Journal of Autism and Developmental Disorders
https://doi.org/10.1007/s10803-022-05763-0

S:I: .DEVELOPMENTAL APPROACH AND TARGETED TREATMENT OF SENSORY

Sensory Phenotypes in Autism: Making a Case for the Inclusion of Sensory Integration Functions

Roseann C. Schaaf[1] · Zoe Mailloux[1] · Elizabeth Ridgway[2] · Alaina S. Berruti[3] · Rachel L. Dumont[1] · Emily A. Jones[4] · Benjamin E. Leiby[5] · Catherine Sancimino[3] · Misung Yi[5] · Sophie Molholm[6]

Accepted: 14 September 2022

Abstract
Sensory features are part of the diagnostic criteria for autism and include sensory hypo/hyper reactivity and unusual sensory interest; however, additional sensory differences, namely differences in sensory integration, have not been routinely explored. This study characterized sensory integration differences in a cohort of children (n = 93) with a confirmed diagnosis of autism (5–9 years) using a standardized, norm-referenced battery. Mean z scores, autism diagnostic scores, and IQ are reported. Participants showed substantial deficits in tactile perception, praxis, balance, visual perception, and visual-motor skills. Relationship with autism diagnostic test scores were weak or absent. Findings suggest additional sensory difficulties that are not typically assessed or considered when characterizing sensory features in autism. These data have implications for a greater understanding of the sensory features in the autism phenotype and the development of personalized treatments.

Keywords Autism · Sensation · Perception · Symptom Assessment

Atypical sensory behaviors are a part of the DSM5 diagnostic criteria for autism spectrum disorder (ASD) (APA, 2013) and include hypo and/or hyper-reactivity to sensation (hereafter referred to as sensory reactivity) and unusual interests in the sensory aspects of the environment. Currently, these are assessed using parent-report measures such as the Sensory Profile 2 (Dunn, 2014), the Sensory Processing Measure 2 (Parham et al., 2007), or the Sensory Experiences Questionnaire (Baranek et al., 2006). These assessments, while valuable, are not intended to capture many important aspects of sensory perceptual and sensorimotor skills in ASD reported in the literature (Robertson & Baron-Cohen, 2015), such as sensory perception (the detection, discrimination, characterizing, and recognizing sensory information), multisensory integration (the process by which inputs from two or more senses are combined to influence perception and behavior (Stein, et al., 2014; Molholm, 2002), praxis (the use of sensory information to plan and execute goal-directed tasks (Ayres, 1989; Mostofsky, 2011), and other sensorimotor functions (such as balance, bilateral motor coordination, and visual motor skills) (Hannant et al., 2016). Collectively, these functions are referred to as 'sensory integration,' or the "integration of sensation for use" (Ayres, 1972, 1979). Research shows that challenges in sensory integration are prevalent in autistic persons and impact functional skills and abilities such as the ability to act and interact in daily life (Smith-Roley et al., 2015; Williams et al., 2018; Travers et al.,2022; Schaaf, et al., 2011; Brandwein, et al., 2013, Crosse, et al., 2019; Crosse, et al., in press). Thus, the sensory differences experienced by autistic persons go beyond

✉ Roseann C. Schaaf
Roseann.Schaaf@jefferson.edu

1 Jefferson Autism Center of Excellence, Department of Occupational Therapy, Thomas Jefferson University College of Rehabilitation Sciences, Philadelphia, PA, USA

2 Department of Pediatrics, Rose F. Kennedy Children's Evaluation and Rehabilitation Center, Albert Einstein College of Medicine, Montefiore, Bronx, NY, USA

3 The Cognitive Neurophysiology Laboratory, Department of Pediatrics, Albert Einstein College of Medicine, 10461 Bronx, NY, USA

4 Queens College and the Graduate Center, City University of New York, Queens, NY, USA

5 Division of Biostatistics, Thomas Jefferson University, Philadelphia, PA, USA

6 Department of Neuroscience, Albert Einstein College of Medicine, 10461 Bronx, NY, USA

Published online: 27 September 2022

sensory reactivity and sensory seeking to include additional types and characteristics. A comprehensive assessment of these functions is necessary to fully appreciate the extent and nature of sensory integrative challenges in autistic persons. These comprehensive assessment data may further inform the sensory features in the autism phenotype and guide individualized interventions.

While there is a preponderance of literature characterizing types, subtypes, and patterns of sensory reactivity in autistic groups, there has been less exploration of these other sensory integration functions and their impact on function and participation in individuals with ASD. Further, most characterizations of sensory functions in ASD are based on parent or caregiver reports of behaviors that are hypothesized to directly link to sensory disturbances rather than a performance-based assessment. Best-practices in assessment of sensory features recommend a combination of proxy reports and observational/performance-based assessments to obtain a comprehensive picture of sensory differences and their impact on function, performance, and participation (Schaaf and Lane, 2015). Hence, there is a need to objectively and systematically characterize sensory integrative differences in ASD to specify their extent and nature clearly. In addition, assessment data about the sensory integrative factors that may be impacting autistic person's function and participation can be helpful for tailoring or individualizing interventions designed to improve sensory and sensorimotor factors that impact participation in activities and tasks. The purpose of this paper is to further characterize sensory differences in ASD by exploring sensory integration functions. To this end, results from the Sensory Integration and Praxis Tests (SIPT; Ayres, 1989) are reported in a cohort of children with ASD. The SIPT is a set of performance-based, standardized, and normed psychometric tests designed to assess function in multiple areas of sensory integration.

Methods

Design

This study utilized a descriptive, cross-sectional analysis of pre-treatment scores on the ADOS-2 and the Sensory Integrative and Praxis Tests.

Participants

The sample reported in this study is from a larger randomized controlled trial of children with ASD who were enrolled in a comparative effectiveness trial of sensory integration treatment. Ethics approval was obtained from the institutional review board at the Albert Einstein College of Medicine. A licensed clinical psychologist with research reliability and extensive experience in the diagnosis of ASD made or confirmed a diagnosis of ASD based on the Autism Diagnostic Observation Schedule, 2nd Edition (ADOS-2; Lord et al., 2012), developmental history, and clinical judgment; and measured IQ using the Wechsler Abbreviated Scale of Intelligence, Second Edition (WASI-II; Wechsler, 2011). Inclusion criteria were a diagnosis of ASD between the ages of 6 and 9.5 years at the onset of the study, a nonverbal IQ score greater than 65, and evidence of sensory dysfunction as measured by the Sensory Integration and Praxis Tests (SIPT; Ayres, 1989) and/or the Sensory Processing Measure (Parham, 2007). Children with limitations in their ability to engage in active, sensory-motor activities (i.e., physical limitations), a genetic syndrome, hearing impairment, or uncorrected visual impairment were excluded from the study. Participant demographics, including age, gender, race, and ethnicity are shown in Table 1. In addition, autism severity scores from the ADOS-2 and IQ scores are shown. As expected, there was a greater number of males than females. Full scale IQ scores ranged from 50 to 166 (mean = 87.6; SD = 20.5) while non-verbal or performance IQ (PIQ) ranged from 56 to 143 (mean = 93.7, SD = 18.5) and autism severity ranged from low to high.

Procedures

The procedures for the collection of intake data for the randomized controlled trial that these data are associated with these data are described in more detail in a recent publication (Beker, et al., 2021). All assessments were completed by research-certified examiners with advanced training.

Instruments

The Sensory Integration and Praxis Tests (SIPT)

The SIPT consists of 17 tests, standardized on 1,997 children ages 4 yrs. to 8 yrs., 11 mo., designed to assess visual, tactile, vestibular and proprioceptive perception, visual–motor skills, praxis, balance, and bilateral integration (Ayres, 1989). The SIPT is used mainly within occupational therapy to test distinct and varied sensory integrative functions. The tests and the function(s) that each test is designed to assess are shown in Table 2. For the current study, the SIPT was administered by an occupational therapist with advanced training in its administration and interpretation. The total test time for the SIPT is about 2–3 h, depending on

Table 1

Demographic Characteristics

	N	N miss	Mean	SD	Min	Max
ADOS2 SA Total (calibrated)	93	0	7.48	1.82	1.00	10.00
ADOS2 RRB Total (calibrated)	93	0	8.62	1.37	4.00	10.00
ADOS2 D-1	93	0	1.38	0.90	0.00	3.00
ADOS2 Severity Score/Comparison Score	93	0	8.08	1.58	5.00	10.00
Age	93	0	7.06	1.08	5.00	9.00
VIQ	93	0	80.67	22.54	45.00	130.0
PIQ	93	0	93.66	18.47	56.00	143.0
FSIQ	93	0	87.61	20.52	50.00	166.0
Gender	**N**	**%**				
Male	80	86.02%				
Female	13	13.98%				
Race	**N**	**%**				
White	24	25.81				
Black or African American	24	25.81				
Asian	8	8.60				
Hawaiian or Pacific Islander	2	2.15				
Multiple Races	17	18.28				
Unknown or refused to answer	12	12.90				
Ethnicity	**N**	**%**				
Hispanic or Latino	51	54.84				
Non-Hispanic or Latino	29	31.18				
Missing	10	10.75				
Unknown or refused to answer	3	3.23				
Age						
5	2	2.15%				
6	35	37.63%				
7	21	22.58%				
8	25	26.88%				
9	10	10.75%				
ADOS D-1						
0	18	19.35%				
1	30	32.26%				
2	37	39.78%				
3	8	8.60%				

Some children did not complete portions of the ADOS testing and thus, total n may vary. ADOS2 = Autism Diagnostic Observation Scale Second Edition; SA = Social Affect; RRB = Restrictive, Repetitive Behaviors, D-1 = Sensory Score. VIQ = verbal intelligence quotient; PIQ = performance intelligence quotient; FSIQ = full scale intelligence quotient

the number of breaks needed. It can be administered in multiple sessions. Testers received advanced training in administration and scoring of SIPT prior to study initiation and were evaluated for adherence to administration procedures by the first author. Psychometric properties of the SIPT are strong (Ayres, 1989); each SIPT test has high interrater reliability (r = .94-0.99), discriminates between typical and atypical samples (p < .01 ;), and has content and construct validity (Ayres, 1989).

Each test of the SIPT is administered using simple visual demonstration and standardized verbal instructions except Praxis on Verbal Command, which is solely language dependent and involves simple language instructions to the child. SIPT yields raw scores that are converted to *z* scores based on age-normative data. On the SIPT, *z* scores ≤ -1.0 indicate areas of concern. One exception is the Post Rotary Nystagmus (PRN) test, where a score of ≤ -1.0 or ≥ + 1.0 are considered clinically meaningful (Ayres, 1989). Thus, the *z* score reflects each participant's rating, with a score falling below − 1.0 indicating below age-expectancy performance. For the 10 participants who exceeded the age norms, the oldest age norm for z scoring is referenced. This produces a conservative assessment of atypicality of SIPT performance.

Table 2 *Sensory Integration and Praxis Tests and Functions They Measure*

Somatosensory Perception	
Manual Form Perception (MFP)	Identification of shapes placed in hand by touch
Finger Identification (FI)	Identification of finger(s) touched without vision
Graphesthesia (GRA)	Replication of simple designs drawn on the dorsum of hand
Kinesthesia (KIN)	FI + Gra + MFP
Praxis	
Postural Praxis (PPr)	Imitation of novel body and hand postures
Oral Praxis (OPr)	Imitation of mouth and facial postures and actions
Sequencing Praxis (SPr)	Imitation of novel hand sequential actions
Praxis on Verbal Command (PrVC)	Ability to demonstrate novel postures and actions based on simple verbal directions
Praxis Composite	PPr, OPr, SPr, PrVC
Vestibular and Proprioceptive Functions and Bilateral Motor Skills	
Kinesthesia (KIN)	Replication of arm position and movement
Standing and Walking Balance (SWB)	Static and dynamic balance
Postrotary Nystagmus (PRN)	Vestibular-ocular reflex following rotation
Bilateral Motor Coordination (BMC):	Replication of bilateral arm and foot movements
Vestibular-Proprioception Composite	Kin, SWB, BMC
Visual Perception and Visual Motor	
Space Visualization (SV)	Motor-free visual spatial perception
Figure Ground Perception (FG)	Motor-free ability to find figures embedded in background
Motor Accuracy (MAc)	Tracing over line with pencil
Design Copying (DC)	Replication of designs by drawing
Constructional Praxis (CPr)	Replication of block structures
Visual Composite	SV + FG + MAC + CPr

Autism Diagnostic Observation Schedule, Second Edition (ADOS-2)

Each participant was administered the ADOS-2, a semi-structured observational assessment developed for a trained examiner to identify behaviors associated with ASD (Lord et al., 2012). It is a reliable and valid instrument used to assess individuals across different developmental levels and chronological ages (Carr, 2013). Based on the age and language level of research participants, ADOS-2 Module 1, 2, or 3 was administered. ADOS-2 severity scores and calibrated domain scores for Social Affect (SA) and Restricted and Repetitive Behaviors (RRB) were generated (Hus et al., 2014).

The ADOS-2 scoring item D-1, Unusual Sensory Interest in Play Material/Person, is used to code all observations of atypical sensory interests or behaviors (Lord et al., 2012). D-1 falls within the RRB category of the ADOS-2 algorithm. Scores range from 0 to 3, with 0 indicating no sensory-related behaviors observed and 3 indicating definite sensory behaviors observed. Examples of sensory behaviors leading to elevated scores on item D-1 include behaviors such as the repetitive feeling of texture, strong interest in the repetition of certain sounds, and prolonged visual examination (Lord et al., 2012).

Cognitive Testing

To determine eligibility for participation in this study, the cognitive ability of all participants was measured using the WASI-II; Wechsler, 2011). The WASI-II is a reliable measure of general cognitive ability, yielding full-scale, verbal, and performance index scores obtained by administering all four subtests (30–45 min) or two subtests (~ 15 min) of the WASI-II. The WASI-II is normed for ages 6–89 years and is appropriate for use with individuals with a wide range of abilities (index scores range from 40 to 160). A non-verbal IQ of ≥ 65 was needed for inclusion in the study. We have found that non-verbal IQ provides a good measure of ability to engage in tasks such as those required for the assessments and treatment in this study.

Data Analysis

Descriptive statistics for the z scores of each SIPT test (group mean, SD, and % $\leq$ -1) are displayed in Table 3, and a depiction of the distribution of the individual scores as well as how they distribute as a function of IQ are displayed in Box Plots on Fig. 1. In addition to reporting on mean z scores for each test, we created composite scores for sensory integrative functions. These four composite scores are based on prior factor analytic studies showing that certain tests cluster on a single factor (Ayres, 1989; Mailloux et al., 2011; Mulligan, 1996). Composite scores were calculated by averaging all non-missing SIPT test z-scores contributing to a particular composite score. These were used to examine whether ADOS Social Affect (SA) score, Restricted Repetitive Behaviors (RRB) score, and ADOS D-1 score and IQ scores were related to SIPT scores using correlational analyses. We used full-scale IQ for these analyses as it provides an overall representation of cognitive ability. A tactile perception composite score was generated from the mean score on three tactile perception tests:

Table 3 *SIPT Tests Mean z Scores, Standard Deviations, Frequency and Percentages*

Test Name and Description	N	Mean z score	SD	Min	Max	Frequency/ percent <-1.0
Tactile Perception						
Manual Form Perception (MFP)	89	-1.76	1.43	-3.00	1.50	61/69
Finger Identification (FI)	83	-0.97	1.32	-3.00	1.62	38/46
Graphesthesia (GRA)	77	-1.77	1.05	-3.00	0.81	60/78
Tactile Perception Composite	90	-1.58	1.02	-3.00	1.20	60/67
Praxis						
Postural Praxis (PPr)	91	-2.37	0.89	-3.00	1.01	84/92
Oral Praxis (OPr)	90	-2.20	0.93	-3.00	1.24	79/88
Sequencing Praxis (SPr)	90	-1.57	1.25	-3.00	2.82	62/69
Praxis on Verbal Command (PrVC)	90	-2.35	1.06	-3.00	0.46	77/86
Praxis Composite	92	-2.14	0.76	-3.00	-0.07	85/92
Vestibular and Proprioceptive Functions and Bilateral Motor Skills						
Kinesthesia (KIN)	69	-1.42	1.21	-3.00	1.33	41/59
Standing Walking Balance (SWB)	92	-2.64	0.64	-3.00	-0.54	89/97
Bilateral Motor Coordination (BMC)	91	-1.04	1.02	-3.00	1.36	52/57
Composite: Kin, SWB, BMC	92	-1.78	0.70	-3.00	0.08	80/87
Visual Perception and Visual Motor						
Space Visualization (SV)	92	-1.25	1.03	-3.00	0.79	54/59
Figure Ground Perception (FG)	93	-1.07	1.06	-3.00	2.45	53/57
Motor Accuracy (MAC)	91	-0.84	1.36	-3.00	2.06	43/47
Design Copying (DC)	90	-1.38	1.49	-3.00	2.15	55/61
Constructional Praxis (CPr)	90	-1.07	1.30	-3.00	1.60	47/52
Visual Composite	93	-1.07	0.84	-2.79	0.99	50/54

SD = standard deviation, min = lowest score; max = highest score; percent = percent of sample

Postrotary Nystagmus (PRN): scores were not included in Vestibular and Proprioceptive Functions and Bilateral Motor Skills composite because scores below – 1.0 and above + 1.0 are indicative of dysfunction. PRN below – 1.0 (n = 24; 29%); PRN above + 1.0 (n = 20; 24%).

Manual Form Perception (MFP), Finger Identification (FI), and Graphesthesia (GRA). Therefore, the composite mean score consists of the MFP, FI, and GRA mean score based on all participants who completed this test. An additional tactile perception test that is part of the SIPT, Localization of Tactile Stimuli, was omitted because this test often shows high scores in children with tactile hyper-reactivity (Ayres, 1989) and thus, may not be a reliable reflection of tactile perception in autistic children, many of whom experience tactile hyper-reactivity.

Similarly, a praxis composite score was generated from three tests of imitation praxis (Postural Praxis (PPr), Oral Praxis (OPr), and Sequencing Praxis (SPr)) and one test of praxis from verbal directions (Praxis on Verbal Command-PrVC). The vestibular-proprioceptive and bilateral motor skills composite score was generated from one test of proprioception (Kinesthesia; KIN), one test of balance (Standing and Walking Balance; SWB), and one test of bilateral motor coordination (BMC). Both balance and bilateral coordination have been consistently associated with vestibular-proprioceptive functions on factor analytic studies (Ayres, 1989; Mailloux et al., 2011; Mulligan, 1996). A test of vestibular function, the Postrotary Nystagmus test, was omitted from the composite score because both high and low scores are reflective of dysfunction, thus negating the use of mean score analyses (Ayres, 1989). A visual perception and visual motor composite score was generated from two motor-free tests of visual perception (Space Visualization; SV) and Figure Ground (FG), two tests of visual motor skills (Motor Accuracy; MAC) and Design Copy (DC)), and one test of block design replication (Constructional Praxis (CPr). We included CPr within this composite because it utilizes visual perception and visual motor skills, and in prior studies, it correlated highly with the other tests in this composite group (Ayres, 1989; Van Jaarsveld et al., 2014).

Results

ADOS-2 Scores

As shown in Table 1, the ADOS-2 SA scores ranged from 4 to 10, with a mean score of 7.5 (1.83). Of note, only one participant obtained an SA total score of 4, and this individual met diagnostic criteria for ASD. ADOS-2 RRB scores ranged from 4 to 10, with a mean score of 8.7 (1.35).

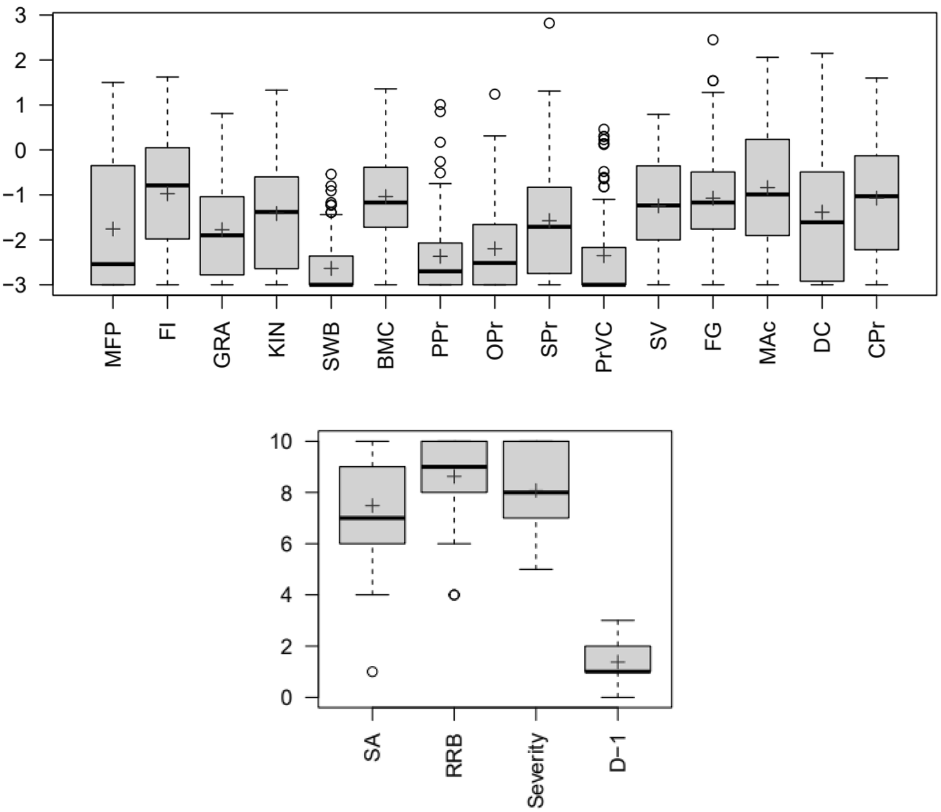

Fig. 1 *Boxplots for SIPT and ADOS* Legend: Dark line represents median; star represents mean. MFP = Manual Form Perception Test, FI = Finger Identification Test, GRA = Graphesthesia Test, KIN = Kinesthesia Test, SWB = Standing and Walking Balance Test, BMC = Bilateral Motor Coordination Test; PPr = Postural Praxis Test, OPr = Oral Praxis Test, SPr = Sequencing Praxis Test, PVC = Praxis on Verbal Command Test, SV = Space Visualization Test, FG = Figure Ground Test, MAC = Motor Accuracy Test, DC = Design Copying Test, CPr = Constructional Praxis Test. ADOS = Autism Diagnostic Observation Schedule 2nd Edition, SA = Social Affect, RRB = Restrictive and Repetitive Behaviors, D-1 = Sensory Item on ADOS2.

ADOS-2 Severity scores ranges from 5 to 10 with a mean score of 8.1 (1.58); and D-1 Score ranged from 0 to 3. Box Plots showing the range of ADOS-2 scores are displayed in Fig. 1.

SIPT Scores

As shown in Table 3; Fig. 1, SIPT group mean *z* scores ranged from − 3.0 to + 2.0, with SWB, PVC, PPr, and OPr showing the lowest mean *z* scores (-2.64, -2.35, 02.37, and − 2.20 respectively). For reference, in normed samples, by definition, the average *z* score is 0, with ± or − 1.0 SD falling within the typical range and below − 1.0, indicating below-average performance. The group mean scores fell below − 1.0 on all the individual tests except for FI (-0.97), which approached − 1.0. The number of participants for each test varies as some participants were not able to complete specific tests, with the KIN test having the lowest n (n = 63 out of 93 participants) and the FG test having the highest n (n = 93 out of 93 participants). Thus, mean scores of the group represent those who completed the test. These and percentage of those with scores below − 1.0 (last column in Table 3) are presented.

To provide information about internal consistency among the SIPT tests grouped into composite scores, we examined correlations among tests in a given composite and calculated Cronbach's alpha to explore the relationship of the grouped tests to the proposed construct. Of note, we did not expect to find high correlations among tests, as each test is designed to measure a unique function(s). We found that the tactile tests had significant correlations with each other (FI and MFP r = .34, p > .01, FI and GRA r = .41, p > .01; FI and GRA r = .32, p > .05); as did the praxis tests (PPr and OPr r = .54, p > .01; PPr and SPr r = .46, p > .01; PPr and PVC r = .48, p > .01; OPr and SPr r = .53 p > .01; and OPr and PVC r = .32, p > .05; SPr and PVC r = .45, p > .01). The Cronbach's alpha for tactile and praxis composites were α = 0.62 and α = 0.70 respectively. The visual tests showed moderate correlations among tests (ranging from r = .19 − .49) and α = 0.66 for Visual Composite. The tests grouped in the vestibular-proprioceptive and bilateral composite were not highly correlated with each other (with the exception of BMC and KIN- r = .40). The Cronbach's alpha for Vestibular-Proprioceptive and Bilateral Composite α = 0.43.

Tactile Perception

The mean z scores on the three tactile perception tests comprising the tactile perception composite score for the group are below − 1.0, with the exception of FI, that approaches − 1.0 (M = − 0.97, SD = 1.32), as shown in Table 3. In terms of percentage of the sample that scored below − 1.0 (shown

Table 4 *Spearman Correlations Among SIPT Composite Scores and ADOS Scores*

	Tactile	Praxis	Vestib-Prop	Visual
ADOS SA (Calibrated)	.043	−.07	.08	−.15
ADOS RRB (calibrated)	.06	.07	−.03	−.01
ADOS Severity Score	.05	−.08	.03	−.14
ADOS D-1	−.14	−.22*	−.24*	−.15

* Correlation is significant at the 0.05 level Vestib-Prop = vestibular, proprioceptive and bilateral integration composite

in last column of Table 3), of the 89 participants that completed the MFP, 69% participants scored less than −1.0 *z* score, 78% scored below −1.0 *z* score on the GRA test, and 46% scored below −1.0 on FI.

For the tactile composite score (FI + GRA + MFP), 67% of the sample scored in the deficient range. The mean *z* score was also in the deficient range (M = -1.58, SD = 1.02). As shown in Table 4, the tactile composite score was not significantly related to the ADOS-2 scores.

Praxis

There are four praxis tests and a praxis composite score. As shown in Tables 3 and 69–92% participants scored substantially below −1.0 on the praxis tests. On PPr, 92% scores below −1.0, 88% on OPr, 69% on SPr, and 86% on PrVC, with all of participants falling below −1.0 *z* score on each test. As shown in Table 3, the mean *z* score for PPr = -2.37 (0.89), OPr mean *z* score = -2.2 (0.93), SPr mean *z* score = -1.57 (1.25) and PrVC mean *z* score = -2.35 (1.06).

For the praxis composite score (PPr + OPr + SPr + PVC) 92% of the sample fell below −1.0 SD, with a mean *z* score of-2.14 (SD = 0.76). The Praxis composite score was not significantly related to the ADOS-2 SA, RRB, or Severity scores, but the correlations between the praxis composite score and ADOS D-1 approached significance (r= -0,22, *p* = .06).

Vestibular, Proprioceptive and Bilateral Motor Skills

These include three tests: Kin, SWB, and BMC, and a composite score. Of note, 97% of the sample scored below −1.0 on the SWB test. 59% of the sample scored below −1.0 on KIN, and 57% scored below −1.0 on BMC. Mean scores for the group are as follows: Kin (M =-1.42, SD = 1.21), BMC (M = -1.04; SD = 1.02), SWB (M = -2.64, SD = 0.64).

On the Vestibular, Proprioceptive and Bilateral Motor Skills Composite score (Kin + SWB + BMC), 87% of the sample fell below −1.0 with group mean *z* score = -1.78 (SD = 0.7). This composite score was not related to the ADOS-2 SA or RRB but the ADOS-2 D1 scores was negatively correlated with the vestibular composite score (r = −.24; p = .03).

Table 5a Correlations of SIPT and Full Scale IQ Scores

SIPT Test	R value
MFP	.46**
FI	.40**
GRA	.51**
Tactile composite	.57**
KIN	.16
SWB	34*
BMC	.52**
Vestibular composite	.53**
PPr	.49**
OPr	.40**
SPr	.53**
PVC	.57**
Praxis composite	.62**
SV	.32*
FG	.50**
MAC	.40**
DC	.42**
CPr	.55**
c	.60**

** p ≤ .001; * p ≤ .05

Visual Perceptual and Visual Motor Skills

These include five tests of visual perception and visual motor skills. In general, about half of the sample scored below −1.0 on these tests. For DC, 61% participants scored below −1.0, SV 59% scored below −1.0, FG 57% scored below −1.0, and MAC where 47% scored below −1.0, and CPr 52% scored below −1.0. Group mean scores on DC (M = -1.37, SD = 1.50), SV (M = -1.25, SD = 1.03), DC (M = -1.05, SD = 1.07), MAC (M = -0.84, SD = 1.36), and CPr (M = -1.07, SD = 1.3). 54% of the sample scored below −1.0 on the Visual Composite Score (SV + FG +, MAC + DC + CPr) with a mean *z* score = -1.07 (SD = 0.84). The Visual Perception and Visual Motor Composite score was not related to the ADOS-2 scores.

IQ and SIPT Tests

In regard to the relationship of SIPT tests to IQ scores, as shown in Table 5a, there were significant relationships among all but two of the SIPT tests (KIN and PRN). To further explore this relationship, a secondary analysis was conducted. In this analysis, SIPT scores below −1.0 in three groups of participants were included: those with full-scale IQ lower than 85 (n = 44), in the range of 85–115 (n = 43), and those above 115 (n = 6). These data are presented in Table 5b. While those in the lower IQ group tend to show a higher percentage of lower SIPT scores in many of the tests, this is not the case across the board. Those with IQ scores between 85 and 115 and above 115 also show substantial

Table 5b SIPT by IQ Scores

	IQ lower than 85 IQs		IQ between 85–115		Upper IQs	
	N below − 1, out of total (all below and above − 1)	**% of sample below − 1**	**N below − 1, out of total (all below and above − 1)**	**% of sample below − 1**	**N below − 1, out of total (all below and above − 1)**	**% of sample below − 1**
SIPT Manual Form Perception (MFP)	35/41	79.55%	23/42	53.49%	3/6	50.00%
SIPT Finger Identification (FI)	24/36	54.55%	12/41	27.91%	2/4	33.33%
SIPT Graphesthesia (GRA)	29/31	65.91%	29/41	67.44%	2/5	33.33%
SIPT Kinesthesia (KIN)	18/24	40.91%	21/40	48.84%	2/5	33.33%
SIPT Standing Walking Balance (SWB)	43/43	97.73%	41/43	95.35%	5/6	83.33%
SIPT Bilateral Motor Coordination (BMC)	34/42	77.27%	16/43	37.21%	2/6	33.33%
SIPT Postural Praxis (PPr)	41/42	93.18%	38/43	88.37%	5/6	83.33%
SIPT Oral Praxis (OPr)	38/41	86.36%	36/41	83.72%	5	83.33%
SIPT Sequencing Praxis (SPr)	37/41	84.09%	23/43	53.49%	2/6	33.33%
SIPT Praxis on Verbal Command (PrVC)	40/41	90.91%	35/43	81.40%	2/6	33.33%
SIPT Space Visualization (SV)	31/43	70.45%	21/43	48.84%	2/6	33.33%
SIPT Figure-Ground (FG)	33/44	75.00%	17/43	39.53%	3/6	50.00%
SIPT Motor Accuracy (MAc)	27/42	61.36%	16/43	37.21%	0/6	0%
SIPT Design Copying (DC)	29/41	65.91%	21/43	48.84%	5/6	83.33%
SIPT Constructional Praxis (CPr)	30/41	68.18%	16/43	37.21%	1/6	16.67%

IQ = Full Scale scores

PRN tests are not reported because scores below – 1.0 and above + 1.0 are indicative of dysfunction

percentages of deficits in many of the SIPT tests. For example, 5 of the 6 participants (in the IQ above 115 group scored in the deficient range (below – 1.0) on SWB, PPr, and OPr. Similarly, a substantial percentage in the IQ group between 85 and 115 scored below – 1.0 on these tests. Thus, although IQ is related to SIPT scores, it does not appear to be the sole influence.

Discussion

In this paper, the sensory integrative functions in a sample of children with ASD are reported. Our approach uses direct measurements from a normed and validated instrument, the SIPT. These data show that autistic children in this sample have sensory-related differences beyond those described in the DSM-5. Most strikingly, they show deficits in tactile perception, proprioception, balance, and praxis. These findings add important knowledge regarding the sensory differences in ASD and point to the need for a more thorough assessment of sensory integrative factors to understand the full range of sensory factors and their contribution to the core behavioral phenotype of ASD and provide additional details regarding the specific sensory functions to consider when designing individualized interventions. Importantly, the SIPT extends well beyond hypo- or hyper-reactivity and provides a method of assessing additional sensory factors. It also provides performance-based assessment that provides data beyond parent/proxy reported observation of behavioral responses to sensation.

Autism has been defined as a disorder of social communication and restricted and repetitive behaviors (APA 2013), however, the scientific and clinical autism community recognizes that ASD has additional important features that impact behavior and function and are critical for developing effective treatments. The findings from this study suggest that it may be valuable to expand the sensory features considered under the restricted and repetitive behaviors designation, showing that sensory integration challenges beyond sensory reactivity are often present. Significantly, the domains identified through the SIPT as particularly vulnerable in this sample have shown that they are amenable therapeutic interventions (Schaaf, et al., 2014; Steinbrenner, et al., 2020). Thus, it is important to recognize these features of ASD when they are present. The SIPT represents one way to do this.

Praxis

In the area of praxis, a substantial number of the participants scored well below age expectancy on all tests. Praxis involves the ability to use sensory information to successfully act and interact (Ayres, 1989; Edwards et al., 2019; Machado et al., 2010; Wolpert et al., 1998). Praxis is more than motor skills; it is a sensorimotor function that depends on adequate perception of sensations to direct and guide motor actions (Ayres, 1989; Berger, 2012). Children in this sample had substantial difficulties with all areas of praxis including body imitation praxis (PPr body and OPr face/mouth), imitating a sequence of novel hand actions (SPr) and executing novel postures and actions in response to simple verbal directions (PrVC; e.g.: “put one hand on your head and one hand on your stomach”). These findings are consistent with MacNeil and Mostofsky (2012), who showed that children with ASD, in comparison to those with ADHD and typically developing, performed significantly worse on tests of praxis. These findings suggest that sensory-related praxis difficulties may be specific to autism.

Praxis is the foundation for important skills and functional abilities, including social interactions. As early as 2003, Rogers and colleagues (2003) showed that children with ASD had significantly greater difficulties in motor imitation in comparison to those with other neurodevelopmental disorders and typically developing controls and suggested that motor imitation may provide a foundation for social connectedness. Later, Smith-Roley and colleagues (2015) showed substantial difficulties in praxis, measured using the SIPT, in a cohort of children with ASD, and found that low scores on praxis tests were significantly associated with difficulties in social participation. Similarly, Dziuk, et al. (2007) showed that praxis in children with ASD was correlated with social impairments and suggested that dyspraxia “may be a core feature of autism or a marker of the neurological abnormalities that underlie the disorder” (p 734). Thus, our data adds to a growing body of literature showing (1) that children with ASD have deficits in praxis, (2) these are associated with underlying sensorimotor factors, and (3) difficulties in praxis may be an important factor impacting social participation in children with ASD. In fact, some scientists now suggest a cognitive-motor model of autism that appreciates this sensory integrative component of ASD (Berger, et al., 2012; Rizzolatti and Fabbri-Destro, 2010; Mostofsky and Ewen, 2011).

Postural Control and Balance

Another important finding in these data is that almost all of the children in the sample showed difficulties in postural control and balance as measured by the SIPT Standing and Walking Balance Test. This test challenges the child’s static and dynamic balance requiring them to stand on one foot with eyes open and closed, walk heel to toe, balance on a half-dowel, and walk on a line. The postural adjustments needed to maintain balance require integration of vestibular, visual, proprioceptive, and tactile information for the execution of adaptive postural and equilibrium responses (Bojanek et al., 2020). Our findings are consistent with the literature showing that autistic persons have greater challenges in balance (Travers et al., 2020; Travers et al., 2013; Lim et al., 2017). Further research shows that postural and balance difficulties are related to other autism features such as social communication (Travers et al., 2013) and repetitive behaviors (Radonovich et al., 2013). Again, these data point to the importance of assessment of sensory integrative functions to obtain a comprehensive understanding of autism and to guide tailored interventions designed to improve function and participation in daily activities and tasks.

Tactile Perception

Difficulties in tactile perception, an area that is rarely assessed in ASD, were found. Usually, sensory testing includes evaluation of tactile reactivity (e.g., hypo and hyper-reactivity) but does not include testing about identification and localization of tactile sensations. Touch is one of the earliest senses to develop, playing a critical role in human development across the lifespan (Ayres, 1964; 1972; Field, 2010; Linden, 2016; Montagu, 1986). The interpretation of touch sensations is critical to human functioning and is essential for using one’s body effectively in the physical world, communicating nonverbally, and sustaining social relationships (Ayres, 1972; Cascio, et al., 2019; Montagu, 1986). Tactile perception provides essential sensory information that informs social communication (Ellingsen et al., 2016), body awareness (Head, 1920; Tresilian, 2012), postural control (Hadders-Algra & Carlberg, 2008), and motor performance (Shumway-Cook & Woolacott, 2007). In their review, Zetler et al. (2019) found a high prevalence of tactile perceptual problems in young children with ASD and concluded that assessment of tactile perception is an important part of a comprehensive evaluation.

It is widely recognized that tactile perception informs awareness of the body by specifying information to the somatosensory cortex (Robbe, 2018). Knowing where the body was touched or what the body is touching allows discrimination of objects, shapes, and textures (Wolfe et al., 2017). Furthermore, touch integrates with other senses, such as vision, vestibular, and proprioception, to guide actions (Ernst & Banks, 2002) and enable participation in activities that require seeing, reaching, touching, and moving (Streri et al., 1993). The speed and accuracy of tactile processing, as well as the integration of tactile input with other sensory data, affects the ease and efficiency of actions such as writing and drawing, manipulating buttons, or finding keys in a bag. Thus, tactile perception is critical for the development of many foundational skills that impact participation in tasks and interactions with others, contributing to the development of body scheme, motor planning ability, and motor skill acquisition. Specifically, in regard to ASD and tactile perception, Cascio and colleagues (2015) showed that parent-reported tactile hyporeactivity in children was associated with a later event-related potential in the somatosensory cortex suggesting delayed processing; and Puts et al. (2014) found that children with ASD had higher detection threshold (decreased reactions) to tactile stimulation providing evidence that decreased tactile perception in ASD may be related to differences in neural processing of touch sensations. Others, however, suggest that decreased tactile perception may reflect more conservative decision-making in children with ASD (Quinde-Zlibut et al., 2020). Clearly, more research is needed to clarify the neural basis of decreased tactile perception in ASD.

Further, tactile perception is related to praxis. In multiple studies across six decades, Ayres and colleagues showed strong and significant associations between tactile perception and praxis (Ayres, 1964, 1965, 1972, 1989; Mulligan, 1998; Mailloux, et al., 2011). This relationship may explain why children who have poor tactile perception often have trouble planning actions in daily life activities, such as donning clothing, playing with toys, or using a writing utensil. Poor tactile functions in children can also impair the development of fine motor skills, in-hand manipulation, and tool use. These functions are needed for success in play, self-care, and academic tasks (Ayres, 2005; Case-Smith, 1991). Ayres (2005) noted this relationship between touch and praxis, stating that, "… tactile input-particularly sensations from the hands, fingers, and mouth are very specific…A detailed picture is formed of these sensations in the sensory cortex, and the person can respond in a very precise way. Writing is a good example of an activity that involves many specific tactile sensations…" p. 92. Hence, tactile perception provides a foundation for praxis. In our sample, many participants showed both tactile perception, praxis difficulties, and delays in daily living skills. Given that tactile perception provides important foundations for engagement in many tasks and activities, it is crucial that it be assessed when considering the sensory factors that may impact participation in tasks and activities.

Visual Perception and Visual Motor Skills

While neuropsychological tests measure visual perceptual function and visuoconstructive abilities with tasks utilizing spatial relationships, visual scanning, and visual discrimination, the SIPT is unique in measuring these specific functions as well as integrated sensory perception and sensorimotor skills such as praxis and balance (Korkman et al., 2007; Lezak et al., 2012; Roid & Miller, 1997). In terms of visual perception and visual motor skills, Smith-Roley, et al. (2015) showed that autistic children exhibited relative strength in visual-related skills. In our sample, however, difficulties with visual perception and visual motor skills were evident, even when IQ was considered, albeit these were not as severe as the other areas. As shown in Table 5, those with IQ scores above 115 show deficits in visual perception and visual motor skills, as do the other IQ groups. It has been suggested that autistic persons may have strength in attending to the details of the visual environment but challenges in global processing or "seeing the forest from the trees" (Robertson and Baron-Cohen, 2017) and "difficulty integrating dynamic (less predictable) visual information into motor commands" (Lim and Mostofsky, 2022; page 99). Further, visual motion perception may evolve more slowly in ASD (Robertson, et al., 2012; Robertson, et al., 2014). These authors suggest that visual motion perception may impact the acquisition of crucial motor, social and communicative development. While it is beyond the scope of this paper to examine the relations of visual perception and visual motor skills to later development in ASD, our findings point to the need for further analysis of these skills and their role in autism.

A case for Measuring Sensory Integration

It is interesting to note that the SIPT composite scores were not strongly correlated with the ADOS-2 SA scores or the ADO-2 S RRB scores. This finding suggests that the SIPT is measuring a unique aspect of ASD that is not captured with the ADOS-2. The SIPT provides a useful, standardized, and norm-referenced assessment of these important but often neglected sensory integrative functions. One hesitation to using the SIPT with ASD children is concern that they may not be able to complete the test battery. By design, the SIPT utilizes simple verbal and physical instructions (i.e., "use your pencil to copy these designs" or "make your body do what I am doing"), making it appropriate for children with ASD who have low language abilities or cognitive skills. All ninety-three participants randomized in this study participated in at least 70% of the SIPT tests, and 66% completed all 17 SIPT tests. Given that participants IQ scores ranged from 50 to 166, our findings show that the SIPT can be used with a wide range of ASD children, including those with low IQ scores. Eight participants had full-scale IQ scores below 70 and of these, two had non-verbal IQ that fell below 60. All eight of these participants were able to complete the SIPT. Further, it appears that although IQ is related to SIPT scores, it is not the sole determinant of these scores, as even children with IQ scores above 85 showed difficulties.

Of note, to make testing of these sensory integrative functions even more accessible, a new test is in the final stages of development. The Evaluation of Ayres Sensory Integration (EASI; (Mailloux, et al. 2020)) evaluates similar functions as the SIPT, but includes updated norms, extends the normative age groups to a wider range (3–12 years of age), and is available in an open-source format. This test will provide an updated option for testing sensory integrative functions. Training on the EASI is available online and in more than 10 languages making it accessible to a wide range of countries and cultures.

In summary, this study adds to the growing body of literature showing that children with ASD who are identified with sensory issues show additional sensory integrative difficulties beyond those named in the DSM5 and beyond those measured by questionnaires designed to assess the presence of sensory differences such as the Sensory Profile (Dunn, 2014), the Sensory Processing Measure (Parham, et al., 2007) and the Sensory Experiences Questionnaire (Baranek, 2005). Our findings highlight the value of testing these important functions to obtain a comprehensive view of the child's sensory integrative strengths and challenges for characterization and personalization of treatment. Often sensory testing is limited to parent report of sensory reactivity (hypo, hyper-reactivity, seeking). While this is a valuable aspect of sensory assessment, this approach may miss important sensory integrative aspects (e.g., tactile perception, balance, praxis) that are an important component of function and participation for children with ASD. Inclusion of these functions in the characterization of ASD may lead to a more comprehensive understanding of the sensory features of ASD. Finally, these sensory integrative functions of ASD are important to consider when designing interventions designed to improve function and participation in daily activities and tasks.

Limitations

There are a few limitations that may impact the interpretation of these data. The sample includes only children who met the criteria for sensory dysfunction, and although this includes upwards of 80% of autistic children (Ben-Sasson, et al., 2019), the sample may not be fully representative of the ASD population. Further, this study consisted of children who participated in a study of sensory integrative treatment, and thus, data may be biased toward families whose children showed sensory differences and were potentially drawn to participate. In creating our composite scores, we calculated a score for children who had at least one SIPT test score leading to some potential errors in summary measures. We performed sensitivity analyses requiring at least 2 subtests and all subtests. In both cases, there was little effect on the distribution of composite scores or in the associations with ADOS scores. In addition, there were ten children who were nine years of age. Given that the highest SIPT normative data comparison group is 8 years 11 months, normative data from this age group this was used for these children. This approach is supported by the fact that normative data on the SIPT plateau at the 8.11 age range. However, it is possible that the SIPT z scores for the 9-year-olds may be an underestimation of their actual performance (i.e. scores may be worse than reported). Finally, it should be noted that the norms for the SIPT are somewhat dated in that they are from 1989 and, thus, may not be representative of the population today. This is one reason that the EASI is being developed, and future analysis of sensory functions in ASD can use this assessment.

Acknowledgements We thank the children and families who participated in this study, and Drs. Joanne Hunt, John Eboli, and Anna Keenaghan, who served as independent evaluators. This study was funded by the National Institute of Child Health and Human Development Clinical trial number (NICHD #RO1HD082814). Dr. Zoe Mailloux is an of the authors of the Evaluation of Ayres Sensory Integration.

Declarations

Conflict of interest Dr. Mailloux is an author of the Evaluation of Ayres Sensory Integration which is mentioned in this article.

References

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). https://doi.org/10.1176/appi.books.9780890425596

Ayres, A. J. (1964). Tactile functions: Their relation to hyperactive and perceptual motor behavior. American Journal of Occupational Therapy, 18, 6–11.

Ayres, A. J. (1965). Patterns of perceptual-motor dysfunction in children: A factor analytic study. *Perceptual and Motor Skills*, *20*(2), 335–368. https://doi.org/10.2466/pms.1965.20.2.335

Ayres, A. J. (1972). *Sensory integration and Learning Disabilities*. Western Psychological Services.

Ayres, A. J. (1979). *Sensory integration and the child*. Western Psychological Services.

Ayres, A. J. (1989). *Sensory Integration and Praxis Tests manual*. Western Psychological Services.

Ayres, A. J. (2005). *Sensory integration and the Child: 25th-anniversary edition*. Western Psychological Services.

Baranek, G. T., David, F. J., Poe, M. D., Stone, W. L., & Watson, L. R. (2005). Sensory Experiences Questionnaire: Discriminating sensory features in young autistic children, developmental delays, and typical development. *Journal of Child Psychology and Psychiatry*, *47*(6), 591–601. https://doi.org/10.1111/j.1469-7610.2005.01546.x

Ben-Sasson, A., Gal, E., Fluss, R., Katz-Zetler, N., & Cermak, S. A. (2019). Update of a meta-analysis of sensory symptoms in ASD: A new decade of research. *Journal of Autism and Developmental Disorders*, *49*(12), 4974–4996.

Beker, S.L, Foxe, J.J., Venticinque, J. Bates, J., Ridgway, E., Schaaf, R.C., Molholm, S (2021). Looking for consistency in an uncertain world: Test-retest reliability of neurophysiological and behavioral readouts in autism. J of Neurodevelopmental Disorders, 13(1): 43. https://doi:10.1186/s11689-021-09383-0

Berger K. A. (2013). Praxis and autism: the psychomotor regulation sensory processing dimension-a report from the field. *Frontiers* *in Integrative Neuroscience*, *6*(129). https://doi.org/10.3389/fnint.2012.00129

Bojanek, E. K., Wang, Z., White, S. P., & Mosconi, M. W. (2020). Postural control processes during standing and step initiation in autism spectrum disorder. *Journal of neurodevelopmental disorders*, *12*(1), 1–13.

Brandwein, A. B., Foxe, J. J., Butler, J. S., Russo, N. N., Altschuler, T. S., Gomes, H., & Molholm, S. (2013). The development of multisensory integration in high-functioning autism: high-density electrical mapping and psychophysical measures reveal impairments in the processing of audiovisual inputs. *Cerebral Cortex*, *23*(6), 1329–1341.

Carr T. (2013) Autism Diagnostic Observation Schedule. In: Volkmar F.R. (eds) Encyclopedia of Autism Spectrum Disorders. Springer, New York, NY. https://doi.org/10.1007/978-1-4419-1698-3_896

Cascio, C. J., Gu, C., Schauder, K. B., Key, A. P., & Yoder, P. (2015). Somatosensory event-related potentials and association with tactile behavioral responsiveness patterns in children with ASD. *Brain Topography*, *28*(6), 895–903. https://doi.org/10.1007/s10548-015-0439-1

Cascio, C. J., Moore, D., & McGlone, F. (2019). Social Touch and Human Development. *Developmental Cognitive Neuroscience*, *35*, 5–11. https://doi.org/10.1016/j.dcn.2018.04.009

Case-Smith, J. (1991). The effects of tactile defensiveness and tactile discrimination on in-hand manipulation. *The American Journal of Occupational Therapy*, *45*(9), 811–818. https://doi.org/10.5014/ajot.45.9.811

Crosse, MJ, Foxe, J.J. Tarrit, Friedman, Molholm, S. (in press). Resolution of Impaired

Multisensory Processing in Autism and the Cost of Switching Sensory Modality.

Communication Biology.

Crosse, M. J., Foxe, J. J., & Molholm, S. (2019). *Developmental Recovery of Impaired Multisensory Processing in Autism and the Cost of Switching Sensory Modality* [Preprint]. BioRxiv. https://doi.org/10.1101/565333

Dunn, W. (2014). *Sensory Profile 2 User's Manual*. San Antonio: Pearson.

Dziuk, M. A., Larson, J. G., Apostu, A., Mahone, E. M., Denckla, M. B., & Mostofsky, S. H. (2007). Dyspraxia in autism: association with motor, social, and communicative deficits. *Developmental Medicine & Child Neurology*, *49*(10), 734–739.

Edwards, L. L., King, E. M., Buetefisch, C. M., & Borich, M. R. (2019). Putting the "sensory" into Sensorimotor Control: The role of sensorimotor integration in goal-directed hand movements after stroke. *Frontiers in Integrative Neuroscience*, *13*. https://doi.org/10.3389/fnint.2019.00016

Ellingsen, D., Leknes. Si, Løseth, G., Wessberg, J& Olausson, H. (2016). The Neurobiology Shaping Affective Touch: Expectation, Motivation, and Meaning in the Multisensory Context. *Frontiers in Psychology*. doi: 10.3389/fpsyg.2015.01986

Ernst, M., Banks, M. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature, 415*. 429–433 (2002). https://doi.org/10.1038/415429a

Field, T. (2010). Touch for socioemotional and physical well-being: A Review. *Developmental Review*, *30*(4), 367–383. https://doi.org/10.1016/j.dr.2011.01.001

Hadders-Algra, M., & Carlberg, E. B. (2008). *Postural Control: A Key Issue in Developmental Disorders*. Wiley-Blackwell.

Hannant, P., Tavassoli, T., & Cassidy, S. (2016). The role of sensorimotor difficulties in autism spectrum conditions. *Frontiers in neurology*, *7*, 124.

Head H. (1920). Aphasia: an historical review. *Brain*, 43:390.

Hus, V., & Lord, C. (2014). The Autism Diagnostic Observation Schedule, module 4: Revised algorithm and standardized severity scores. *Journal of Autism and Developmental Disorders*, *44*(8). 1996–2012. https://doi.org/10.1007/s10803-014-2080-3

Korkman, M., Kirk, U., & Kemp, S. (2007). *NEPSY-Second Edition (NEPSY-II)*. San Antonio, TX: Harcourt Assessment.

Lezak, M. D., Howieson, D. B., Bigler, E. D., & Tranel, D. (2012). *Neuropsychological Assessment* (5th ed.). Oxford University Press.

Lim, Y. H., Partridge, K., Girdler, S., & Morris, S. L. (2017). Standing postural control in individuals with autism spectrum disorder: systematic review and meta-analysis. *Journal of Autism and Developmental Disorders*, *47*(7). https://doi.org/10.1007/s10803-017-3144-y

Lidstone, D. E., & Mostofsky, S. H. (2021). Moving toward understanding autism: Visual-motor integration, imitation, and social skill development. *Pediatric Neurology*, *122*, 98–105.

Linden, D. J. (2016). *Touch: The science of hand, heart, mind*. Penguin.

Lord, C., Rutter, M., DiLavore, P. C., Risi, S., Gotham, K., & Bishop, S. L. (2012). Autism diagnostic observation schedule, (ADOS-2), Part 1: Modules 1–4 (2nd ed.). Los Angeles, Western Psychological Services.

MacNeil, L. K., & Mostofsky, S. H. (2012). Specificity of dyspraxia in children with autism. *Neuropsychology*, *26*(2), 165–171. https://doi.org/10.1037/a0026955

Machado, S., Cunha, M., Velasques, B., Minc, D., Teixeira, S., Domingues, C. A., Silva, J. G., Bastos, V. H., Budde, H., Cagy, M., Basile, L., Piedade, R., Ribeiro, P. (2010). Sensorimotor integration: basic concepts, abnormalities related to movement disorders and sensorimotor training-induced cortical reorganization. *Revista de Neurología, 51*(7), 427–436.

Mailloux, Z., Smith-Roley, S., Parham, L.D., Ruzzano, L., **Schaaf, R.C.** (2018). Introduction to the Evaluation of Ayres Sensory Integration. American Journal of Occupational Therapy. 72(1): 7201195030p1-7201195030p7. https://doi-org.proxy1.lib.tju.edu/10.5014/ajot.2018.028241

Mailloux, Z., Mulligan, S., Smith Roley, S., Blanche, E., Cermak, S., Coleman, G., Bodison, S., Lane, C. (2011). *Verification and Clarification of Patterns of Sensory Integrative Dysfunction.* American Journal of Occupational Therapy. *65*(2). 143–151.

Melnick, M.D., Harrison, B.R., Parks, S., Bennetto, L., Tadin, D (2013). A strong interactive link between sensory discriminations and intelligence. Curr Biol, June 3, 23(11): 1013-7. https://doi:10.1016/j.cub.2013.04.053

Molholm, S., Ritter, W., Murray, M. M., Javitt, D. C., Schroeder, C. E., & Foxe, J. J. (2002). Multisensory auditory-visual interactions during early sensory processing in humans: A high-density electrical mapping study. *Cognitive Brain Research*, *14*(1), 115–128. https://doi.org/10.1016/S0926-6410(02)00066-6

Montagu, A. (2010). *Touching: The Human Significance of the Skin*. General Books.

Mostofsky, S. H., & Ewen, J. B. (2011). Altered connectivity and action model formation in autism is autism. *The Neuroscientist*, *17*(4), 437–448. https://doi.org/10.1177/1073858410392381

Mulligan, S. (1996) Cluster analysis of scores of children on the Sensory Integration and Praxis Tests. *The Occupational Therapy Journal of Research*, 20 (4). 256–270

Mulligan, S. (1998). Patterns of Sensory Integrative Dysfunction: A Confirmatory Analysis. *American Journal of Occupational Therapy. 52*(10). 819–828.

Parham, L. D., Ecker, C., Kuhaneck, H., Henry, D. A., & Glennon, T. J. (2007). *Sensory Processing Measure* (2nd ed.). Western Psychological Services.

Puts, N. A., Wodka, E. L., Tommerdahl, M., Mostofsky, S. H., & Edden, R. A. (2014). Impaired tactile processing in children with autism spectrum disorder. *Journal of Neurophysiology*, *111*(9), 1803–1811. https://doi.org/10.1152/jn.00890.2013.

Quinde-Zlibut, J.M., Okitondo, D.D., Williams, Z., Weitlauf, A.,…. Cascio, C. (2020). Elevated thresholds for light touch in children with autism reflect more conservative perceptual decision –making rather than a sensory deficit. Frontiers in Human Neuroscience, 14:122. https://10.3389/fnhum.2020.00122.

Radonovich, K., Fournier, K. A., & Hass, C. J. (2013). Relationship between postural control and restricted, repetitive behaviors in autism spectrum disorders. *Frontiers in integrative neuroscience* (*7*)28. https://doi.org/10.3389/fnint.2013.00028

Rizzolatti, G., and Fabbri-Destro, M. (2010). Mirror neurons: from discovery to autism. *Exp. Brain Res*. *200*(3–4). https://doi.org/10.1007/s00221-009-2002-3

Robbe, D. (2018). To move or to sense? incorporating somatosensory representation into striatal functions. *Current Opinion in Neurobiology*, *52*, 123–130. https://doi.org/10.1016/j.conb.2018.04.009

Robertson, C. E., Martin, A., Baker, C. I., & Baron-Cohen, S. (2012). Atypical integration of motion signals in autism spectrum conditions. *PLoS ONE*, *7*(11). https://doi.org/10.1371/journal.pone.0048173

Robertson, C. E., Thomas, C., Kravitz, D. J., Wallace, G. L., Baron-Cohen, S., Martin, A., & Baker, C. I. (2014). Global motion perception deficits in autism are reflected as early as primary visual cortex. *Brain*, *137*(9), 2588–2599. https://doi.org/10.1093/brain/awu189

Robertson, C. E., & Baron-Cohen, S. (2017). Sensory perception in autism. *Nature Reviews Neuroscience*, *18*(11), 671–684. https://doi.org/10.1038/nrn.2017.112

Rogers, S. J., Hepburn, S. L., Stackhouse, T., & Wehner, E. (2003). Imitation performance in toddlers with autism and those with other developmental disorders. *Journal of Child Psychology and Psychiatry*, *44*(5), 763–781. https://doi.org/10.1111/1469-7610.00162

Roid, G. H., & Miller, L. J. (1997). *Leiter international performance scale-revised (Leiter-R)*. Wood Dale, IL: Stoelting,10.

Roley, S. S., Mailloux, Z., Parham, L. D., Schaaf, R. C., Lane, C. J., & Cermak, S. (2015). Sensory integration and praxis patterns in children with autism. *The American Journal of Occupational Therapy*, *69*(1). https://doi.org/10.5014/ajot.2015.012476.

Schaaf, R. C., Benevides, T., Mailloux, Z., Faller, P., Hunt, J., Van Hooydonk, E., … & Kelly, D. (2014). An intervention for sensory difficulties in children with autism: A randomized trial. *Journal of autism and developmental disorders*, *44*(7), 1493–1506.

Schaaf, R. C., & Lane, A. E. (2015). Toward a best-practice protocol for assessment of sensory features in ASD. *Journal of Autism and Developmental Disorders*, *45*(5), 1380–1395.

Shumway-Cook, A., & Woollacott, M. H. (2007). *Motor control: Translating research into clinical practice*. Lippincott Williams & Wilkins.

Streri, A. (1993). *Seeing, reaching, touching: The relations between vision and touch in infancy*. Harvester Wheatsheaf.

Steinbrenner, J. R., Hume, K., Odom, S. L., Morin, K. L., Nowell, S. W., Tomaszewski, B., … & Savage, M. N. (2020). Evidence-Based Practices for Children, Youth, and Young Adults with Autism. *FPG Child Development Institute*.

Stein, B. E., Stanford, T. R., & Rowland, B. A. (2014). Development of multisensory integration from the perspective of the individual neuron. *Nature Reviews Neuroscience*, *15*(8), 520–535. https://doi.org/10.1038/nrn3742

Travers, B. G., Powell, P. S., Klinger, L. G., & Klinger, M. R. (2013). Motor difficulties in autism spectrum disorder: linking symptom severity and postural stability. *Journal of autism and developmental disorders*, *43*(7). https://doi.org/10.1007/s10803-012-1702-x

Travers, B. G., Lee, L., Klans, N., Engeldinger, A., Taylor, D., Ausderau, K., Skaletski, E. C., & Brown, J. (2022). Associations among daily living skills, motor, and sensory difficulties in autistic and nonautistic children. American *Journal of Occupational Therapy*, *76.* https://doi.org/10.5014/ajot.2022.045955

Tresilian J. (2012). *Sensorimotor control & Learning: An introduction to the behavioral neuroscience of action.* NY, NY: Palgrave Macmillan.

Van Jaarsveld, A., Mailloux, Z., Smith Roley, S., Raubenheimer, J.(2014) Patterns of sensory integration dysfunction in children from South Africa, South African Journal of Occupational Therapy 44 (2), 2–6.

Wechsler, D. (2011). *Wechsler Abbreviated Scale of Intelligence (2nd ed.)*. Pearson.

Williams, K. L., Kirby, A. V., Watson, L. R., Sideris, J., Bulluck, J., & Baranek, G. T. (2018). Sensory features as predictors of adaptive behaviors: A Comparative Longitudinal Study of children with autism spectrum disorder and other developmental disabilities. *Research in Developmental Disabilities*, *81*, 103–112. https://doi.org/10.1016/j.ridd.2018.07.002

Travers, B. G., Lee, L., Klans, N., Engeldinger, A., Taylor, D., Ausderau, K., Skaletski, E. C., & Brown, J. (2022). Associations among daily living skills, motor, and sensory difficulties in autistic and nonautistic children. *The American Journal of Occupational Therapy*, *76*(2). https://doi.org/10.5014/ajot.2022.045955

Wolfe, J.M., Kluender, K.R., Levi, D.M. Bartoshuk, L.M., Herz, R.S., Klatsky, R.L., & Merfeld, D.M. (2017). *Sensation & perception,* 5th Edition. Sunderland, Massachusetts: Sinauer Associates, Inc.

Wolpert, D. M., Goodbody, S. J., and Husain, M. (1998). Maintaining internal representations: the role of the human superior parietal lobe. *Nature Neuroscience.* 1, 529–533. doi: 10.1038/2245.

Zappullo, I., Senese, V. P., Milo, R., Positano, M., Cecere, R., Raimo, G., & Conson, M. (2022). Specific global–local visual processing abilities mediate the influence of non-social autistic-like traits on mental rotation. *Journal of Autism and Developmental Disorders*. https://doi.org/10.1007/s10803-021-05412-y

Zetler, N. K., Cermak, S. A., Engel-Yeger, B., & Gal, E. (2019). Somatosensory Discrimination in People With Autism Spectrum Disorder: A Scoping Review. *The American Journal of Occupational Therapy*, *73*(5). https://doi.org/10.5014/ajot.2019.029728