JSLHR

Research Article

Sensory Responsiveness Is Linked With Communication in Infant Siblings of Children With and Without Autism

Jacob I. Feldman,[a,b] Sweeya Raj,[c] Sarah M. Bowman,[b] Pooja Santapuram,[d] Alexandra J. Golden,[d] Claire Daly,[e] Kacie Dunham,[a,f,g] Evan Suzman,[h] Ashley E. Augustine,[i] Varsha Garla,[c] Aine Muhumuza,[c] Carissa J. Cascio,[g,j,k,l] Kathryn L. Williams,[m] Anne V. Kirby,[n] Bahar Keceli-Kaysili,[b] and Tiffany G. Woynaroski[b,g,k,l]

Purpose: Differences in communication development impact long-term outcomes of children with autism. Previous research has identified factors associated with communication in children with autism, but much of the variance in communication skill remains unexplained. It has been proposed that early differences in sensory responsiveness (i.e., hyporesponsiveness, hyperresponsiveness, and sensory seeking) may produce "cascading effects" on communication. Evidence for this theory is limited, however, as relations between sensory responsiveness and communication in the earliest stages of development have not been well established. The purpose of this study was to evaluate (a) whether infants with a heightened likelihood of autism diagnosis (i.e., infants with an older sibling with autism) differ from infants at general population–level likelihood of autism (i.e., infants with an older, nonautistic sibling) on patterns of sensory responsiveness, (b) whether early sensory responsiveness is correlated with concurrent communication, and (c) whether the aforementioned between-groups differences and associations are moderated by age.
Method: Participants were 40 infants (20 infants with an older sibling with autism, 20 infants with an older, nonautistic sibling) aged 12–18 months. A series of observational and parent report measures of sensory responsiveness and communication skill were administered.
Results: Group differences in sensory responsiveness across the 12- to 18-month period were limited (i.e., only observed for one measure of hyporesponsiveness), though selected differences in sensory responsiveness (i.e., parent-reported hyperresponsiveness and sensory seeking) emerged between groups over this developmental window. Parent-reported hyporesponsiveness was unconditionally, negatively associated with communication skills. Associations between expressive communication and (a) parent-reported sensory seeking and (b) an observational measure of hyperresponsiveness were moderated by age.
Conclusions: This study provides new insights into the nature of sensory responsiveness and theorized links with communication skill in infants at elevated and general population–level likelihood of autism diagnosis. Further work is needed to better characterize the effects of interest in a larger sample spanning a wider age range.
Supplemental Material: https://doi.org/10.23641/asha.14515542

[a]Department of Hearing and Speech Sciences, Vanderbilt University, Nashville, TN
[b]Department of Hearing and Speech Sciences, Vanderbilt University Medical Center, Nashville, TN
[c]Neuroscience Undergraduate Program, Vanderbilt University, Nashville, TN
[d]Vanderbilt School of Medicine, Vanderbilt University, Nashville, TN
[e]Psychology Undergraduate Program, Vanderbilt University, Nashville, TN
[f]Neuroscience Graduate Program, Vanderbilt University, Nashville, TN
[g]Vanderbilt Brain Institute, Vanderbilt University, Nashville, TN
[h]Master's Program in Biomedical Sciences, Vanderbilt University, Nashville, TN
[i]Biological Sciences Undergraduate Program, Vanderbilt University, Nashville, TN
[j]Department of Psychiatry and Behavioral Sciences, Vanderbilt University Medical Center, Nashville, TN
[k]Vanderbilt Kennedy Center, Vanderbilt University Medical Center, Nashville, TN
[l]The First Center for Autism and Innovation, Vanderbilt University, Nashville, TN
[m]Division of Occupational Science and Occupational Therapy, University of North Carolina at Chapel Hill
[n]Department of Occupational and Recreational Therapies, The University of Utah, Salt Lake City

Correspondence to Jacob I. Feldman: j.i.feldman@vumc.org

Sarah M. Bowman is now at Augusta University/University of Georgia Medical Partnership at the Medical College of Georgia, Athens.

Disclosure: The authors have declared that no competing interests existed at the time of publication.

Ashley E. Augustine is now at School of Medicine, Case Western Reserve University, Cleveland, OH.
Jacob I. Feldman and Sweeya Raj contributed equally to this article.
Editor-in-Chief: Patrick Finn
Received April 22, 2020
Revision received October 9, 2020
Accepted January 21, 2021
https://doi.org/10.1044/2021_JSLHR-20-00196

Autism is a highly prevalent neurodevelopmental condition that has been diagnosed in approximately 2 million people in the United States and tens of millions of people worldwide (Baio et al., 2018). This disorder comes at high economic and personal costs for the individual, the family, and society (Amendah et al., 2011; Rogge & Janssen, 2019), in large part due to the impact of the condition on long-term social, academic, and vocational outcomes (e.g., Billstedt et al., 2007; Chamak & Bonniau, 2016; Howlin et al., 2004; Sevaslidou et al., 2019). Long-term outcomes of individuals with autism are improved when receptive and expressive communication abilities are optimized early in life (e.g., Billstedt et al., 2007; Eisenberg, 1956; Gillberg & Steffenburg, 1987; Kobayashi et al., 1992; Lotter, 1974; Rutter et al., 1967).

Sensory Responsiveness as a Probable Factor Associated With Communication

Previous research has identified several predictors of expressive and receptive communication in autism (see Yoder et al., 2015, for a review). However, even when we consider these predictors, much of the variance in communication skill remains unexplained (e.g., Yoder et al., 2015). One factor that has not been commonly considered in studies of communication development, but that may account for variance in communication abilities in children with autism, is sensory responsiveness (i.e., behavioral patterns of responding to sensory stimuli). Past work has shown that sensory responsiveness covaries with concurrent communication in persons on the spectrum (e.g., Baranek et al., 2013; Feldman et al., 2020; Foss-Feig et al., 2012; Watson et al., 2011; Williams et al., 2018). The aforementioned studies, though, have focused only on children and adults (i.e., preschool age and older) on the autism spectrum.

Differences in Sensory Responsiveness Observed in Children With Autism

Children with autism may show a broad range of differences in sensory responsiveness. These differences include hyperresponsiveness (i.e., exaggerated or defensive responses to sensory stimuli, such as covering one's ears in response to loud sounds; Baranek et al., 2007), hyporesponsiveness (i.e., reduced or absent responses to sensory stimuli; Baranek et al., 2013), and sensory seeking (i.e., craving of or fascination with certain sensory experiences; Ben-Sasson et al., 2009). It has been proposed that differences in sensory responsiveness, particularly in the earliest stages of development, may influence the manner in which a child engages with their environment and thereby produce cascading effects on the acquisition of communication skills (Cascio et al., 2016). For example, an infant exhibiting high levels of hyporesponsiveness may fail to orient to social stimuli, resulting in fewer opportunities to interact with and learn from their surroundings and develop communication skills within the context of their everyday lives (Baranek et al., 2018; Damiano-Goodwin et al., 2018). If this is the case, then intervening upon early sensory responsiveness may translate to improved communication, likely by boosting engagement, in this population (Cascio et al., 2016; Wallace et al., 2020). This "cascading effects" theory is intuitively appealing, given that the early development of neural systems for basic sensation and perception precedes and influences those for communication (Gottlieb, 1971; Lickliter & Bahrick, 2000). However, evidence for this theory at present is limited, as the developmental sequelae of early differences in sensory responsiveness have not yet been firmly established.

Likelihood That Differences in Sensory Responsiveness Are Emerging Early in Life

At least some disruptions in sensory responsiveness have been observed early in the course of development in children with autism (e.g., as young as 2–6 months of age; Bryson et al., 2007; Dawson et al., 2000). Importantly, several past reports suggest that differences in sensory responsiveness may emerge earlier in development than the social and communication differences associated with autism (e.g., Baranek, 1999a; Dawson et al., 2000; Mulligan & White, 2012). Early alterations in sensory responsiveness, however, may be difficult to detect because they are reportedly (a) not consistently apparent between birth and 3 years of age and/or (b) seemingly increasing and becoming consolidated across early childhood (Ben-Sasson et al., 2019).

These findings suggest the need to employ multiple measures of sensory responsiveness and study children early in life who are somewhat heterogeneous in regard to chronological age in order to hone in on the developmental period wherein these sensory differences emerge and are linked with communication. The theorized associations between early sensory differences and communication may be particularly important to study between 12 months, when spoken words are expected to emerge, and 18 months, when infants with delayed communication development presently tend to be identified and referred for early intervention (Webb et al., 2014).

Rationale for Focusing on Sensory Responsiveness in Infant Siblings of Children With Autism

The primary challenge to systematically assessing early-emerging patterns of sensory responsiveness and their relations with communication is that autism cannot always be definitively diagnosed in the earliest stages of life (i.e., in infancy and toddlerhood; Ozonoff et al., 2015, 2018). A potential solution is to prospectively follow infants and toddlers who are known to be at increased likelihood for a future diagnosis of autism and other language and communication impairments (Costanzo et al., 2015). Infant and toddler siblings of children already diagnosed with autism (Sibs-autism) are one such group. Approximately 19% of Sibs-autism will go on to receive a diagnosis of autism themselves (Ozonoff et al., 2011), while about 20% of Sibs-autism will be diagnosed with language delay/disorder (Landa et al., 2012; Yirmiya et al., 2007), and many others will present with subclinical features associated with autism such as social communication differences and atypical patterns of sensory responsiveness (e.g., Brian et al., 2008; Damiano-Goodwin et al., 2018; Ozonoff et al., 2008, 2011). The expected heterogeneity in both communication skill and sensory responsiveness makes Sibs-autism an ideal population for examining hypothesized relations between these features. Furthermore, given the high likelihood of communication difficulties and autism diagnosis in Sibs-autism, there is a pressing need to evaluate whether early differences in sensory responsiveness might ultimately be helpful, from a clinical standpoint, for explaining concurrent phenotypic variance or predicting future communication challenges.

Study Aims and Hypotheses

To our knowledge, no study to date has examined the relations between atypical sensory responsiveness and communication in infancy and toddlerhood. In a preliminary test of the cascading effects theory, this study thus tested the degree to which atypical patterns of sensory responsiveness are associated with concurrent communication abilities in Sibs-autism and a comparison group of infants at relatively lower, general population–level likelihood of autism (i.e., infant siblings of nonautistic, otherwise typically developing children [Sibs-NA]). Specifically, the aims of the project were to (a) evaluate whether sensory responsiveness, as indexed using several previously developed and validated measures, differs on average between Sibs-autism and Sibs-NA; (b) determine if atypical patterns of sensory responsiveness in infancy exhibit concurrent associations with receptive and expressive communication; and (c) evaluate whether the aforementioned group differences and associations differ depending on chronological age.

We hypothesized that Sibs-autism would exhibit increased presence of behaviors associated with atypical patterns of sensory responsiveness (i.e., increased hyporesponsiveness, hyperresponsiveness, and/or seeking behaviors) relative to Sibs-NA on average between 12 and 18 months of age, but that some differences in sensory responsiveness may just be emerging over the 12- to 18-month period. We further anticipated that there would be a broad range of variability in sensory responsiveness across groups and that atypical sensory responsiveness (i.e., increased hyporesponsiveness, hyperresponsiveness, and/or sensory seeking) would be negatively associated with concurrent communication, at least in relatively older infants and toddlers, for whom disruptions in sensory responsiveness were, perhaps, more likely to be apparent.

Method

The Vanderbilt University Institutional Review Board approved recruitment and study procedures. Parents provided written informed consent, and families were compensated for their participation. Participants completed all study measures in one to three visits to the Vanderbilt University Medical Center scheduled over the course of a 2-week period.

Participants

Analyses were conducted on 40 infants and toddlers between the ages of 12 and 18 months (± 30 days; 20 Sibs-autism, 20 Sibs-NA). Groups were matched on chronological age, biological sex, and mental age (see Table 1). Inclusion criteria for infants in both groups were (a) full-term birth, (b) no concomitant genetic disorders, (c) no known adverse neurological history, (d) primarily English-speaking household, and (e) at least one older sibling. For the Sibs-autism group, infants were required to have at least one older sibling with autism diagnosed by a licensed clinician according to *Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition* criteria (American Psychiatric Association, 2013). The records of older siblings with autism were reviewed by a member of our research team to confirm diagnostic status ($n = 15$) at the time of the infant sibling's entry to the study; when records were not available, a licensed clinician administered the Autism Diagnostic Observation Schedule (Lord et al., 2012) and independently confirmed the diagnosis ($n = 5$). For the Sibs-NA group, infants were required to have (a) only nonautistic older siblings, as confirmed by screening below the threshold for autism concern (i.e., < 15) on the Social Communication Questionnaire (Rutter et al., 2003) and a screening questionnaire for developmental delay administered by a member of the study team; (b) no first-degree relatives diagnosed with autism; (c) no prior history or present indicators of developmental delays or disorders per parent report; and (d) an Early Learning Composite on the Mullen Scales of Early Learning (MSEL; Mullen, 1995) of greater than 70.

Measures of Sensory Responsiveness

Several observational and parent report measures of sensory responsiveness were utilized in this study, with the goal of creating aggregates of hyporesponsiveness, hyperresponsiveness, and sensory seeking in order to increase the stability and thus the potential construct validity of indices of sensory response patterns (Rushton et al., 1983). See Table 2 for a list of variables derived from these measures.

Sensory Experiences Questionnaire

The Sensory Experiences Questionnaire Version 2.1 (SEQ; Baranek et al., 2006) is a parent report measure that characterizes sensory behaviors across a range of sensory

Table 1. Means, standard deviations, and group differences for selected variables by group.

Variable	Sibs-autism (n = 20) *M* (*SD*)	Sibs-NA (n = 20) *M* (*SD*)
Chronological age (months)	13.70 (1.9)	13.85 (2.0)
Mental age (months)	13.15 (1.3)	14.48 (2.2)
Mullen ELC	89.04 (12.5)	99.25 (10.0)
Biological sex	11 male, 9 female	11 male, 9 female

Note. Sibs-autism and Sibs-NA groups were nonsignificantly different on biological sex and chronological age; groups differed on Mullen ELC and mental age ($ps < .05$). Sibs-autism = infant siblings of children diagnosed with autism; Sibs-NA = infant siblings of nonautistic, otherwise typically developing children; Mental age = average of Visual Reception, Fine Motor, Expressive Language, and Receptive Language age equivalency scores from the Mullen Scales of Early Learning (Mullen, 1995); Mullen ELC = Early Learning Composite standard score from the Mullen Scales of Early Learning (Mullen, 1995).

modalities, response patterns, and social and nonsocial contexts. Mean scores for hyporesponsiveness, hyperresponsiveness, and sensory seeking from this measure were used in analyses.

Infant/Toddler Sensory Profile Caregiver Questionnaire

The Sensory Profile (SP; Dunn, 1999) is an 81-item parent report measure that characterizes early sensory processing. From this measure, we derived the low registration (hyporesponsiveness), sensation seeking (sensory seeking), sensory sensitivity, and sensation avoiding (hyperresponsiveness) indices for use in analyses. Scores on this measure were reflected (i.e., raw scores were subtracted from the maximum observed score + 1) to ensure consistency of interpretation with other measures (i.e., wherein higher scores are indicative of increased presence of the behaviors of interest).

Sensory Processing Assessment

The Sensory Processing Assessment (SPA; Baranek, 1999b) is a 15-min observational assessment that evaluates a child's responses (seeking and/or avoiding behaviors, orienting, and habituation responses) to novel toys and environmental sensory stimuli that are either social or nonsocial in nature. From this measure, we derived the sensory seeking intensity mean rating score and the sensory seeking inventory to index sensory seeking behavior (see Damiano-Goodwin et al., 2018), the avoidance mean score to index hyperresponsiveness, and the orienting mean score to index hyporesponsiveness.

Test of Sensory Functions in Infants

The Test of Sensory Functions in Infants (TSFI; DeGangi & Greenspan, 1989) is a brief observational measure of sensory processing and reactivity for infants. The Tactile Deep Pressure, Visual-Tactile Integration, and Vestibular Stimulation subscales measure infants' responses to being rubbed on the arm, stomach, foot, and mouth by the examiner, having objects with different sensory properties (e.g., a furry mitt, a sticky piece of tape, a rubber ball) placed

Table 2. Summary of variables used in analyses.

Assessment	Type	Variables used in analyses
Measures of sensory responsiveness		
Sensory Experiences Questionnaire Version 2.1 (Baranek et al., 2006)	Parent report	Sensory seeking,[a] hyperresponsiveness,[b] and hyporesponsiveness[c] mean scores
Sensory Profile (Dunn, 1999)	Parent report	Low registration (Hypo),[c] sensation seeking (Seeking),[a] sensory sensitivity (Hyper),[b] and sensation avoiding (Hyper)[b] scores
Sensory Processing Assessment (Baranek, 1999b)	Observational	Sensory seeking intensity[d] and inventory,[d] avoidance (Hyper), and orientation (Hypo) mean scores
Test of Sensory Functions in Infants (DeGangi & Greenspan, 1989)	Observational	Hyporesponsiveness and hyperresponsiveness mean scores
Measures of communication		
Mullen Scales of Early Learning (Mullen, 1995)	Observational	Receptive[e] and expressive[f] language age equivalency scores
MacArthur–Bates Communicative Development Inventories (Fenson et al., 2007)	Parent report	Raw number of words child understands (receptive vocabulary)[e] and says (expressive vocabulary)[f]
Vineland Adaptive Behavior Scales–Second Edition (Sparrow et al., 2005)	Parent report	Receptive communication[e] and expressive communication[f] age equivalency scores

Note. The construct purportedly tapped by each variable is indicated in parentheses when not transparent. Hypo = hyporesponsiveness; Seeking = sensory seeking, Hyper = hyperresponsiveness. Variables were aggregated to measure (a) parent-reported sensory seeking, (b) parent-reported hyperresponsiveness, (c) parent-reported hyporesponsiveness, (d) sensory seeking as measured by the Sensory Processing Assessment, (e) receptive communication, and (f) expressive communication.

on different parts of their bodies, and being lifted and turned through different axes. For the purposes of this study, these three subtests were scored on a hyperresponsiveness scale and a hyporesponsiveness scale (Bowman et al., 2018). Behaviors scored on the hyperresponsiveness scale included various adverse responses to stimuli (e.g., withdrawing from, pushing away from, or kicking away stimuli); behaviors on the hyporesponsiveness scale were based on lack of reaction to stimuli (e.g., not orienting or looking to stimuli, displaying neutral affect throughout stimulation). The coding manual for this measure is available upon request from the corresponding author.

Interrater Reliability of Observational Measures of Sensory Responsiveness

Primary coders for the observational measures of sensory responsiveness (i.e., SPA, TSFI) were naïve to sibling status. Eleven TSFI and SPA samples (26.8%) were chosen at random and coded for fidelity of procedure and interrater reliability by a secondary coder. Examiners and primary coders were naïve to which samples would be selected. Intraclass correlation coefficients quantifying interrater reliability for TSFI variables were .986 and .800 for hyperresponsiveness and hyporesponsiveness, respectively. Intraclass correlation coefficients for SPA variables were .907 for orienting (hyporesponsiveness); .820 and .810 for sensory seeking intensity and sensory seeking inventory, respectively; and .894 for avoidance (hyperresponsiveness). Therefore, interrater reliability for all observational variables was good to excellent.

Creation of Sensory Responsiveness Aggregates

Several indices from the Sensory Experiences Questionnaire and the SP purported to tap the same construct were sufficiently intercorrelated (i.e., displayed moderate–large bivariate correlations; i.e., $r \geq .4$; Cohen & Cohen, 1984) to generate aggregate variables by averaging component scores following z transformation to increase their stability and potential predictive validity (Rushton et al., 1983). We created parent report aggregates for sensory seeking ($r = .52$), hyporesponsiveness ($r = .45$), and hyperresponsiveness ($r = .47$, .51, and .66; see Supplemental Material S1 for intercorrelations between all variables derived for use in analyses). However, indices from observational measures were not sufficiently correlated with one another or with indices derived from the aforementioned parent report measures to be aggregated and thus were analyzed separately.

Measures of Receptive and Expressive Communication

Mullen Scales of Early Learning

The MSEL (Mullen, 1995) is a standardized test that assesses development in several domains, including expressive and receptive language, for children from birth to 68 months. From this measure, we characterized participants by calculating the Early Learning Composite standard score and mental age (i.e., average of age equivalency scores across Fine Motor, Visual Reception, Receptive Language, and Expressive Language domains). The age equivalency scores from the receptive and expressive language scales were utilized in analyses.

MacArthur–Bates Communicative Development Inventories

The MacArthur–Bates Communicative Development Inventories (MCDI; Fenson et al., 2007) is a parent report that assesses early vocabulary and broader spoken language ability for infants aged 8–18 months. We utilized the MCDI: Words and Gestures version in order to calculate raw scores for both receptive and expressive vocabulary across the age range of interest.

Vineland Adaptive Behavior Scales–Second Edition

The Vineland Adaptive Behavior Scales–Second Edition (VABS-2; Sparrow et al., 2005) is a parent report measure that assesses adaptive function in several domains, including receptive and expressive communication. The age equivalency scores from the receptive and expressive communication scales were utilized in analyses.

Creation of Communication Aggregates

All measures purported to tap expressive and receptive communication, respectively, were correlated at $r \geq .4$ (see Supplemental Material S1), supporting the creation of communication aggregate scores using the corresponding component variables (following z-score transformation) from the MCDI, VABS-2, and MSEL.

Analytic Plan

Prior to conducting analyses, all variables of interest were evaluated for normality, specifically for skewness > |1.0| and kurtosis > |3.0| (see Tabachnick & Fidell, 2001). Three variables (i.e., MCDI words understood, TSFI hyporesponsiveness, and the SPA sensory seeking inventory) were corrected for positive skew with a square root transformation, one variable (i.e., VABS-2 receptive communication age equivalency scores) was corrected for positive skew with a logarithmic transformation, and one variable (i.e., SP sensory sensitivity) was corrected for negative skew with a cubic transformation (Osborne, 2002).

Missing data (ranging from 0% to 20% across variables) were then imputed using the missForest package (Stekhoven & Bühlmann, 2012) in R (R Core Team, 2020). Participants were generally missing data due to omitting responses to or overlooking selected questions on parent report questionnaires, which precluded derivation of discrete component variables; no participant was missing variables from more than one measure of the same construct (i.e., three participants were missing one variable derived from one sensory and one communication measure, three participants were missing one variable derived from one communication measure, and four participants were missing one variable derived from one sensory measure). Thus, our data can be considered missing completely at random. Additionally, the amount of missing data per variable was considerably lower than current recommendations for high-quality research (Miller et al.,

2019) and for use of imputation to handle missingness (e.g., Enders, 2010).

To answer our first research question, independent-samples t tests were carried out to evaluate between-groups differences in indices of sensory responsiveness. Additionally, the effectsize package in R was used to calculate Cohen's d (Ben-Shachar et al., 2020). To answer our second research question, zero-order correlations were evaluated for each index of sensory responsiveness with expressive communication and receptive communication aggregates.

To answer our third research question, we conducted a series of multiple regression analyses. First, to assess whether chronological age moderated between-groups differences, multiple regression analyses were run for each index of sensory responsiveness, wherein the index of sensory responsiveness of interest was the dependent variable and group, age, and Group × Age product terms were entered into the model as independent variables. Then, to assess whether chronological age moderated associations between sensory responsiveness and communication, regression models were run with expressive and receptive communication aggregates as the dependent variables and the predictors (i.e., indices of sensory responsiveness of interest), age, and Sensory Index × Age interaction terms were entered as the independent variables. Additionally, the effectsize package in R was used to calculate Cohen's f^2 effect size for each interaction term (Ben-Shachar et al., 2020; R Core Team, 2020).

For all regression analyses, Cook's D was utilized to monitor for the presence of undue influence (defined as Cook's $D \geq 1$); no statistical outliers were detected in any analysis. Interaction effects were probed at $p \leq .1$ using ± 1 SD and mean values for chronological age in PROCESS (Hayes, 2017). This slightly lower threshold for Type I errors was used in testing interaction effects in order to decrease our risk of making Type II errors, as interaction effects are often difficult to detect with small sample sizes (Aiken & West, 1991; Fairchild & MacKinnon, 2009). For this reason, an alpha level < .1 threshold is employed for flagging significant interaction effects by default in statistics programs (e.g., R Core Team, 2020) and is commonly utilized in testing moderated effects in the autism literature (e.g., Sandbank, Bottema-Beutel, Crowley, Cassidy, Dunham, et al., 2020; Sandbank, Bottema-Beutel, Crowley, Cassidy, Feldman, et al., 2020).

Results

Group Differences

Independent-samples t tests indicated that groups, on average, significantly differed on only one index of sensory responsiveness, TSFI hyporesponsiveness ($t = 2.17$, $p = .036$), with Sibs-autism presenting with higher scores compared to Sibs-NA (all other p values testing mean differences > .05; see Table 3). However, multiple regression analyses indicated that some between-groups differences of interest were moderated by chronological age, specifically parent-reported sensory seeking and parent-reported hyperresponsiveness (p values for Sensory Index × Group product terms in regression models testing moderated effects = .07 and .09, respectively; see Table 3). For these variables, the effect of sibling group did vary according to the putative moderator, chronological age. Specifically, at younger ages, Sibs-NA tended to score higher (i.e., show slightly more features consistent with the relevant pattern of sensory responsiveness) than Sibs-autism, whereas at older ages, Sibs-autism tended to score higher than Sibs-NA (see Figure 1). These moderated effects suggest that between-groups differences in the anticipated direction are emerging for sensory seeking and hyperresponsiveness patterns over the 12- to 18-month period.

Links With Communication

Across 12- to 18-month-old infants, expressive communication was significantly associated with parent-reported sensory seeking ($r = -.32$, $p = .045$), parent-reported hyporesponsiveness ($r = -.32$, $p = .044$; see Figure 2A), and TSFI hyperresponsiveness ($r = -.39$, $p = .014$), such that increased behaviors associated with each pattern of sensory responsiveness were associated with decreased expressive communication (see Table 4). Additionally, parent-reported hyporesponsiveness ($r = -.32$, $p = .040$; see Figure 2B) and TSFI hyperresponsiveness ($r = -.43$, $p = .005$) were negatively correlated with receptive communication across the 12- to 18-month age range (see Table 5). No other sensory indices had significant zero-order correlations with expressive or receptive communication (see Tables 4 and 5). Partial correlations demonstrated that all significant zero-order associations were robust to controlling for chronological age, with the exception of the association between expressive communication and parent-reported sensory seeking (see Supplemental Material S2).

The relation between parent-reported sensory seeking and expressive communication as well as the relation between TSFI hyperresponsiveness and expressive communication, however, were moderated by chronological age (p values for Sensory Index × Chronological Age product terms in regression models testing moderated effects = .080 and .098, respectively). In both cases, the association became more negative (i.e., trended in the anticipated direction) with increasing age. The aforementioned moderated effects are depicted using ± 1 SD and mean values for chronological age in Figures 3A and 3B, respectively. Johnson–Neyman tests utilized to derive precise cut-points along the continuous moderator of chronological age indicated relations with expressive communication became significantly negative at 15.55 months for parent-reported sensory seeking and at 13.47 months for TSFI hyperresponsiveness. In regard to receptive communication, no associations were moderated by age.

Post Hoc Analyses

A series of post hoc analyses was conducted considering MSEL Early Learning Composite, mental age, and biological sex as covariates in all regression models. These

Table 3. Results of regression analyses testing group differences in sensory responsiveness according to chronological age.

Sensory index	Unconditional group difference		Conditional group differences (values from full multiple regression model)			
	t	Cohen's *d*	*B* Group	*B* Age	*B* Age × Group	Cohen's f^2 for interaction
PR Seeking	−0.70	−0.22	2.17	0.53	−2.27[a]	.100
PR Hypo	1.41	0.45	0.86	0.44	−1.21	.024
PR Hyper	0.46	0.15	1.80	1.14*	−2.10[a]	.083
SPA Seeking	−0.52	−0.16	0.47	0.25	−0.43	.003
SPA Orienting (Hypo)	1.75	0.55	−0.50	−0.04	0.02	.001
SPA Avoidance (Hyper)	0.28	0.09	0.34	0.32	−0.44	.003
TSFI Hypo	2.17*	0.69	−1.28	−0.29	1.04	.019
TSFI Hyper	0.93	0.10	1.51	0.49	−1.83	.058

Note. Cohen's *d* values of ≥ 0.2, ≥ 0.5, and ≥ 0.8 represent small, medium, and large effects, respectively (Cohen, 1988). Cohen's f^2 values of ≥ .02, ≥ .15, and ≥ .35 represent small, medium, and large effects, respectively (Cohen, 1988). *B* = unstandardized coefficient from multiple regression model testing moderated effects for each regressor (i.e., group, age, and Age × Group interaction term); PR = parent-reported; Seeking = sensory seeking; Hypo = hyporesponsiveness; Hyper = hyperresponsiveness; SPA = Sensory Processing Assessment (Baranek, 1999b); TSFI = Test of Sensory Functions in Infants (DeGangi & Greenspan, 1989).

[a]Group difference was significantly moderated by age ($p_{interaction} < .10$).

*$p < .05$.

analyses were carried out because (a) prior research indicates some degree of covariation between cognitive ability and/or cognitive level and sensory responsiveness in young children with autism (e.g., Baranek et al., 2007, 2013), (b) sibling groups significantly differed in mental age and MSEL Early Learning Composite in this sample (see Table 1), and (c) there are known sex differences in autism (e.g., Hiller et al., 2014; Nowell et al., 2019). In these full models, mental age was the only covariate that accounted for significant variance; thus, this variable was retained in post hoc models to further explore the influence of mental age on effects of interest.

In regard to group differences, the unconditional group difference on TSFI hyporesponsiveness and the conditional group difference on parent-reported hyperresponsiveness according to chronological age were robust to including mental age as a covariate. In regard to observed zero-order

Figure 1. Group differences between infants with an older sibling with autism (Sibs-autism; in red) and infants with an older, nonautistic sibling (Sibs-NA; in black) in (A) parent-reported sensory seeking and (B) parent-reported hyperresponsiveness differed by chronological age. At younger ages, Sibs-NA tended to score higher (i.e., show slightly more features consistent with the relevant pattern of sensory responsiveness) than Sibs-autism, whereas at older ages, Sibs-autism tended to score higher than Sibs-NA. Results suggest that between-groups differences in the anticipated direction are emerging for sensory seeking and hyperresponsiveness patterns over the 12- to 18-month period. Note that these graphs depict the observed means at each age rather than predicted values.

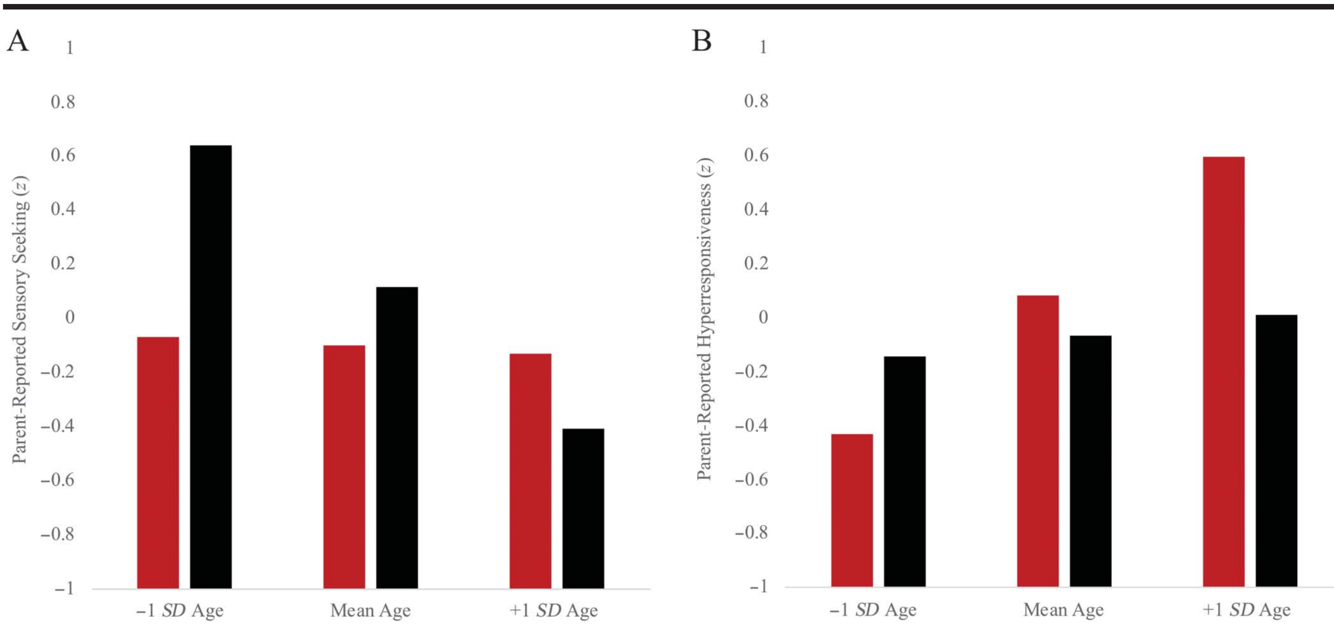
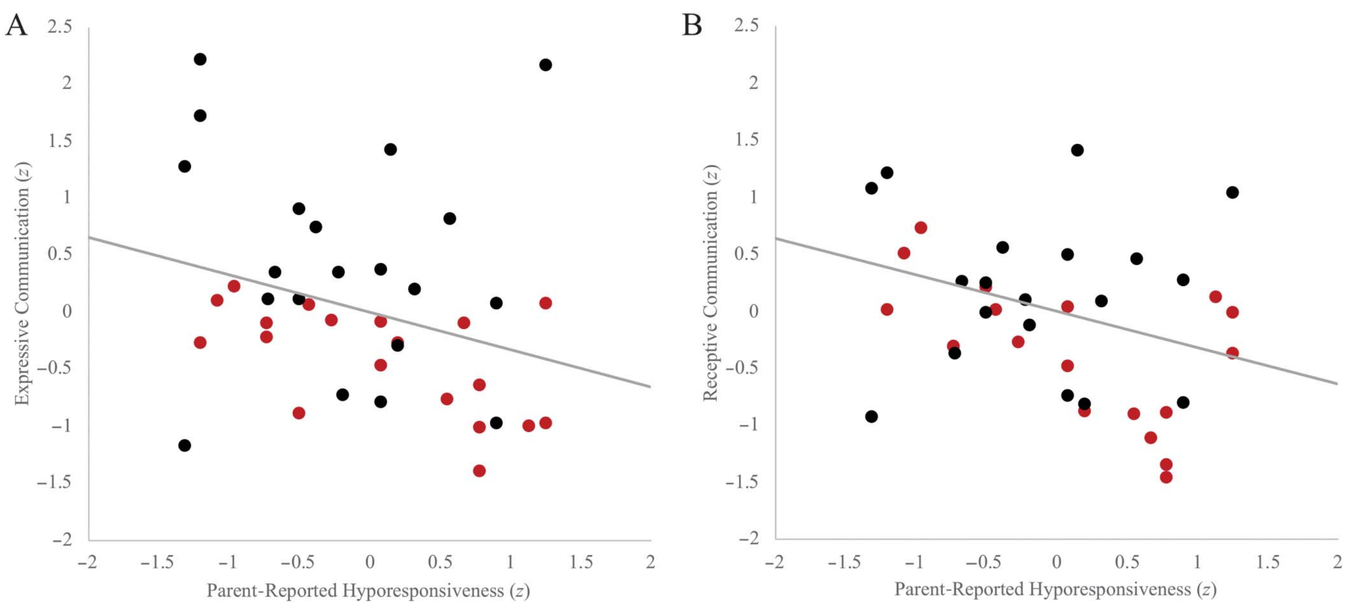


Figure 2. Parent-reported hyporesponsiveness is significantly and negatively correlated with (A) expressive communication and (B) receptive communication across groups, with moderate effect sizes. Red dots represent infants with an older sibling with autism, and black dots represent infants with an older, nonautistic sibling.



correlations, the relations between parent-reported hyporesponsiveness and both expressive and receptive communication, as well as the relation between TSFI hyperresponsiveness and receptive communication, were robust to including mental age as a covariate.

The significant moderated association between parent-reported sensory seeking and expressive communication by chronological age was also robust to including mental age as a covariate. Additionally, selected moderated associations between sensory responsiveness and communication that were nonsignificant in models that did not include covariates surpassed our a priori–specified threshold for statistical significance when controlling for mental age. Specifically, in the model including mental age as a covariate, the relation for the SPA seeking with both expressive communication ($p_{\text{interaction}}$ = .071) and receptive communication ($p_{\text{interaction}}$ = .013) varied according to chronological age.

Discussion

This study represents a preliminary test of the cascading effects framework in infants at high-level versus general

Table 4. Zero-order and moderated associations between indices of sensory responsiveness and expressive communication.

Sensory index	Zero-order correlation	Values from full multiple regression model predicting expressive communication			
		B Age	*B* Sensory index	*B* Sensory × Age	Cohen's f^2 for interaction
PR Seeking	−.32*	0.21**	1.82	−0.14[a]	.088
PR Hypo	−.32*	0.25**	0.07	−0.03	.004
PR Hyper	.00	0.27**	−0.18	0.00	.000
SPA Seeking	.04	0.23**	0.63	−0.04	.017
SPA Orienting (Hypo)	−.21	0.29	0.08	−0.03	.001
SPA Avoidance (Hyper)	−.08	0.32**	1.11	−0.01	.015
TSFI Hypo	.03	0.25**	0.81	−0.07	.001
TSFI Hyper	−.39*	0.31**	3.62	−0.32[a]	.080

Note. Zero-order correlations (i.e., Pearson's *r*) of ≥ .1, ≥ .3, and ≥ .5 represent small, medium, and large effects, respectively (Cohen, 1988). Cohen's f^2 values of ≥ .02, ≥ .15, and ≥ .35 represent small, medium, and large effects, respectively (Cohen, 1988). *B* = unstandardized coefficient from multiple regression model testing moderated effects for each regressor (i.e., group, age, and Age × Group interaction term); PR = parent-reported; Seeking = sensory seeking; Hypo = hyporesponsiveness; Hyper = hyperresponsiveness; SPA = Sensory Processing Assessment (Baranek, 1999b); TSFI = Test of Sensory Functions in Infants (DeGangi & Greenspan, 1989).

[a]Group difference was significantly moderated by age ($p_{\text{interaction}} < .10$).

*$p < .05$. **$p < .01$.

Table 5. Zero-order and moderated associations between indices of sensory responsiveness and receptive communication.

Sensory index	Zero-order correlation	Values from full multiple regression model predicting receptive communication			
		B Age	*B* Sensory index	*B* Sensory × Age	Cohen's f^2 for interaction
PR Seeking	−.22	0.22**	0.04	−0.01	.000
PR Hypo	−.32*	0.23**	−0.13	−0.01	.001
PR Hyper	.11	0.24**	−0.04	0.00	.000
SPA Seeking	.06	0.24**	−0.26	0.02	.003
SPA Orienting (Hypo)	−.22	0.19	−0.53	0.02	.001
SPA Avoidance (Hyper)	−.10	0.28*	0.53	−0.01	.005
TSFI Hypo	.18	0.25**	3.49	−0.20	.006
TSFI Hyper	−.43**	0.24*	0.80	−0.12	.012

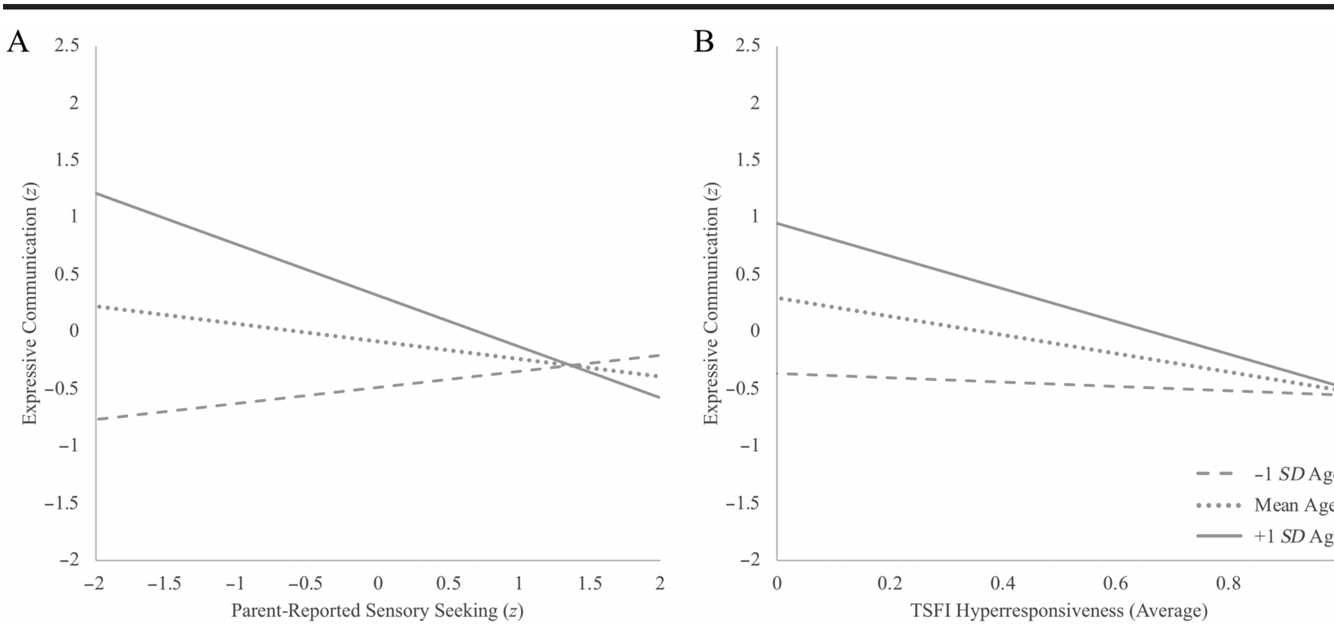
Note. Zero-order correlations (i.e., Pearson's *r*) of ≥ .1, ≥ .3, and ≥ .5 represent small, medium, and large effects, respectively (Cohen, 1988). Cohen's f^2 values of ≥ .02, ≥ .15, and ≥ .35 represent small, medium, and large effects, respectively (Cohen, 1988). *B* = unstandardized coefficient from multiple regression model testing moderated effects for each regressor (i.e., group, age, and Age × Group interaction term); PR = parent-reported; Seeking = sensory seeking; Hypo = hyporesponsiveness; Hyper = hyperresponsiveness; SPA = Sensory Processing Assessment (Baranek, 1999b); TSFI = Test of Sensory Functions in Infants (DeGangi & Greenspan, 1989).

$^*p < .05$. $^{**}p < .01$.

population–level likelihood for a future diagnosis of autism. Findings suggest that unconditional between-groups differences in patterns of sensory responsiveness across the 12- to 18-month period are limited, with only a single variable (TSFI hyporesponsiveness) differentiating Sibs-autism and Sibs-NA on average. Trends within the data suggest, however, that selected differences in sensory responsiveness, particularly parent-reported hyperresponsiveness and sensory seeking, may be emerging over this developmental window. These moderated effects, on the whole, accord with prior reports from Baranek et al. (2018), who previously reported that correlations between at least some atypical patterns of sensory responsiveness (i.e., sensory seeking) and later social development were not apparent until later in the second year of life in infants at increased likelihood for autism.

Notably, a large amount of individual variation was observed in our indices of sensory responsiveness across sibling groups, and these individual differences were useful for explaining variance in communication skill. Unconditional, zero-order associations with expressive and receptive

Figure 3. Several relations between sensory responsiveness and expressive communication were moderated by chronological age across groups. The relations between expressive communication and (A) parent-reported sensory seeking and (B) hyperresponsiveness as measured by the Test of Sensory Functions in Infants (TSFI; DeGangi & Greenspan, 1989) were moderated by chronological age. In both cases, the associations of interest became more negative (suggesting that more atypical patterns of sensory responsiveness were associated with reduced communication skill) with advancing age (dashed line = −1 *SD* age, dotted line = mean age, solid line = +1 *SD* age).



communication were observed for parent-reported hyporesponsiveness. This finding is consistent with theory and prior findings for associations between metrics of hyporesponsiveness and a range of higher level social, communication, and language skills in children diagnosed with autism (Baranek et al., 2013; Feldman et al., 2020; Watson et al., 2011).

Other associations of interest varied according to chronological age across the developmental period of interest (i.e., 12–18 months). Specifically, relations between expressive communication and both parent-reported sensory seeking and hyperresponsiveness, as measured by the TSFI, were moderated by age. In both cases, the association with expressive communication became increasingly negative with advancing chronological age. The lack of anticipated negative associations for these particular patterns of sensory responsiveness with communication at earlier ages may indicate that some sensory responses that have been considered "atypical" in clinical populations (e.g., sensory seeking, which appeared to be present but to decrease over this age range in the Sibs-NA) are adaptive (or at a minimum not maladaptive) earlier in life. Alternatively, it is possible that, at earlier ages, there is simply less variability in communication ability (at least as indexed by the measures employed here) that can be explained by sensory responsiveness; a truncated range of scores can attenuate associations of interest (Huck, 1992). Future studies may consider measures that may be more sensitive to individual variation in communication skill earlier in life (e.g., measures of prelinguistic skill; Woynaroski et al., 2016). Collectively, findings suggest that hyporesponsiveness, when present, may impact the acquisition of communication skills as early as 12 months of age, but that other patterns of sensory responsiveness of interest may not have clinical utility for predicting communication impairments until relatively later in the course of development (i.e., 13–15 months).

Notably, our ability to detect effects of interest differed according to the sensory measure used. Although the use of multiple measures for each construct of interest is a strength of this study, several variables purported to tap the same pattern of sensory responsiveness were not sufficiently intercorrelated with one another to warrant aggregation. Parent report measures, on the whole, tended to display better convergent validity and utility for detecting effects of interest (supporting their discriminative and predictive validity) than observational measures. The relative strength of parent report measures as observed here may result from parents' ability to draw on their experiences with their child across a broader range of contexts and stimuli than can be readily assessed via observational measures, thereby improving their ability to provide more representative estimates of their children's sensory response patterns. It should also be noted that scores from the two observational measures of sensory responsiveness were not intercorrelated, though this may be due to the fact that the TSFI predominantly assesses responses to tactile and vestibular stimuli while the SPA predominantly assesses responses to auditory, visual, and tactile stimuli. Relatively little is known about the psychometrics of observational measures of sensory assessments in infants at this time; therefore, additional information is needed in order to guide measure selection for future research and, ultimately, for clinical practice.

This study provides new insights into the nature of sensory responsiveness and theorized links with communication skill in infants, but it is not without limitations. A primary limitation of this study is the relatively small sample size representing a fairly circumscribed developmental period. In addition, the concurrent correlational study design limits our ability to draw conclusions about directionality or causality of observed relations between sensory disruptions and communication skill. Future studies prospectively following a larger sample of infants over a more extended developmental period are necessary in order to hone in on the precise point(s) wherein differences in sensory response patterns emerge and negatively impact developmental trajectories. Furthermore, in this preliminary test of the cascading effects theory in infant siblings of children with and without autism, we did not correct for multiple comparisons, and our lower threshold for significance in probing interaction effects was liberal. Though these methodological choices were necessary for decreasing our risk of making a Type II error in a relatively small scale study, they do increase the risk of making a Type I error. A more conservative analytic approach (and accordingly, scaled-up sample sizes to ensure sufficient power) is warranted for future work, now that effect sizes of interest have been established.

Finally, in this initial study, we were unable to parse out effects according to infants' diagnostic outcome (as opposed to simply "likelihood") group. Future research should evaluate whether the finding that Sibs-autism show increased sensory alterations relative to Sibs-NA for some patterns of sensory responsiveness with increasing age may be driven at least in part by the Sibs-autism who go on to receive an autism diagnosis. It is notable as well that this study was focused on a singular group at heightened likelihood of autism—younger siblings of children who are diagnosed with the condition. Additional work is therefore also required to determine whether the present results generalize to other groups at increased likelihood for autism, such as infants identified via broad-based community screening (e.g., via measures such as the First Year Inventory; Reznick et al., 2007; see Baranek et al., 2018). Another clinical population at elevated likelihood for autism diagnosis (i.e., at least 3–4 times the general population level) is infants with Down syndrome (DS; DiGuiseppi et al., 2010; Kent et al., 1999). It has previously been reported that children with DS, like children with autism, present with differences in sensory responsiveness (Bruni et al., 2010; Subramaniam, 2009; Wuang & Su, 2011); however, associations between sensory responsiveness and communication have not been studied in DS. In long term, this line of research has the potential to facilitate our early identification and remediation of communication impairments across a number of populations at heightened likelihood for neurodevelopmental conditions.

Acknowledgments

This work was supported by National Institutes of Health Grant U54 HD083211 (Principal Investigator [PI]: Neul), National Center for Advancing Translational Sciences Grant KL2TR000446 and National Institute on Deafness and Other Communication Disorders Grant 1R21DC016144 (PI: Woynaroski), National Institutes of Health Grant T32 MH064913 (PI: Winder), National Science Foundation Research Traineeship Grant DGE 19-22697 (PI: Wallace), and Vanderbilt Institute for Clinical and Translational Research Award VR14759 (PIs: Cascio and Woynaroski). The authors are grateful to the Adventure Science Center in Nashville, TN for their Living Labs Partnership.

References

Aiken, L. S., & West, S. G. (1991). *Multiple regression: Testing and interpreting interactions*. Sage.

Amendah, D., Grosse, S. D., Peacock, G., & Mandell, D. S. (2011). The economic costs of autism: A review. In D. Amaral, D. Geschwind, & G. Dawson (Eds.), *Autism spectrum disorders* (pp. 1347–1360). Oxford University Press. https://doi.org/10.1093/med/9780195371826.003.0088

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

Baio, J., Wiggins, L., Christensen, D. L., Maenner, M. J., Daniels, J., Warren, Z., Kurzius-Spencer, M., Zahorodny, W., Rosenberg, C. R., White, T., Durkin, M. S., Imm, P., Nikolaou, L., Yeargin-Allsopp, M., Lee, L.-C., Harrington, R., Lopez, M., Fitzgerald, R. T., Hewitt, A., . . . Dowling, N. F. (2018). Prevalence of autism spectrum disorder among children aged 8 years—Autism and Developmental Disabilities Monitoring Network, 11 sites, United States, 2014. *MMWR Surveillance Summaries*, *67*(6), 1–23. https://doi.org/10.15585/mmwr.ss6706a1

Baranek, G. T. (1999a). Autism during infancy: A retrospective video analysis of sensory-motor and social behaviors at 9–12 months of age. *Journal of Autism and Developmental Disorders*, *29,* 213–224. https://doi.org/10.1023/A:1023080005650

Baranek, G. T. (1999b). *Sensory processing assessment for young children (SPA)* [Unpublished manuscript]. University of North Carolina at Chapel Hill.

Baranek, G. T., Boyd, B. A., Poe, M. D., David, F. J., Watson, L. R., & MacLean, W. E., Jr. (2007). Hyperresponsive sensory patterns in young children with autism, developmental delay, and typical development. *American Journal of Mental Retardation*, *112*(4), 233–245. https://doi.org/10.1352/0895-8017(2007)112[233:HSPIYC]2.0.CO;2

Baranek, G. T., David, F. J., Poe, M. D., Stone, W. L., & Watson, L. R. (2006). Sensory Experiences Questionnaire: Discriminating sensory features in young children with autism, developmental delays, and typical development. *The Journal of Child Psychology and Psychiatry*, *47*(6), 591–601. https://doi.org/10.1111/j.1469-7610.2005.01546.x

Baranek, G. T., Watson, L. R., Boyd, B. A., Poe, M. D., David, F. J., & McGuire, L. (2013). Hyporesponsiveness to social and nonsocial sensory stimuli in children with autism, children with developmental delays, and typically developing children. *Development and Psychopathology*, *25*(2), 307–320. https://doi.org/10.1017/S0954579412001071

Baranek, G. T., Woynaroski, T. G., Nowell, S., Turner-Brown, L., DuBay, M., Crais, E. R., & Watson, L. R. (2018). Cascading effects of attention disengagement and sensory seeking on social symptoms in a community sample of infants at-risk for a future diagnosis of autism spectrum disorder. *Developmental Cognitive Neuroscience*, *29,* 30–40. https://doi.org/10.1016/j.dcn.2017.08.006

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. https://doi.org/10.1007/s10803-019-04180-0

Ben-Sasson, A., Hen, L., Fluss, R., Cermak, S. A., Engel-Yeger, B., & Gal, E. (2009). A meta-analysis of sensory modulation symptoms in individuals with autism spectrum disorders. *Journal of Autism and Developmental Disorders*, *39,* 1–11. https://doi.org/10.1007/s10803-008-0593-3

Ben-Shachar, M. S., Makowski, D., & Lüdecke, D. (2020). *Compute and interpret indices of effect size*. CRAN. https://github.com/easystats/effectsize

Billstedt, E., Carina Gillberg, I., & Gillberg, C. (2007). Autism in adults: Symptom patterns and early childhood predictors. Use of the DISCO in a community sample followed from childhood. *The Journal of Child Psychology and Psychiatry*, *48*(11), 1102–1110. https://doi.org/10.1111/j.1469-7610.2007.01774.x

Bowman, S. M., Feldman, J. I., Keceli-Kaysili, B., Santapuram, P., Augustine, A. E., Golden, A. J., Suzman, E., Broderick, N., Cascio, C. J., & Woynaroski, T. G. (2018). *Stability of indices of sensory responsiveness in infants at risk for autism spectrum disorder* [Poster presentation]. Gatlinburg Conference on Research and Theory in Intellectual Disabilities, San Diego, CA, United States.

Brian, J., Bryson, S. E., Garon, N., Roberts, W., Smith, I. M., Szatmari, P., & Zwaigenbaum, L. (2008). Clinical assessment of autism in high-risk 18-month-olds. *Autism*, *12*(5), 433–456. https://doi.org/10.1177/1362361308094500

Bruni, M., Cameron, D., Dua, S., & Noy, S. (2010). Reported sensory processing of children with Down syndrome. *Physical & Occupational Therapy in Pediatrics*, *30*(4), 280–293. https://doi.org/10.3109/01942638.2010.486962

Bryson, S. E., Zwaigenbaum, L., Brian, J., Roberts, W., Szatmari, P., Rombough, V., & McDermott, C. (2007). A prospective case series of high-risk infants who developed autism. *Journal of Autism and Developmental Disorders*, *37*(1), 12–24. https://doi.org/10.1007/s10803-006-0328-2

Cascio, C. J., Woynaroski, T., Baranek, G. T., & Wallace, M. T. (2016). Toward an interdisciplinary approach to understanding sensory function in autism spectrum disorder. *Autism Research*, *9*(9), 920–925. https://doi.org/10.1002/aur.1612

Chamak, B., & Bonniau, B. (2016). Trajectories, long-term outcomes and family experiences of 76 adults with autism spectrum disorder. *Journal of Autism and Developmental Disorders*, *46*(3), 1084–1095. https://doi.org/10.1007/s10803-015-2656-6

Cohen, J. (1988). *Statistical power analysis for the behavioural sciences*. Routledge.

Cohen, J., & Cohen, P. (1984). *Applied multiple regression*. Erlbaum.

Costanzo, V., Chericoni, N., Amendolaba, F. A., Casula, L., Muratori, F., Scattoni, M. L., & Apicella, F. (2015). Early detection of autism spectrum disorders: From retrospective home video studies to prospective "high risk" sibling studies. *Neuroscience & Biobehavioral Reviews*, *55,* 627–635. https://doi.org/10.1016/j.neubiorev.2015.06.006

Damiano-Goodwin, C. R., Woynaroski, T. G., Simon, D. M., Ibañez, L. V., Murias, M., Kirby, A., Newsom, C. R., Wallace, M. T., Stone, W. L., & Cascio, C. J. (2018). Developmental sequelae and neurophysiologic substrates of sensory seeking in infant siblings of children with autism spectrum disorder. *Developmental Cognitive Neuroscience*, *29,* 41–53. https://doi.org/10.1016/j.dcn.2017.08.005

Dawson, G., Osterling, J., Meltzoff, A. N., & Kuhl, P. (2000). Case study of the development of an infant with autism from birth to two years of age. *Journal of Applied Developmental Psychology*, *21*(3), 299–313. https://doi.org/10.1016/S0193-3973(99)00042-8

DeGangi, G. A., & Greenspan, S. I. (1989). *Test of Sensory Functions in Infants (TSFI)*. Western Psychological Services. https://doi.org/10.1080/J006v08n04_02

DiGuiseppi, C., Hepburn, S., Davis, J. M., Fidler, D. J., Hartway, S., Lee, N. R., Miller, L., Ruttenber, M., & Robinson, C. (2010). Screening for autism spectrum disorders in children with Down syndrome: Population prevalence and screening test characteristics. *Journal of Developmental and Behavioral Pediatrics*, *31*(3), 181–191. https://doi.org/10.1097/DBP.0b013e3181d5aa6d

Dunn, W. (1999). *Sensory profile* [Database record]. APA PsycTests. https://doi.org/10.1037/t15155-000

Eisenberg, L. (1956). The autistic child in adolescence. *American Journal of Psychiatry*, *112*(8), 607–612. https://doi.org/10.1176/ajp.112.8.607

Enders, C. K. (2010). *Applied missing data analysis*. Guilford Press.

Fairchild, A. J., & MacKinnon, D. P. (2009). A general model for testing mediation and moderation effects. *Prevention Science*, *10*(2), 87–99. https://doi.org/10.1007/s11121-008-0109-6

Feldman, J. I., Cassidy, M., Liu, Y., Kirby, A. V., Wallace, M. T., & Woynaroski, T. G. (2020). Relations between sensory responsiveness and features of autism in children. *Brain Sciences*, *10*(11), Article 775. https://doi.org/10.3390/brainsci10110775

Fenson, L., Marchman, V. A., Thal, D. J., Dale, P. S., & Reznick, J. S. (2007). *MacArthur–Bates Communicative Development Inventories: User's guide and technical manual*. Brookes.

Foss-Feig, J. H., Heacock, J. L., & Cascio, C. J. (2012). Tactile responsiveness patterns and their association with core features in autism spectrum disorders. *Research in Autism Spectrum Disorders*, *6*(1), 337–344. https://doi.org/10.1016/j.rasd.2011.06.007

Gillberg, C., & Steffenburg, S. (1987). Outcome and prognostic factors in infantile autism and similar conditions: A population-based study of 46 cases followed through puberty. *Journal of Autism and Developmental Disorders*, *17*(2), 273–287. https://doi.org/10.1007/BF01495061

Gottlieb, G. (1971). *Ontogenesis of sensory function in birds and mammals*. Academic Press.

Hayes, A. F. (2017). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach*. Guilford Press.

Hiller, R. M., Young, R. L., & Weber, N. (2014). Sex differences in autism spectrum disorder based on DSM-5 criteria: Evidence from clinician and teacher reporting. *Journal of Abnormal Child Psychology*, *42*(8), 1381–1393. https://doi.org/10.1007/s10802-014-9881-x

Howlin, P., Goode, S., Hutton, J., & Rutter, M. (2004). Adult outcome for children with autism. *The Journal of Child Psychology and Psychiatry*, *45*(2), 212–229. https://doi.org/10.1111/j.1469-7610.2004.00215.x

Huck, S. W. (1992). Group heterogeneity and Pearson's *r*. *Educational and Psychological Measurement*, *52*(2), 253–260. https://doi.org/10.1177/0013164492052002001

Kent, L., Evans, J., Paul, M., & Sharp, M. (1999). Comorbidity of autistic spectrum disorders in children with Down syndrome. *Developmental Medicine & Child Neurology*, *41*(3), 153–158. https://doi.org/10.1111/j.1469-8749.1999.tb00574.x

Kobayashi, R., Murata, T., & Yoshinaga, K. (1992). A follow-up study of 201 children with autism in Kyushu and Yamaguchi areas, Japan. *Journal of Autism and Developmental Disorders*, *22,* 395–411. https://doi.org/10.1007/BF01048242

Landa, R. J., Gross, A. L., Stuart, E. A., & Bauman, M. (2012). Latent class analysis of early developmental trajectory in baby siblings of children with autism. *The Journal of Child Psychology and Psychiatry*, *53*(9), 986–996. https://doi.org/10.1111/j.1469-7610.2012.02558.x

Lickliter, R., & Bahrick, L. E. (2000). The development of infant intersensory perception: Advantages of a comparative convergent-operations approach. *Psychological Bulletin*, *126*(2), 260–280. https://doi.org/10.1037/0033-2909.126.2.260

Lord, C., Rutter, M., DiLavore, P., Risi, S., Gotham, K., & Bishop, S. L. (2012). *Autism Diagnostic Observation Schedule, Second Edition (ADOS-2) manual (Part I): Modules 1–4*. Western Psychological Services.

Lotter, V. (1974). Factors related to outcome in autistic children. *Journal of Autism and Childhood Schizophrenia*, *4*(3), 263–277. https://doi.org/10.1007/BF02115232

Miller, D., Spybrook, J., & Caverly, S. (2019). *Missing data in group design studies: Revisions in WWC standards version 4.0* [Webinar]. Institute of Education Science. https://ies.ed.gov/ncee/wwc/Multimedia/45

Mullen, E. M. (1995). *Mullen Scales of Early Learning*. AGS.

Mulligan, S., & White, B. P. (2012). Sensory and motor behaviors of infant siblings of children with and without autism. *American Journal of Occupational Therapy*, *66*(5), 556–566. https://doi.org/10.5014/ajot.2012.004077

Nowell, S. W., Jones, D. R., & Harrop, C. (2019). Circumscribed interests in autism: Are there sex differences? *Advances in Autism*, *5*(3), 187–198. https://doi.org/10.1108/AIA-09-2018-0032

Osborne, J. (2002). Notes on the use of data transformations. *Practical Assessment, Research, and Evaluation*, *8,* Article 6. https://doi.org/10.7275/4vng-5608

Ozonoff, S., Macari, S., Young, G. S., Goldring, S., Thompson, M., & Rogers, S. J. (2008). Atypical object exploration at 12 months of age is associated with autism in a prospective sample. *Autism*, *12*(5), 457–472. https://doi.org/10.1177/1362361308096402

Ozonoff, S., Young, G. S., Brian, J., Charman, T., Shephard, E., Solish, A., & Zwaigenbaum, L. (2018). Diagnosis of autism spectrum disorder after age 5 in children evaluated longitudinally since infancy. *Journal of the American Academy of Child & Adolescent Psychiatry*, *57*(11), 849–857. https://doi.org/10.1016/j.jaac.2018.06.022

Ozonoff, S., Young, G. S., Carter, A., Messinger, D., Yirmiya, N., Zwaigenbaum, L., Bryson, S., Carver, L., Constantino, J. N., Dobkins, K., Hutman, T., Iverson, J. M., Landa, R., Rogers, S., Sigman, M., & Stone, W. (2011). Recurrence risk for autism spectrum disorders: A Baby Siblings Research Consortium study. *Pediatrics*, *128*(3), e488–e495. https://doi.org/10.1542/peds.2010-2825

Ozonoff, S., Young, G. S., Landa, R. J., Brian, J., Bryson, S., Charman, T., Chawarska, K., Macari, S. L., Messinger, D., Stone, W. L., Zwaigenbaum, L., & Iosif, A.-M. (2015). Diagnostic stability in young children at risk for autism spectrum disorder: A Baby Siblings Research Consortium study. *The Journal of Child Psychology and Psychiatry*, *56*(9), 988–998. https://doi.org/10.1111/jcpp.12421

R Core Team. (2020). *R: A language and environment for statistical computing* (Version 4.0.2). https://www.R-project.org/

Reznick, J. S., Baranek, G. T., Reavis, S., Watson, L. R., & Crais, E. R. (2007). A parent-report instrument for identifying one-year-olds at risk for an eventual diagnosis of autism: The First Year Inventory. *Journal of Autism and Developmental Disorders*, *37*(9), 1691–1710. https://doi.org/10.1007/s10803-006-0303-y

Rogge, N., & Janssen, J. (2019). The economic costs of autism spectrum disorder: A literature review. *Journal of Autism and Developmental Disorders*, *49*(7), 2873–2900. https://doi.org/10.1007/s10803-019-04014-z

Rushton, J. P., Brainerd, C. J., & Pressley, M. (1983). Behavioral development and construct validity: The principle of aggregation. *Psychological Bulletin*, *94*(1), 18–38. https://doi.org/10.1037/0033-2909.94.1.18

Rutter, M., Bailey, A., & Lord, C. (2003). *The Social Communication Questionnaire*. Western Psychological Services.

Rutter, M., Greenfeld, D., & Lockyer, L. (1967). A five to fifteen year follow-up study of infantile psychosis. II. Social and behavioural outcome. *The British Journal of Psychiatry*, *113*(504), 1183–1199. https://doi.org/10.1192/bjp.113.504.1183

Sandbank, M., Bottema-Beutel, K., Crowley, S., Cassidy, M., Dunham, K., Feldman, J. I., Crank, J., Albarran, S. A., Raj, S., Mahbub, P., & Woynaroski, T. G. (2020). Project AIM: Autism intervention meta-analysis for studies of young children. *Psychological Bulletin*, *146*(1), 1–29. https://doi.org/10.1037/bul0000215

Sandbank, M., Bottema-Beutel, K., Crowley, S., Cassidy, M., Feldman, J. I., Canihuante, M., & Woynaroski, T. (2020). Intervention effects on language in children with autism: A Project AIM meta-analysis. *Journal of Speech, Language, and Hearing Research*, *63*(5), 1537–1560. https://doi.org/10.1044/2020_JSLHR-19-00167

Sevaslidou, I., Chatzidimitriou, C., & Abatzoglou, G. (2019). The long-term outcomes of a cohort of adolescents and adults from Greece with autism spectrum disorder. *Annals of General Psychiatry*, *18*(1), Article 26. https://doi.org/10.1186/s12991-019-0250-6

Sparrow, S. S., Cicchetti, D. V., & Bella, D. A. (2005). *Vineland Adaptive Behavior Scales–Second Edition*. Pearson. https://doi.org/10.1037/t15164-000

Stekhoven, D. J., & Bühlmann, P. (2012). missForest—Non-parametric missing value imputation for mixed-type data. *Bioinformatics*, *28*(1), 112–118. https://doi.org/10.1093/bioinformatics/btr597

Subramaniam, A. (2009). *Sensory processing in children with Down syndrome* [Master's thesis, The State University of New York at Buffalo]. ProQuest Dissertations & Theses Global.

Tabachnick, B., & Fidell, L. (2001). *Using multivariate statistics* (4th ed.). Allyn & Bacon.

Wallace, M. T., Woynaroski, T. G., & Stevenson, R. A. (2020). Multisensory integration as a window into orderly and disrupted cognition and communication. *Annual Review of Psychology*, *71,* 193–219. https://doi.org/10.1146/annurev-psych-010419-051112

Watson, L. R., Patten, E., Baranek, G. T., Poe, M., Boyd, B. A., Freuler, A., & Lorenzi, J. (2011). Differential associations between sensory response patterns and language, social, and communication measures in children with autism or other developmental disabilities. *Journal of Speech, Language, and Hearing Research*, *54*(6), 1562–1576. https://doi.org/10.1044/1092-4388(2011/10-0029)

Webb, S. J., Jones, E. J. H., Kelly, J., & Dawson, G. (2014). The motivation for very early intervention for infants at high risk for autism spectrum disorders. *International Journal of Speech-Language Pathology*, *16*(1), 36–42. https://doi.org/10.3109/17549507.2013.861018

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

Woynaroski, T. G., Watson, L. R., Gardner, E., Newsom, C. R., Keceli-Kaysili, B., & Yoder, P. J. (2016). Early predictors of growth in diversity of key consonants used in communication in initially preverbal children with autism spectrum disorder. *Journal of Autism and Developmental Disorders*, *46*(3), 1013–1024. https://doi.org/10.1007/s10803-015-2647-7

Wuang, Y.-P., & Su, C.-Y. (2011). Correlations of sensory processing and visual organization ability with participation in school-aged children with Down syndrome. *Research in Developmental Disabilities*, *32*(6), 2398–2407. https://doi.org/10.1016/j.ridd.2011.07.020

Yirmiya, N., Gamliel, I., Shaked, M., & Sigman, M. (2007). Cognitive and verbal abilities of 24- to 36-month-old siblings of children with autism. *Journal of Autism and Developmental Disabilities*, *37*(2), 218–229. https://doi.org/10.1007/s10803-006-0163-5

Yoder, P., Watson, L. R., & Lambert, W. (2015). Value-added predictors of expressive and receptive language growth in initially nonverbal preschoolers with autism spectrum disorders. *Journal of Autism and Developmental Disorders*, *45*(5), 1254–1270. https://doi.org/10.1007/s10803-014-2286-4