05$ between autistic and typical participants included in the between-groups analysis.

length (25, 30, 35, 40, 45, and 60 s) and, at the end of each trial, to report the number of heartbeats detected to the experimenter. For the heartbeat tracking task, participants were given the following instructions: *'Without putting your hands on your body, can you count each heartbeat you feel in your body from the time you hear "start" to when you hear "stop". Count in your head and I will ask you afterwards how many you felt.'* Following each trial, participants were asked to score their confidence on a five-point scale ranging from *'I don't know'* (no heartbeat awareness) to *'I'm sure'* (full perception of heartbeat).

For the heartbeat discrimination task, each trial consisted of ten tones presented at 440 Hz and of 100 ms duration, which were triggered by the heartbeat. Under the asynchronous condition, a delay of 300 ms was inserted, adjusting for the average (~250 ms) between the R-wave and the arrival of the pressure wave at the finger (Payne, Symeonides, Webb, & Maxwell, 2006). Tones were thus presented at 250 ms or 550 ms after the R-wave, which correspond to maximum and minimum synchronicity judgements respectively (Wiens & Palmer, 2001). At the end of each trial, participants signaled to the experimenter whether they believed the tones to be synchronous or asynchronous with their heartbeats. Each participant was provided with the following instructions: '*You will hear ten beeps. Can you tell me if you think the beeps are in sync (at the same time as your heartbeats), or out of sync (at a different time to your heartbeats)?'*. On each trial, participants indicated a number between 1 and 5 to the experimenter to signal their confidence in their interoceptive decision, where 1 indicated minimum possible confidence and 5 indicated maximum possible confidence.

A subset of autistic (n = 12) and typical (n = 17) participants completed a counting control task. This was to assess their ability to attend to and accurately count an external stimulus, and acted as a control task for the counting of internal stimuli they were required to perform in the heartbeat tracking task. They were required to silently count auditory-presented tones that numbered 5, 20 or 33, and afterwards report the number to the experimenter. Each participant was provided with the following instructions: *'Can you count each beep you hear from the time you hear "start" to when you hear "stop". Count in your head and I will ask you afterwards how many you heard.'* Following each trial, participants were required to score their confidence on a five-point scale ranging from *'I don't know'* (no tone awareness) to *'I'm sure'* (full perception of tone).

Interoceptive sensibility was determined using the awareness subscale of the Porges Body Perception Questionnaire, a 45-item questionnaire designed for adults (Garfinkel & Critchley, 2013; Porges, 1993). No data are available from the authors on this scale's validation (Mehling et al., 2009). However, Critchley et al. (2004) have found that scores on this subscale correlate with grey matter volume in the right anterior insula in typical participants. The Cronbach's alpha in our sample was 0.698 in the autistic children and 0.846 in the typically developing children. To make the scale suitable for children, we modified it by simplifying some of the language and removing 6 items, which were deemed collapsible into other items (see Table 2 for examples and Supplementary Materials for the entire modified subscale). This subscale incorporated 39 bodily sensations (e.g. stomach and gut pains) and participants indicated their awareness of each sensation using a five-point scale ranging from 'never' (1) to 'always' (5). This subjective measure of interoceptive sensibility denotes the participant's belief in his/her own interoceptive aptitude, irrespective of actual (objectively-determined) interoceptive accuracy.

Interoceptive awareness was calculated for the heartbeat discrimination task using the correspondence between accuracy (correct synchronous/asynchronous decisions) and confidence assessed via self-rating on the trial-by-trial five-point scale.

Anxiety was assessed in children via self-report using the Spence Children's Anxiety Scale (SCAS, Child Version, Spence, 1998), which has previously been validated for use in autistic as well as typically developing children (Gillott, Furniss, & Walter, 2001). The child-report SCAS has been found to have good reliability and validity (Spence, 1997), with an internal reliability coefficient of 0.93 and a Guttman split-half reliability of 0.92. This questionnaire contains 45 questions and was developed to assess the severity of anxiety symptoms broadly in line with the dimensions of anxiety disorder proposed by the DSM-IV (DSM-IV-TR, 2000). The scale assesses six domains of anxiety including generalized anxiety, panic/agoraphobia, social phobia, separation anxiety, obsessive compulsive disorder and physical injury fears with questions such as *'I worry about things'* and *'I have to think of special thoughts to stop bad things from happening (like numbers or words)'*, and a

Table 2
Simplification of language in Porges Body Perception Questionnaire.

Original Porges Body Perception Questionnaire (Porges, 1993)	Adaptation for Children
'During most situations I am aware of:'	'Most of the time I can feel myself:'
1) 'Swallowing frequently'	1) 'Swallowing a lot'
3) 'An urge to cough to clear my throat'	3) 'A need to cough to clear my throat'
13) 'An urge to urinate'	13) 'Need to go to the toilet (wee)'
17) 'A bloated feeling because of water retention'	17) 'A swollen tummy'
24) 'Stomach distension or bloatedness'	

four-point response scale which runs from 'never' (0) to 'always' (3). The Cronbach's alpha for this scale in our sample was 0.863 in autistic children and 0.836 in typical children. T-scores are currently available for males and females between the ages of 8 and 15 years of age. As such, it was possible to calculate t-scores from total SCAS scores in 56 out of 75 participants (see Table 1).

Autism severity was measured in autistic children using the Autism Diagnostic Observation Schedule – 2nd edition (ADOS; Lord et al., 2012). Social communication difficulties were also measured in all children using the Social Communication Questionnaire (SCQ; Rutter, Bailey, & Lord, 2003). The SCQ is a screening tool for ASD based on the Autism Diagnostic Interview-Revised (ADI-R; Lord, Rutter, & Le Couteur, 1994). In the initial validation study, the SCQ identified a cut-off score of 15 or over as potentially indicative of an ASD, which has been since been revised to 12. It discriminates well between ASD and non-ASD cases with a sensitivity of 0.85 and a specificity of 0.75 (Berument, Rutter, Lord, Pickles, & Bailey, 1999).

2.3. General procedure

Following informed consent, all participants performed the cardiac perception (interoceptive) tasks. To prevent the temporal timing of tones priming participants towards their own heart rate, the heartbeat discrimination task was always presented after the heartbeat tracking task. Just prior to starting the heartbeat tracking task, participants were asked to sit quietly and told to focus internally, to try to feel their heart beating. This was repeated a total of six times using a variety of randomized trial lengths (25, 30, 35, 40, 45, and 60s). Once this task was completed, participants then performed the heartbeat discrimination task. This procedure was repeated a total of ten times. As described above, a subset of children completed the counting control task. This was repeated three times.

Questionnaires (SCAS, Awareness section of Porges Body Perception Questionnaire) were completed by all participants at the time of testing. Younger children and those with more limited language skills had the questions read out to them by the experimenter and indicated their answers using a visual scale. Older participants completed the questionnaires themselves in the presence of the experimenter. IQ assessment was administered to all children using the Wechsler Abbreviated Scales of Intelligence – 2nd edition (WASI-II; Wechsler, 2011). The Autism Diagnostic Observation Schedule – 2nd edition (ADOS; Lord et al., 2012) was administered to all autistic children. The parents of all children completed the SCQ.

2.4. Data analysis

2.4.1. Interoceptive accuracy

To derive measures for interoceptive accuracy, heartbeat tracking scores were calculated on a trial-by-trial basis based upon the ratio of perceived to actual heartbeats: $1\text{-}|nbeats_{real} - nbeats_{reported}|/(nbeats_{real} + nbeats_{reported})/2$ (Garfinkel et al., 2015; Hart, McGowan, Minati, & Critchley, 2013) and these were averaged to form a mean heartbeat tracking score. This measure calculates interoceptive accuracy independent of the number of heartbeats in the trial by normalizing the absolute error in perceived heartbeats as a function of the overall number of heartbeats. This interoceptive accuracy score was also used to analyze performance across trial lengths (i.e., to explore whether accuracy changed in trials of different lengths). In addition, to highlight biases in reporting, interoceptive accuracy across trial length was also probed using the heartbeat (HB) error score (HB actual − HB reported). Interoceptive accuracy for the heartbeat discrimination task was assessed as a ratio of correct to incorrect synchronicity judgements.

2.4.2. Interoceptive sensibility

To assess interoceptive sensibility, mean and total scores on the awareness section of the Porges Body Perception Questionnaire were calculated for each participant. Garfinkel proposes using total score as opposed to the mean (Garfinkel et al., 2015, 2016), but this would have required us to exclude six participants for missing responses. Results were found to be comparable using the mean and total score (with those participants with missing responses excluded). Here, we primarily report mean scores to allow for the maximum inclusion of data, but additionally reference total scores where this is deemed informative.

2.4.3. Interoceptive awareness

Employing a method similar to Khalsa et al. (2008), a mixed ANOVA was used to determine if there were differences in confidence between incorrect and correct trials between the two groups of participants (autistic children, typical children). Higher confidence on correct trials than incorrect trials indicates good interoceptive awareness.

2.4.4. Interoceptive trait prediction error (ITPE)

The ITPE was defined operationally as the difference between objective interoceptive accuracy and subjective interoceptive sensibility. For each interoceptive accuracy and sensibility variable (heartbeat tracking score, heartbeat detection score, and Awareness subsection of the Porges Body Perception Questionnaire), scores were converted to standardized z scores. On a within-participant basis, ITPE values were calculated as the difference between interoceptive sensibility and interoceptive accuracy. ITPEs were calculated separately using accuracy scores from each task (heartbeat tracking $ITPE_T$ and heartbeat discrimination $ITPE_D$), using in each case the sensibility score provided by the awareness subsection of the Porges Body Perception Questionnaire. Positive values of ITPE indicate a propensity for individuals to overestimate their interoceptive ability, while negative scores reflect a propensity for individuals to underestimate their own interoceptive ability.

2.5. Statistical analyses

The data were initially screened to assess for normality and the potential confounding effects of sex and chronological age, and for any group differences on the counting control task and Social Communication Questionnaire (SCQ), using correlation analyses, independent *t*-tests, and mean rank Mann-Whitney *U* tests where the assumption of normality was violated (see 'Initial data screening' in Results section).

Between-groups analyses were conducted to test for any differences in total anxiety score, interoceptive accuracy on the heartbeat tracking and discrimination tasks, interoceptive sensibility, interoceptive awareness, interoceptive performance as a function of trial duration and interoceptive trait prediction error using independent *t*-tests, mean rank Mann-Whitney *U* tests where the assumption of normality was violated, and mixed model two-way ANOVAs. These analyses were conducted on the age- and IQ-matched samples (n = 30 in each group).

Within-groups analyses were conducted to test for relations between the different dimensions of interoception, and the relationship between interoception, autism severity and anxiety using correlation and multiple regression analyses. These analyses were conducted on all participants tested (n = 75), but are also verified in the matched groups (n = 30 per group). To control for multiple comparisons a more stringent alpha level of $p < 0.01$ was employed in such cases.

3. Results

3.1. Initial data screening

The data were initially checked for normality using Kolmogorov-Smirnov tests (see Supplementary Materials for full statistics). In all cases where the assumption of normality has been violated, equivalent non-parametric statistics will be reported. Encouragingly, no significant difference was found between autistic and typical children on the

counting control task [$U = 92$, $p = 0.774$]. There was no significant relationship between sex and interoceptive accuracy on the heartbeat counting task [$r^s(73) = -0.036$, $p = 0.760$], the heartbeat discrimination task [$r^s(73) = -0.086$, $p = 0.464$], interoceptive sensibility [$r(73) = 0.099$, $p = 0.397$, $ITPE_T$ [$r(73) = -0.023$, $p = 0.844$] or $ITPE_D$ [$r^s(73) = -0.001$, $p = 0.996$]. There was no relationship between chronological age and interoceptive accuracy on the heartbeat tracking task [$r^s(73) = -0.139$, $p = 0.233$], the heartbeat discrimination task [$r^s(73) = -0.091$, $p = 0.436$], interoceptive sensibility [$r(73) = -0.031$, $p = 0.790$], $ITPE_T$ [$r(73) = 0.056$, $p = 0.634$] or $ITPE_D$ [$r^s(73) = -0.062$, $p = 0.599$]. As expected, the autistic children had significantly higher scores than the typical children on the Social Communication Questionnaire (SCQ) [$U = 0.500$, $p < 0.001$, $d = 3.284$]. The authors of the Spence Children's Anxiety Scale (Spence, 1998) suggest a t-score of 60 as indicative of sub-clinical or elevated levels of anxiety. Seven autistic participants and seven typically developing participants in the sample met this criterion.

3.2. Between-Groups analysis

3.2.1. Anxiety

Autistic children reported higher levels of anxiety than typical children but this did not reach significance [$U = 256$, $p = 0.094$] (see Table 3 for mean scores).

3.2.2. Interoceptive accuracy

Autistic children showed significantly reduced interoceptive accuracy on the heartbeat tracking task compared to typical children [$U = 232.50$, $p = 0.001$, $d = -1.09$], replicating that seen in Garfinkel et al. (2016) (see Fig. 1a). The heartbeat discrimination task did not, however, reveal any group differences in interoceptive accuracy [$U = 431.50$, $p = 0.782$, $d = 0.046$]. See Table 3.

3.2.3. Interoceptive sensibility

In contrast to that found in Garfinkel et al. (2016), the awareness subscale of the Porges Body Perception Questionnaire did not reveal any group differences in interoceptive sensibility [$t(58) = 0.194$, $p = 0.847$, $d = 0.050$] with very similar average scores in the autistic and typical children (see Fig. 1b). This was replicated when we used Garfinkel et al.'s (2016) preferred method of taking the total score as opposed to the mean score [$t(42) = 1.869$, $p = 0.069$, $d = 0.564$], where there was actually a trend towards higher scores in typical children (mean = 92.74, SD = 14.43) than autistic children (mean = 85.32, SD = 11.89).

Table 3
Between-groups analysis. Means and standard deviations of anxiety and dimensions of interoception in autistic and typical children and adolescents.

	Autistic children (n = 30) M (SD)	Typical children (n = 30) M (SD)
Anxiety	34.44 (16.86)	25.79 (11.75)
Heartbeat tracking*	0.11 (0.64)	0.59 (0.25)
Heartbeat discrimination	0.48 (0.16)	0.47 (0.21)
Interoceptive sensibility	2.28 (0.45)	2.26 (0.41)
Interoceptive confidence*	0.50 (0.23)	0.40 (0.20)
$ITPE_T$*	0.47 (1.36)	−0.47 (1.11)
$ITPE_D$	0.04 (1.15)	0.04 (1.49)

Notes: Asterisks indicates significant differences between autistic children and typical children at the $p < 0.05$ alpha level. Anxiety was gauged using the Spence Children's Anxiety Scale (SCAS; Spence, 1998). Interoceptive sensibility was measured using the awareness subsection of Porges Body Perception Questionnaire (Porges, 1993), and reflects the mean score. Interoceptive confidence represents mean confidence rating on the heartbeat discrimination task. Despite comparable accuracy to typically developing participants on this task (see heartbeat discrimination scores), autistic participants reported elevated confidence. Interoceptive trait prediction error is defined as the difference between subjective interoceptive sensibility on the Awareness subscale of the Porges Body Perception Questionnaire (Porges, 1993) and objective accuracy on the heartbeat tracking task ($ITPE_T$) or the heartbeat discrimination task ($ITPE_D$).

3.2.4. Interoceptive awareness

We conducted a mixed two-way ANOVA to examine potential group differences in confidence between incorrect and correct trials. Higher confidence on correct trials than incorrect trials indicates good interoceptive awareness. One typical child from the matched groups had not been incorrect on any trials so was excluded from this analysis.

There was no main effect of response on confidence [$F(1,57) = 1.720$, $p = 0.195$, $\eta^2p = 0.029$] but there was a significant effect of group [$F(1,57) = 7.988$, $p = 0.006$, $\eta^2p = 0.123$], with autistic children [M = 3.86, SD = 0.98] having reported significantly higher confidence than typical children [M = 3.26, SD = 0.69] (see Fig. 1c). There was, however, no significant interaction between response and group [$F(1,57) = 2.561$, $p = 0.115$, $\eta^2p = 0.043$].

3.2.5. Interoceptive performance as a function of trial duration

Ten participants were excluded from this analysis because they had failed to complete all six trial durations (6 autistic children, 4 typical children). Kolmogorov-Smirnov tests indicated errors were normally distributed [$p > 0.05$ for all conditions]. There was a significant main effect of group on interoceptive accuracy [$F(1,47) = 6.155$, $p = 0.017$, $\eta^2p = 0.116$]. There was no significant main effect of trial duration on interoceptive accuracy [$F(3.845,180.714) = 1.423$, $p = 0.230$, $\eta^2p = 0.029$. There was also no significant interaction effect [$F(3.845,180.7140 = 0.596$, $p = 0.659$, $\eta^2p = 0.013$ (see Fig. 2a).

A parallel analysis was conducted using heartbeat error score (observed – reported heartbeats). This revealed a significant main effect of trial duration [$F(3.486, 163.862) = 20.604$, $p < 0.001$, $\eta^2p = 0.305$]. There was a significant main effect of group [$F(1,47) = 4.084$, $p = 0.049$, $\eta^2p = 0.080$] but no significant interaction effect [$F(3.486, 163.862) = 1.474$, $p = 0.218$, $\eta^2p = 0.030$] (see Fig. 2b).

3.2.6. Interoceptive trait prediction error

The ITPE, defined here as in Garfinkel et al. (2016), is the difference between subjective sensibility and objective accuracy for the heartbeat tracking task ($ITPE_T$) and the heartbeat discrimination task ($ITPE_D$). As in Garfinkel et al. (2016), we found a significant group difference in $ITPE_T$ [$t(58) = 2.934$, $p = 0.005$, $d = 0.761$]. There was no significant group difference in $ITPE_D$ [$U = 447.50$, $p = 0.971$, $d = 0.179$].

3.3. Analyses of individual differences

3.3.1. Relations between the different dimensions of interoception

Across the entire sample, the two objective measures of interoceptive accuracy (heartbeat tracking and heartbeat discrimination) were not significantly correlated [$r_s(73) = -0.114$, $p = 0.328$]. Examination of the above correlation in each of the two groups separately also revealed no significant relationships in autistic children [$r_s(28) = -0.172$, $p = 0.363$] or typically developing children [$r_s(43) = -0.043$, $p = 0.779$].

Across the entire sample, the two objective measures of interoceptive accuracy (heartbeat tracking and heartbeat discrimination) did not correlate with interoceptive sensibility [$r_s(73) = -0.071$, $p = 0.543$, and $r_s(73) = 0.023$, $p = 0.845$, respectively]. Further, no significant relationship was found when the two objective measures of interoceptive accuracy (heartbeat tracking and heartbeat discrimination) and interoceptive sensibility were correlated in each of the groups separately: for autistic children [$r_s(28) = 0.112$, $p = 0.557$; $r_s(28) = 0.117$, $p = 0.537$, respectively], typically developing children [$r_s(43) = -0.174$, $p = 0.254$; $r_s(43) = -0.019$, $p = 0.900$, respectively] (Fig. 3).

The latter results are in line with previous findings from adult

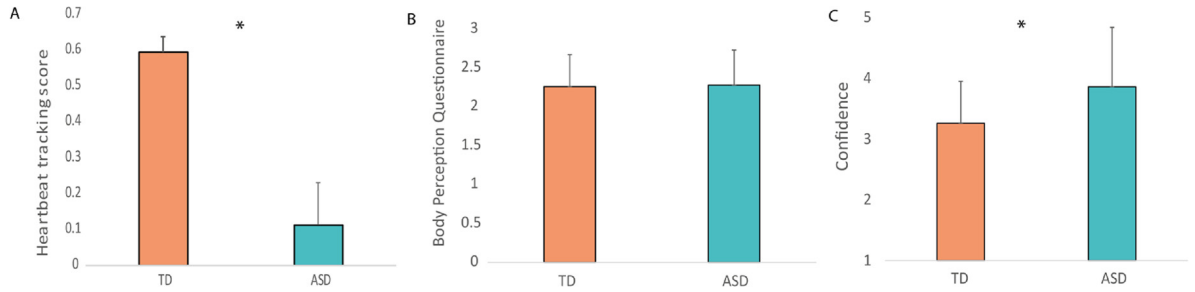

Fig. 1. A) Replicating that seen in the previous adult study, interoceptive accuracy, as gauged using heartbeat tracking, was significantly higher in typical than autistic children. B) In contrast to Garfinkel et al.'s adult study, no group differences were found in self-assessed inteoceptive sensibility, gauged using the Awareness subsection of the Porges Body Perception Questionnaire (Porges, 1993). C) Autistic children reported significantly higher confidence in their interoceptive judgements on the heartbeat discrimination task than typical children, despite no siginificant difference in performance. Asterisks indicates significant difference between autistic children and typical children at the $p < 0.05$ alpha level.

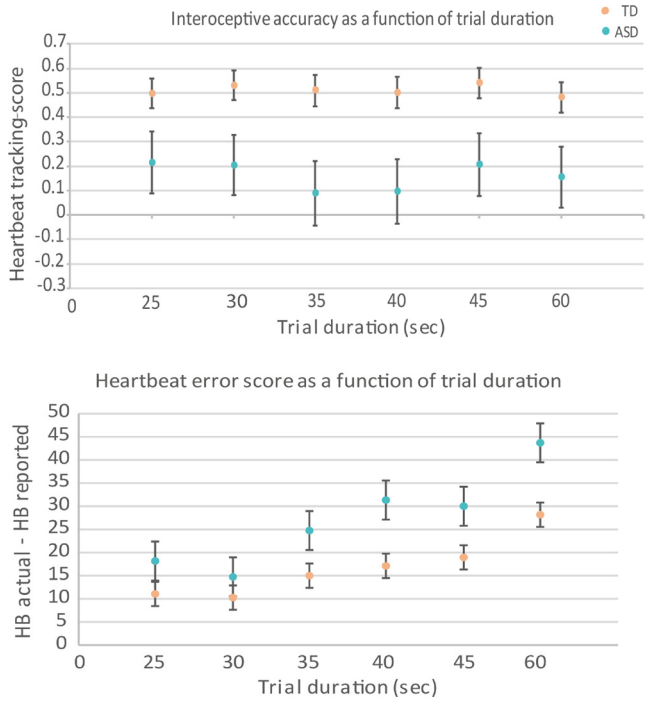

Fig. 2. A) Interoceptive accuracy was significantly higher in typical than autistic children at all trial durations. B) Heartbeat error score was significantly higher in autistic than typical children at all trial durations.

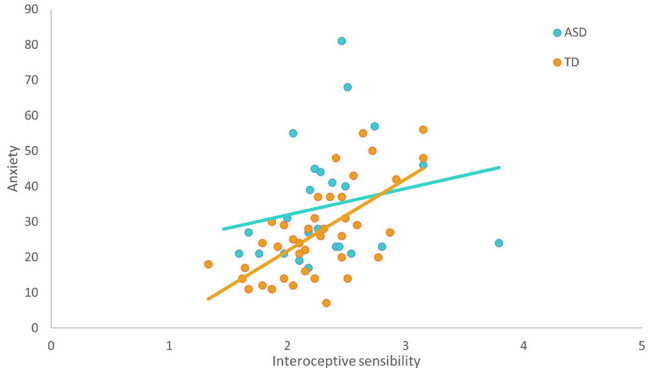

Fig. 3. Of the three facets of interception (introceptive accuracy, sensibility and $IPTE_T$), interoceptive sensibility was the best predictor of anxiety in autistic and typically developing children.

autistic (Garfinkel et al., 2016) and nonclinical (Garfinkel et al., 2015) samples, although a moderately significant relationship is usually seen between the two objective measures of interoceptive accuracy, with the closest correspondence usually seen for the extreme groups of very good and very poor perceivers (Knoll & Hodapp, 1992).

3.3.2. Relationship to autism severity

There was a significant negative relationship between autism severity, operationalized as comparison score on the ADOS-2, and interoceptive sensibility [$r(28) = -0.405$, $p = 0.026$] and $ITPE_D$ [$r_s(28) = -0.518$, $p = 0.003$]. There was no significant relationship between autism severity and interoceptive accuracy on the heartbeat tracking task [$r_s(28) = -0.043$, $p = 0.821$], heartbeat discrimination task [$r_s(28) = 0.159$, $p = 0.400$], or $ITPE_T$ [$r(28) = -0.172$, $p = 0.364$].

3.3.3. Relationship to anxiety

Across the entire sample, anxiety was significantly positively related to interoceptive sensibility [$r_s(64) = 0.518$, $p < 0.001$], but not interoceptive accuracy [$r_s(73) = -0.122$, $p = 0.329$]. Examination of each group separately revealed a significant relationship between interoceptive sensibility and anxiety in the typical group [$r_s(39) = 0.611$, $p < 0.001$] but this relationship was only at trend significance in the autistic group [$r_s(23) = 0.388$, $p = 0.055$]. There was also no significant relationship between anxiety and interoceptive accuracy in the autistic group [$r_s(23) = 0.198$, $p = 0.343$] or TD group [$r_s(39) = -0.181$, $p = 0.257$].

Addressing our central hypothesis, we tested for a correlation between anxiety and ITPE. Replicating the positive relationship found in Garfinkel et al. (2016), we found a positive relationship between $ITPE_T$ and anxiety [$r_s(64) = 0.248$, $p = 0.045$]. There was no significant relationship between $ITPE_D$ and anxiety [$r_s(64) = -0.166$, $p = 0.182$]. When the relationship between anxiety and $ITPE_T$ was tested in each group separately, there was no significant relationship between anxiety and $IPTE_T$ in the autistic group [$r_s(23) = 0.012$, $p = 0.956$] or the typical group [$r_s(23) = 0.021$, $p = 0.956$].

A multiple regression analysis was conducted to dissect the relative contributions of interoceptive accuracy, interoceptive sensibility, $IPTE_T$ and group membership (autistic or typical) to anxiety. A Kolmogorov-Smirnov test indicated residuals were normally distributed [$D(66) = 0.072$, $p = 0.200$]. The model was significant [$F(4,61) = 4.937$, $p = 0.002$], with an R square of 0.195. The only significant predictor of anxiety score in this model, however, was interoceptive sensibility (see Table 4), accounting for 19.8% of the variance in anxiety (R square = 0.198). For every unit increase in interoceptive sensibility, total anxiety score increases by 0.445.

The same result is obtained when only the participants included in the between-groups analysis are entered, yielding a significant model [$F(4,52) = 3.233$, $p = 0.020$], with interoceptive sensibility as the only

Table 4
Standardized beta coefficients, t and p statistics for each predictor variable in the multiple regression analysis.

	β	t	p
Interoceptive accuracy	−0.057	−0.333	0.740
Interoceptive sensibility	0.440	2.994	0.004*
$ITPE_T$	−0.024	−0.122	0.903
Group	−0.200	−1.675	0.099

Notes: Asterisks indicates a significant predictor of self-report anxiety at the $p < 0.05$ alpha level. $ITPE_T$ denotes the interoceptive trait prediction error for the heartbeat tracking task.

significant predictor of anxiety [$\beta = 0.365$, $t = 2.209$, $p = 0.032$].

4. Discussion

Higher levels of anxiety were observed in autistic children than typically developing children, although contrary to previous reports (Garfinkel et al., 2016; Kim et al., 2000; Simonoff et al., 2008), this did not reach statistical significance. Supporting our hypotheses, we also see reduced interoceptive accuracy in this population on a heartbeat tracking task (Schandry, 1981), lending support to the theory that autism could arise though a compromised interoceptive channel (Garfinkel et al., 2016; Quattrocki & Friston, 2014). No group differences were found in interoceptive accuracy on the heartbeat discrimination task, despite a significant group difference in confidence ratings on this task. To ensure that our task was developmentally appropriate for the age range and population under investigation here, only ten trials were used for this task. It is therefore possible that these null findings could represent a lack of experimental power, as a recent study suggests that at least 40–60 trials may be needed to yield good reliability on this measure (Kleckner, Wormwood, Simmons, Barrett, & Quigley, 2015). Notwithstanding, it is notable that Garfinkel et al. (2016) used only 20 trials on the same task with their autistic and non-autistic adults and found no group differences, just as we did here. Future studies should nevertheless seek to remedy this power issue.

Moreover, it is worth noting that using the analysis strategy of the heartbeat discrimination task, as in Garfinkel et al. (2016), it is possible that a participant could simply guess each answer, with a 50% chance of achieving a correct response. As such, this method is therefore a potentially less sensitive that the heartbeat tracking task, and might overestimate the performance of participants. If that were the case, it could be that the interoceptive abilities of the autistic participants were thus overestimated, leading to our finding of no group differences on this task, in contrast to the heartbeat tracking task.

We did not replicate Garfinkel et al.'s finding of an association between autism and increased interoceptive sensibility. If the Awareness Scale of the Porges Body Perception Questionnaire does indeed tap subjective sensitivity to internal sensations, then autistic children do not report elevated levels like their adult counterparts. According to a dimensional model of interoception (Garfinkel & Critchley, 2013), the dissociation between interoceptive facets should be greatest in those who are poorest in interoceptive accuracy (Garfinkel et al., 2015). We may not observe group differences in interoceptive sensibility in children because their interoceptive accuracy (regardless of diagnosis) is higher than usually seen in adulthood. As interoceptive accuracy decreases with age, interoceptive sensibility scores should increase, and so should anxiety scores.

Despite the lack of group differences in interoceptive sensibility, we replicated Garfinkel et al.'s finding of a positive relationship between interoceptive trait prediction error and self-report anxiety. As in Garfinkel et al.'s (2016) sample, individuals with a large discrepancy between their interoceptive sensibility and interoceptive accuracy scores reported the highest rates of anxiety. This finding lends support to the theory, proposed by Paulus and Stein (2006), that individuals who are prone to anxiety show an altered interoceptive trait prediction signal. They argue that it is this discrepancy between observed and expected body states that triggers the symptoms of anxious affect, worrisome rumination and avoidance behaviors.

Although we found a significant association between interoceptive trait prediction error and anxiety, when all interoceptive dimensions were entered into the model together, the most significant predictor of anxiety in these children was interoceptive sensibility. This relationship – the more interoceptive sensations a child is subjectively aware of, the higher their anxiety – is compatible with the existing literature on anxiety. In anxiety disorders, increased self-report of somatic sensations has been observed (Barlow, 1988; Beck, Emery, & Greenberg, 1985; Clark, 1986). It is hypothesized that the individual then engages in a subsequent cognitive appraisal of these sensations with their interpretation biased towards danger and catastrophe (Domschke, Stevens, Pfleiderer, & Gerlach, 2010). Anxiety disorder patients report a higher frequency of bodily sensations relating to panic in childhood and adolescence compared to healthy people (Ehlers, 1993), pointing to maladaptive learning processes during development.

It is possible that differences between the present findings and those of Garfinkel et al. (2016) in the relationship between interoceptive facets and anxiety reflect differences in how anxiety was measured in these two populations. The Spence Children's Anxiety Scale (SCAS; Spence, 1998) measures anxiety symptoms across a number of domains (see Methods and Materials) using developmentally appropriate language. Anxiety was assessed using the Spielberger State/Trait Anxiety Inventory (STAI; Spielberger, 2010) in Garfinkel et al. (2016), which, unlike the SCAS, makes a distinction between State (reflecting the participant's current symptoms at that moment in time) and Trait anxiety (their general dispositional proclivity). It is also possible that the proneness of participants to report various types of anxiety symptoms alters developmentally. As such, the construct of anxiety may not be identical for child, adolescent and adult participants, and may therefore relate differently to various interceptive facets at these developmental stages.

We found elevated confidence for interoceptive estimates on the heartbeat discrimination task in autistic children, despite comparable performance to typically developing participants (and reduced accuracy on another – the heartbeat tracking – task). When asked to judge how sure they were that their answer on the heartbeat discrimination task is accurate, autistic children reported higher levels of certainty than typically developing children. Taken together, these results are suggestive of a difficulty mapping certainty to task performance in autism, at least in the interoceptive domain. No significant differences in this interoceptive dimension were found in Garfinkel et al.'s (2016) adult study, and this marks a novel finding in the autism literature. We note that in Garfinkel et al.'s (2015) seminal formulation of interoceptive dimensions, mean confidence ratings are considered under the umbrella of interoceptive sensibility, reflecting an individual's perceived interoceptive ability. As such, despite a lack of group differences on the Awareness Scale of the Porges Body Perception Questionnaire, this finding of higher mean confidence ratings on the heartbeat discrimination task, could be considered indicative of elevated interoceptive sensibility.

It has previously been suggested that autism may be characterized by altered metacognition (Friston, Lawson, & Frith, 2013; Lawson, Rees, & Friston, 2014). These accounts use the term "metacognition" to refer to the estimation of precision or confidence in prior beliefs. The little empirical literature that exists on metacognition in autism has somewhat ambiguously operationalized metacognitive reasoning as in the present paper, as a general conscious evaluation process, and produced mixed results across a range of performance evaluation tasks. There are some findings of impaired meta-memory (the ability to self-monitor memory processes) in autistic adults (Grainger, Williams, & Lind, 2014) and children (Wilkinson, Best, Minshew, & Strauss, 2010) but also some findings of no impairment in autistic children (Farrant,

Boucher, & Blades, 1999). Interoceptive awareness is defined and measured as the trial-wise correspondence between accuracy and confidence. The skills required for this ability may be subtly different to those required to perform self-evaluation of overall past performance. This area of research clearly warrants further attention, with a need to both assess metacognitive ability in a variety of domains and unify the theoretical accounts of unconscious precision optimization and the experimental findings of altered conscious metacognition.

The data presented here suggest that high interoceptive sensibility in childhood, unlike in adulthood, is not associated with autism; instead, it is related to anxiety. In typical children high interoceptive sensibility is accompanied by high interoceptive accuracy. Autistic children's decreased interoceptive accuracy, in combination with elevated confidence in their interoceptive judgements then, is what differentiates them from typical children. Examination of our data in combination with Garfinkel et al.'s (2016) suggests that, by adulthood, the discrepancy between how aware autistic individuals think they are of their interoceptive signals, and how aware they actually are, has become a heightened interoceptive trait prediction error.

In conclusion, these findings underscore the need for research examining the characteristics of autism within a developmental framework, as recommended by Bishop (1997) and Karmiloff-Smith (1998). Indeed, researchers and clinicians are increasingly questioning whether cognitive models that are recognized as valid in adults can be applied to children in the absence of rigorous empirical testing (Hodson, McManus, Clark & Doll, 2008; Schmitz et al., 2012). The recent study by Mash et al. (2017) highlights the importance of considering interoception in autism within a developmental framework. They found that age-related changes in interoceptive accuracy in autism and typical development are moderated by individual differences in IQ and suggest that autistic individuals may have a different lifespan trajectory of interoceptive processing, relative to typically developing individuals. Understanding the developmental trajectory of anxiety both in typical development and in autism should inform a number of endeavors, including predicting outcomes and the optimal timing of interventions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.biopsycho.2018.05.003.

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