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

Longitudinal Relations Between Early Sensory Responsiveness and Later Communication in Infants with Autistic and Non-autistic Siblings

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Abstract

Early differences in sensory responsiveness may contribute to difficulties with communication among autistic children; however, this theory has not been longitudinally assessed in infants at increased familial versus general population-level likelihood for autism (Sibs-autism vs. Sibs-NA) using a comprehensive battery of sensory responsiveness and communication. In a sample of 40 infants (20 Sibs-autism, of whom six were later diagnosed with autism; 20 Sibs-NA), we tested (a) associations between sensory responsiveness at 12–18 months and communication 9 months later and (b) evaluated whether such associations were moderated by sibling group, autism diagnosis, or age. We found negative zero-order correlations between sensory responsiveness (i.e., caregiver reported hyperresponsiveness and hyporesponsiveness; an observational measure of hyperresponsiveness) and later communication. Additionally, caregiver reported sensory seeking was negatively associated with later expressive communication only in Sibs-NA. Limitations include our relatively small sample size of infants diagnosed with autism. Implications for future research are discussed.

Keywords Sensory responsiveness · Sensory reactivity · Communication · Infant siblings · Baby sibs · Predictors

Autism is a neurodevelopmental condition that affects approximately two million people in the United States and tens of millions of people worldwide (Baio et al., 2018; Maenner et al., 2021). With differences in sensory responsiveness now recognized as a core feature of autism (American Psychiatric Association, 2013), there has been an increased interest in sensory function in autistic individuals[1] (e.g., Cascio et al., 2016; Robertson & Baron-Cohen, 2017; Schauder & Bennetto, 2016). It has been proposed that differences in sensory responsiveness, particularly early in life, may impact a child's ability to engage with and learn from their environment, thereby producing "cascading effects" on development across domains and ultimately causing or contributing to core and related features of autism (Bradshaw et al., 2022; Cascio et al., 2016; Wallace et al., 2020), in particular differences in communication (Bahrick & Todd, 2012; Damiano-Goodwin et al., 2018; Santapuram et al., 2022). The acquisition of communication skills in early childhood has been repeatedly linked with quality of life and long-term outcomes of autistic children (e.g., social, academic, and vocational success; Billstedt et al., 2007; Eisenberg, 1956; Gillberg & Steffenburg, 1987; Kobayashi et al., 1992); thus, identifying early predictors of communication in this population is imperative.

There is a large literature supporting differences in sensory responsiveness, specifically hyperresponsiveness (i.e., exaggerated responses to sensory stimuli), hyporesponsiveness (i.e., reduced or absent responses to sensory stimuli), and sensory seeking (i.e., craving of or fascination with

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[1] We have opted to use identity-first language (e.g., autistic individuals) in this report to align with the preferences of the community and current recommendations for researchers (Bottema-Beutel et al., 2021; Bury et al., 2020).

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certain sensory experiences), in autistic children and adults compared to non-autistic peers (see Ben-Sasson et al., 2009, 2019; Kirby et al., 2022). Increased report of these patterns of sensory responsiveness is associated with lower social communication scores in autistic children and adults (Foss-Feig et al., 2012; Horder et al., 2014; Lane et al., 2010; Nowell et al., 2020; Williams et al., 2018) and lower language scores in autistic preschoolers and children (Baranek et al., 2013; Feldman et al., 2020; Nowell et al., 2020; Watson et al., 2011), lending some support to the cascading effects hypothesis.

However, testing theories that rely on observations of early development in autistic children, such as the cascading effects theory, is challenging given that autism cannot always be reliably diagnosed until at least the second year of life (e.g., Luyster et al., 2009; Woolfenden et al., 2012). Historically, researchers have utilized retrospective analyses to study sensory development in infancy (e.g., Baranek, 1999a; Freuler et al., 2012), but more recent efforts have examined the longitudinal impacts of early sensory development by focusing on infants at increased likelihood for developing autism (e.g., Baranek et al., 2018; Damiano-Goodwin et al., 2018; Nowell et al., 2020; Wolff et al., 2019). By prospectively following these infants, we can study the emergence and the sequelae of altered sensory functioning in the earliest stages of development in children who will go on to be diagnosed with autism. In one branch of this research focused on community-referred infants with autistic features early in life, differences in sensory responsiveness, specifically elevated hyporesponsiveness and sensory seeking, during the second year of life has been associated with lower communication scores later in life (Baranek et al., 2018; Grzadzinski et al., 2021).

Another line of research has focused on infants who are known to be at elevated likelihood of autism because they have an autistic older sibling (Sibs-autism; Ozonoff et al., 2011); approximately one-third of these infants will be diagnosed with autism or a language impairment (Charman et al., 2017; Ozonoff et al., 2011). For example, in a large-scale analysis of Sibs-autism, both hyporesponsiveness and sensory seeking were associated with concurrent communication at 24 months (Wolff et al., 2019). Although Wolff et al. (2019) included all three patterns of sensory responsiveness in their analyses, they only utilized caregiver report measures of sensory responsiveness (i.e., the Sensory Experiences Questionnaire [SEQ]; Baranek et al., 2006) and communication (i.e., the Vineland Adaptive Behavior Scales [VABS-2]; Sparrow et al., 2005) and did not carry out any longitudinal analyses. In another large-scale study of both Sibs-autism and infants at lower familial likelihood for autism (i.e., infants with only non-autistic older siblings; Sibs-NA), Narvekar et al. (2022) found that perceptual sensitivity at 14 and 24 months were related to social communication differences at 36 months; however, they did not comprehensively evaluate sensory processing differences associated with autism.

More recent work in our laboratory (Feldman et al., 2021) has focused on differences between Sibs-autism and Sibs-NA. We found that some alterations in sensory responsiveness were detectable in the developmental window between 12 and 18 months of age. Additionally, we found that select indices of sensory responsiveness were associated with concurrent communication outcomes, either unconditionally (e.g., link between caregiver reported hyporesponsiveness and both receptive and expressive communication) or only in older infants [e.g., associations between expressive communication and both caregiver reported sensory seeking and hyperresponsiveness as measured by the Test of Sensory Functions in Infants (TSFI)]. Though the aforementioned work, collectively, provided preliminary empirical support for theorized links between early sensory responsiveness and communication skills across the 12–18 month period in Sibs-autism, conclusions about directionality or causality of observed associations between atypical sensory responsiveness and communication skill could not be drawn, given the cross-sectional and concurrent correlational nature of the designs.

The present study, thus, seeks to expand upon our previous work by exploring the potential longitudinal links between early sensory responsiveness and later communication skills. To expand upon our previous study, we prospectively followed the same sample of 20 Sibs-autism and 20 Sibs-NA. For this study, we added to our comprehensive evaluation of infants' sensory responsiveness at 12–18 months of age by measuring their communication skills 9 months later (Time 2; i.e., at 21–27 months). We sought to evaluate (a) whether sensory responsiveness in infancy, as indexed using several previously developed and validated caregiver report and observational measures, is associated with later receptive and expressive communication, and whether the aforementioned associations vary according to (b) sibling group (Sibs-autism and Sibs-NA) and/or (c) chronological age when sensory measures were collected, given our previous findings that concurrent correlations were moderated by age (see Feldman et al., 2021). We additionally explored whether relations of interest varied according to preliminary diagnostic outcome (i.e., Sibs-autism who were diagnosed with autism during the study period [Sibs-autism-dx] versus Sibs-autism who were not diagnosed with autism during the study period [Sibs-autism-nodx] and Sibs-NA).

Method

Study Design

The Vanderbilt University Institutional Review Board approved all recruitment and study procedures. Parents

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

	Sibs-autism			Sibs-NA
	Total (n = 20)	Sibs-autism-dx (n = 6)	Sibs-autism-nodx (n = 14)	Total (n = 20)
	M (SD)	M (SD)	M (SD)	M (SD)
Time 1 variables				
Chronological Age (Months)	13.75 (1.9)	12.67 (0.8)	14.21 (2.0)	13.75 (2.0)
Mental Age (Months)	13.30 (1.4)	12.54 (1.5)	13.63 (1.3)	14.49 (2.2)
Mullen ELC	89.93 (12.6)	86.83 (16.3)	91.26 (11.1)	99.85 (9.4)
Time 2 variables				
Mullen Expressive Lang. AEQ	19.05 (4.7)	15.00 (2.7)	20.79 (4.3)	25.95 (7.8)
Mullen Receptive Lang. AEQ	17.90 (6.7)	11.17 (2.2)	20.79 (5.8)	27.03 (6.9)
VABS Expressive Com. AEQ	20.95 (6.0)	15.17 (5.1)	23.43 (4.4)	24.14 (5.2)
VABS Receptive Com. AEQ	21.30 (8.3)	14.00 (5.5)	24.43 (7.3)	26.61 (4.8)
MCDI Vocabulary†	110.67 (106.7)	45.83 (36.1)	138.45 (115.6)	230.39 (158.2)
Demographic variables	*n*	*N*	*n*	*n*
Biological sex	11 Male 9 Female	4 Male 2 Female	7 Male 7 Female	11 Male 9 Female
Race	20 White	6 White	14 White	18 White 2 Multiple
Ethnicity	1 Hispanic or Latino 19 Non-Hispanic or Latino	6 Non-Hispanic or Latino	1 Hispanic or Latino 13 Non-Hispanic or Latino	20 Non-Hispanic or Latino

Sibs-autism = infant siblings of autistic children, Sibs-autism-dx = Sibs-autism who were diagnosed with autism during the study period, Sibs-autism-nodx = Sibs-autism who were not diagnosed with autism during the study period, Sibs-NA = infant siblings of non-autistic, otherwise typically developing children. Sibs-autism information is summarized both across and within (i.e., for autism and non-autism) diagnostic outcome subgroups. Time 1 = 12–18 months, Time 2 = 9 months later (i.e., 21–27 months). 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), Lang. = Language, AEQ = age equivalency scores, VABS = Vineland Adaptive Behavior Scales, second edition (Sparrow et al., 2005), Com. = Communication, MCDI = MacArthur-Bates Communicative Development Inventories (Fenson et al., 2007). Sibs-autism and Sibs-NA groups were non-significantly different on biological sex and chronological age; groups differed on Mullen ELC and mental age at Time 1 and all variables at Time 2 (p values < .05). †Values represent back-transformed values, as this variable was transformed with a square-root transformation prior to analyses

provided written informed consent, and families were compensated for their participation.

Participants were recruited when they were between the ages of 12–18 months (± 30 days; resulting in one infant who was 11 months old at the time of the initial evaluation) from advertisements, at outreach events at the Adventure Science Center, and through flyers handed out at Vanderbilt outpatient clinics and preschools for children with autism. We followed these infants longitudinally. In this study, we will be reporting results relevant to their first outcome visit, 9 months after study entry (Time 2; i.e., 21–27 months). At each time point, infants completed all study measures in one to three visits to Vanderbilt University Medical Center scheduled over the course of a 2-week period.

Participants

Analyses were conducted on 40 infants and toddlers (20 Sibs-autism, 20 Sibs-NA). This sample was previously included in Feldman et al. (2021), which focused on concurrent correlations between sensory responsiveness and communication at the entry time-point in our study. Groups were matched on chronological age and biological sex (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 as diagnosed by a licensed clinician according to DSM-5 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 ADOS-2 (Lord et al., 2012) and independently confirmed the diagnosis (n = 5). For the Sibs-NA group, infants were required to have (a) only

Table 2 Summary of component variables derived for use in analyses

Assessment	Type	Component variables
Measures of sensory responsiveness		
Sensory Experiences Questionnaire version 2.1 (Baranek et al., 2006)	Caregiver Report	Sensory Seeking[a], Hyperresponsiveness[b], and Hyporesponsiveness[c] mean scores
Sensory Profile (Dunn, 1999)	Caregiver 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)	Caregiver Report	Raw number of words child understands and says (expressive vocabulary)[f]
Vineland Adaptive Behavior Scales, second edition (Sparrow et al., 2005)	Caregiver Report	Receptive Communication[e] and Expressive Communication[f] age equivalency scores

The construct purportedly tapped by each variable is indicated in parentheses when not transparent. Seeking = Sensory Seeking, Hyper = Hyperresponsiveness, Hypo = Hyporesponsiveness. Variables were aggregated to measure: [a]caregiver reported sensory seeking, [b]caregiver reported hyperresponsiveness, [c]caregiver reported hyporesponsiveness, [d]sensory seeking as measured by the Sensory Processing Assessment, [e]receptive communication, and [f]expressive communication

non-autistic 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 interview for developmental delay, (b) no first-degree relatives diagnosed with autism, (c) no prior history or present indicators of developmental delays or disorders per caregiver report, and (d) an Early Learning Composite on the Mullen Scales of Early Learning (MSEL; Mullen, 1995) greater than 70.

Measures of Sensory Responsiveness

Several observational and caregiver report measures of sensory responsiveness were utilized in the present study in an attempt to increase the stability, and thereby the potential construct validity, of indices of hyporesponsiveness, hyperresponsiveness, and sensory seeking (Cronbach & Meehl, 1955; Rushton et al., 1983). See Table 2 for a list of variables derived from these measures.

Sensory Experiences Questionnaire (SEQ)

The SEQ version 2.1 (Baranek et al., 2006) is a caregiver report measure that characterizes behaviors across a range of sensory modalities, response patterns, and social and non-social contexts. Mean scores for hyporesponsiveness, hyperresponsiveness, and sensory seeking were derived from this measure for use in analyses.

Infant/Toddler Sensory Profile Caregiver Questionnaire (SP)

The SP (Dunn, 1999) is an 81-item caregiver 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 (SPA)

The 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 non-social 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. Higher scores indicated greater presence of these patterns of sensory responsiveness.

Coders were naïve to sibling status. Eleven samples (26.8%) were randomly selected for coding by a second rater; intraclass correlation coefficients (ICC) for SPA variables were 0.907 for orienting (hyporesponsiveness), 0.820 and 0.810 for sensory seeking intensity and sensory seeking inventory, respectively, and 0.894 for avoidance (hyperresponsiveness), indicating good to excellent interrater reliability for these observational variables (see Feldman et al., 2021 for more detailed information).

Test of Sensory Functions in Infants (TSFI)

The 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 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. 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). Higher scores indicated greater presence of these patterns of sensory responsiveness. The coding manual for this measure is available upon request from the corresponding author.

As with the SPA, eleven samples were randomly selected for coding by a second naïve coder. Interrater reliability for variables derived from this measure was high (intraclass correlation coefficients [ICC] = 0.986 and 0.800 for mean hyperresponsiveness and hyporesponsiveness, respectively; see Feldman et al., 2021 for more detailed information).

Creation of Sensory Responsiveness Aggregates

Indices from the SEQ and SP purported to tap sensory seeking, hyporesponsiveness, and hyperresponsiveness were highly intercorrelated (r values indexing covariation between component variables ≥ 0.4; see Table S1), allowing us to create caregiver report aggregates following z-score transformation (Rushton et al., 1983; see Feldman et al., 2021 for more complete information on intercorrelations). Higher scores indicated greater presence of these patterns of sensory responsiveness. However, indices from observational measures were not sufficiently correlated with one another or with indices derived from the aforementioned caregiver report measures to be aggregated and, thus, were analyzed separately.

Measures of Receptive and Expressive Communication

The following communication measures were collected at study entry and at Time 2 (21–27 months; the outcome measurement period that is the focus of the present study).

Mullen Scales of Early Learning (MSEL)

The MSEL (Mullen, 1995) is a standardized test that assesses development in several domains, including expressive and receptive language, for children birth-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 scales). The age equivalency scores from the receptive and expressive language scales were derived for use in analyses.

MacArthur-Bates Communicative Development Inventories (MCDI)

The MCDI (Fenson et al., 2007) is a caregiver report measure that assesses early vocabulary and broader spoken language ability. We utilized the MCDI: Words and Sentences version to calculate raw scores for the number of words each child understands and says (i.e., expressive vocabulary) across the age range of interest. Note that the Words and Sentences version of this measure does not yield a receptive vocabulary score.

Vineland Adaptive Behavior Scales, Second Edition (VABS-2)

The VABS-2 (Sparrow et al., 2005) is a caregiver 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 derived for use in analyses.

Creation of Communication Aggregates

All measures purported to tap expressive and receptive communication, respectively, were correlated at $r \geq 0.4$ at Time 2, supporting the creation of communication aggregate scores using the corresponding component variables (following z-score transformation) from the MCDI, VABS-2, and MSEL (see Table S2).

Autism Diagnostic Assessment

All infants in both groups received a comprehensive autism diagnostic assessment by a licensed clinician at Time 2. This assessment included a research reliable administration of the ADOS-2 toddler module (Luyster et al., 2009) and a caregiver interview. Four infants in the Sibs-autism group were diagnosed at Time 2.

As a part of the larger ongoing study (see Study Design), most infants have also now been re-assessed after their third birthday (i.e., at 36–47 months) via a diagnostic battery that included an appropriate module of the ADOS-2 (Lord et al., 2012) and a clinical interview. At this later timepoint, three of the infants diagnosed with autism at Time 2 continued to meet criteria for a diagnosis, while the fourth did not complete their in-person evaluation at Time 3 due to the COVID-19 pandemic (see Missing Data); however, this infant's caregivers reported continued features consistent with an autism diagnosis. An additional two infants in the Sibs-autism group had been diagnosed with autism at the Time 3 measurement period, for a total of six infants with a preliminary diagnosis of autism in the longitudinal dataset (i.e., in the Sibs-autism-dx group; see Table 1). No infants in the Sibs-NA group were diagnosed with autism at either timepoint.

Missing Data

Missing data were imputed using the *missForest* package (Stekhoven & Bühlmann, 2012) in R (R Core Team, 2022). To aid data imputation, all available communication data from longitudinal study visits (which are ongoing as part of the larger project) were included as auxiliary variables in the datasheet. Prior to imputing missing data, all variables of interest were evaluated for normality, specifically for skewness > |1.0| and kurtosis > |3.0| (see Tabachnick & Fidell, 2001). Three variables included in analyses (i.e., TSFI hyporesponsiveness, SPA sensory seeking inventory, MCDI expressive vocabulary) were corrected for positive skew with a square root transformation (Osborne, 2002). One additional variable included in analyses (i.e., SP sensory sensitivity) was corrected for negative skew with a square transformation.

Analytic Plan

To answer our first research question, zero-order correlations were evaluated for each index of sensory responsiveness with expressive communication and receptive communication aggregates. Then, to assess whether sibling group moderated associations between sensory responsiveness and communication, regression models were run with expressive and receptive communication aggregates as the dependent variables and the index of sensory responsiveness of interest, group, and sensory index*group interaction term as the independent variables. This method was also used to assess whether the associations of interest were moderated by age and preliminary diagnostic outcome (i.e., Sibs-autism-dx versus Sibs-autism-nodx and Sibs-NA).

Interaction effects were probed at $p \leq .1$ in PROCESS (Hayes, 2017). This slightly lower threshold for Type I errors was used in testing interaction effects 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 < 0.1 threshold is employed for flagging significant interaction effects by default in statistics programs (e.g., R Core Team, 2022) and is commonly utilized in testing moderated effects in the autism literature (e.g., Feldman et al., 2021; Sandbank et al., 2020). For our only continuous putative moderator (chronological age at Time 1), we also utilized Johnson-Neyman tests to interpret significant moderation models.

Table 3 Zero-order associations between indices of sensory responsiveness and later communication

Time 1 Sensory Index	Time 2 Expressive communication	Time 2 Receptive communication
Caregiver reported seeking	−0.16	−0.16
Caregiver reported hypo	−0.15	**−0.47****
Caregiver reported hyper	0.13	**−0.33***
SPA seeking	−0.02	0.01
SPA orienting (hypo)	−0.26	−0.26
SPA avoidance (hyper)	−0.08	−0.04
TSFI hypo	0.00	0.07
TSFI hyper	**−0.46****	−0.30

Time 1 = Initial visit (i.e., 12–18 months), Time 2 = 9 months later (i.e., 21–27 months), Hypo = Hyporesponsiveness, Hyper = Hyperresponsiveness, SPA = Sensory Processing Assessment (Baranek, 1999b), TSFI = Test of Sensory Functions in Infants (DeGangi & Greenspan, 1989)

Bolded values are statistically significant, *$p < .05$, **$p < .01$

Results

Unconditional Links with Communication

See Table 3 for zero-order correlations between early sensory responsiveness and later communication. Although most of the correlations trended in the anticipated direction, only three were significant. Time 2 receptive communication was significantly predicted by caregiver reported hyporesponsiveness ($r = -.47$, $p = .002$; see Fig. 1A) and

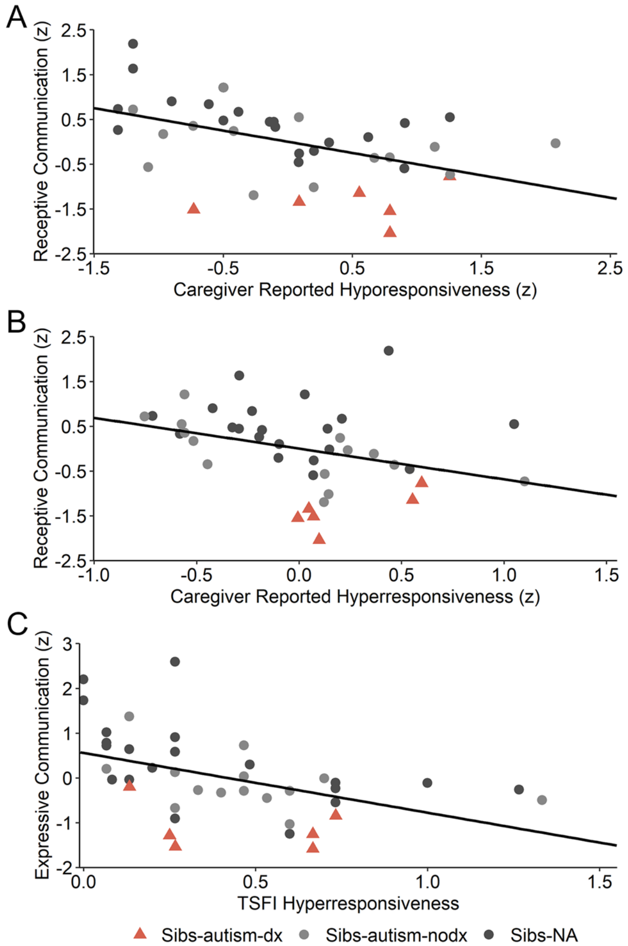

Fig. 1 Selected unconditional relations between sensory responsiveness and later communication. *Note* Figures depict unconditional associations between patterns of early sensory responsiveness at Time 1 (i.e., at 12–18 months) and communication at Time 2 (9 months later; i.e., at 21–27 months). Time 2 receptive communication was significantly predicted by **A** caregiver reported hyporesponsiveness ($r = -.47$, $p = .002$) and **B** caregiver reported hyperresponsiveness ($r = -.33$, $p = .036$). **C** Time 2 expressive communication was significantly predicted by hyperresponsiveness scores from the Test of Sensory Functions in Infants (TSFI; DeGangi & Greenspan, 1989; $r = -.46$, $p = .003$). Sibs-autism-dx (orange triangles) = infants with at least one autistic older sibling who did receive an autism diagnosis, Sibs-autism-nodx (light grey circles) = infants with at least one autistic older sibling who did not receive an autism diagnosis, Sibs-NA (dark grey circles) = infants with only non-autistic older siblings

caregiver reported hyperresponsiveness ($r = -.33$, $p = .036$; see Fig. 1B). Additionally, TSFI hyperresponsiveness significantly predicted Time 2 expressive communication ($r = -.46$, $p = .003$; see Fig. 1C).

Links with Communication as Moderated by Sibling Group

Multiple regression analyses indicated that one relation between indices of sensory responsiveness and later expressive communication was moderated by sibling group (see Table 4 for a summary of models testing associations according to sibling group and Tables S3-S4 for full multiple regression output). Specifically, the relation between caregiver reported sensory seeking and expressive communication at Time 2 varied according to sibling group ($\beta_{interaction} = -1.05$, $p = .020$, Cohens' $f^2 = 0.12$; see Fig. 2). Caregiver reported sensory seeking significantly predicted expressive communication at Time 2 in the Sibs-NA (β for Sibs-NA = –0.53, $p = .016$) but not in the Sibs-autism (β for Sibs-autism = 0.15, $p = .52$).

Links with Communication as Moderated by Preliminary Diagnostic Outcome

Multiple regression analyses indicated that none of the relations between indices of sensory responsiveness and communication at Time 2 were moderated by preliminary diagnostic outcome status (i.e., Sibs-autism-dx versus Sibs-autism-nodx and Sibs-NA; see Table 4 for a summary and Tables S5–S6 for full output).

Links with Communication as Moderated by Age

Only one of the associations (i.e., the relation between SPA avoidance and expressive communication at Time 2) was moderated by chronological age at Time 1, $\beta_{interaction} = -1.63$, $p = .091$, Cohens' $f^2 = 0.06$ (see Tables 4, S7–S8). However, there was no significant result for the Johnson-Neyman test for the moderated relation, so we cannot interpret this significant result.

Post-hoc Analyses

A series of post-hoc analyses was run to evaluate whether our significant findings were robust to controlling for (a) chronological age and (b) communication at study entry. All significant zero-order associations (i.e., TSFI hyperresponsiveness and expressive communication, caregiver reported hyporesponsiveness and receptive communication, caregiver reported hyperresponsiveness and receptive communication) remained statistically significant when controlling for age. These relations were also robust to controlling for communication at study entry.

None of the significant moderated relations were robust to controlling for communication at study entry. However, when controlling for age, there was a persistent trend towards a significant moderated relation between caregiver reported sensory seeking and expressive communication according to sibling group (p for the interaction term = .108). Notably, we have limited power to detect interaction effects when including covariates in regression models in the present sample.

Table 4 Relations between sensory responsiveness and later communication as moderated by sibling group, preliminary diagnostic outcome, and age

Time 1 Sensory Index	Moderation by sibling group				Moderation by outcome				Moderation by age			
	Expressive β_{int} (f^2)		Receptive β_{int} (f^2)		Expressive β_{int} (f^2)		Receptive β_{int} (f^2)		Expressive β_{int} (f^2)		Receptive β_{int} (f^2)	
Caregiver reported seeking	**−1.05***	(0.12)	−0.47	(0.02)	−0.12	(0.00)	0.07	(0.00)	0.14	(0.00)	−0.48	(0.00)
Caregiver reported hypo	−0.31	(0.01)	−0.37	(0.01)	−0.30	(0.01)	−0.50	(0.02)	0.15	(0.00)	0.40	(0.00)
Caregiver reported hyper	0.61	(0.04)	0.61	(0.04)	−0.54	(0.02)	−0.78	(0.03)	1.43	(0.04)	1.48	(0.05)
SPA seeking	0.25	(0.02)	0.01	(0.00)	−0.61	(0.02)	−0.31	(0.00)	0.42	(0.00)	1.61	(0.06)
SPA orienting (Hypo)	0.38	(0.00)	0.07	(0.00)	−0.13	(0.00)	−0.28	(0.00)	1.06	(0.02)	0.48	(0.00)
SPA avoidance (Hyper)	−0.56	(0.03)	−0.04	(0.00)	0.22	(0.00)	0.10	(0.00)	**−1.63**†	(0.06)	−0.17	(0.00)
TSFI hypo	0.09	(0.00)	−0.35	(0.01)	−0.13	(0.00)	−0.09	(0.00)	−1.63	(0.04)	0.30	(0.00)
TSFI hyper	−0.42	(0.01)	0.00	(0.00)	−0.24	(0.00)	0.01	(0.00)	−1.46	(0.04)	−0.69	(0.01)

Time 1 = Initial visit (i.e., 12–18 months), Expressive = expressive communication composite scores at Time 2 (9 months later; i.e., 21–27 months), Receptive = receptive communication composite scores at Time 2, β_{int} = Standardized regression coefficient for the sensory*putative moderator interaction term in the multiple regression model predicting the communication index of interest (i.e., sensory*sibling group for Sibling Group, sensory*autism diagnosis or not for Outcome, sensory*age for Age), f^2 = Cohen's f^2, Hypo = Hyporesponsiveness, Hyper = Hyperresponsiveness, SPA = Sensory Processing Assessment (Baranek, 1999b), TSFI = Test of Sensory Functions in Infants (DeGangi & Greenspan, 1989)

Bolded values are statistically significant, $^{\dagger}p < .1$, $^{*}p < .05$

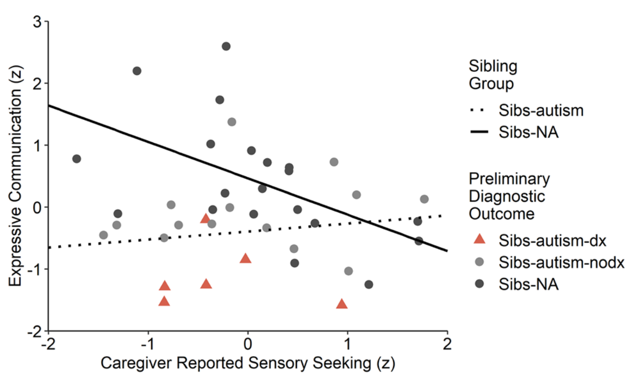

Fig. 2 The relation between caregiver reported sensory seeking and later expressive communication is moderated by sibling group. *Note* The relation between caregiver reported sensory seeking at Time 1 (i.e., at 12–18 months) and expressive communication at Time 2 (9 months later; i.e., at 21–27 months) was moderated by sibling group (β for the sibling group × sensory seeking term in the multiple regression model = − 1.05, p = .020, Cohen's f^2 = 0.12). The relation was significant and in the anticipated direction for the infant siblings of non-autistic children (Sibs-NA; dark grey dots and solid line; β = − 0.53, p = .016) but not in the infant siblings of autistic children (Sibs-autism; dotted line, β = 0.15, p = .52). In this figure, Sibs-autism who did and did not go on to receive an autism diagnosis are denoted by orange triangles (Sibs-autism-dx) and light grey circles (Sibs-autism-nodx), respectively

Discussion

This study sought to expand our previous work on concurrent associations between early patterns of sensory responsiveness and later receptive and expressive communication by evaluating longitudinal links between these domains in the same sample of infants at increased and general population-level familial likelihood for a later diagnosis of autism (Sibs-autism and Sibs-NA). Findings suggest that indices of sensory responsiveness derived during the 12–18 month developmental period predict later communication in different ways.

Three sensory indices were significant predictors of subsequent communication outcomes, unconditionally (i.e., not covarying for or conditional upon any other variables, such as putative moderators), across both groups of infants. Specifically, increased caregiver reported hyporesponsiveness and hyperresponsiveness significantly predicted lower receptive communication scores at Time 2 (i.e., 9 months later), while increased hyperresponsiveness as measured via the TSFI significantly predicted lower expressive communication scores at Time 2. These relations held when controlling for several additional factors, including chronological age and entry-level communication, suggesting that selected indices of sensory responsiveness are promising as value-added predictors of communication across Sibs-autism and Sibs-NA (Yoder et al., 2015).

The aforementioned findings, on the whole, are consistent with the cascading effects theory (Cascio et al., 2016). The present results provide increased empirical support for the notion that hyporesponsiveness is associated with poor communication outcomes across autistic children and infants at elevated likelihood for the condition (e.g., Baranek et al., 2013; Feldman et al., 2020; Grzadzinski et al., 2021), likely because this particular pattern of sensory responsiveness manifests via reduced orienting towards, and likely subsequently engaging with and learning from, one's environment. In contrast, this is the first study to our knowledge to find unconditional, longitudinal links between early hyperresponsiveness and later communication. It is possible that early hyperresponsiveness to sensory stimuli may cause infants to become hyperselective or hyperrestrictive to certain sensory aspects of social experiences, contributing to social withdrawal and disrupting communication development. Alternatively, hyperresponsiveness may cause infants to become distracted by irrelevant information in social settings, leading to interference with opportunities for engagement and thereby contributing to communication delay and disorder.

These results also accord with some of the cross-sectional work previously conducted on Sibs-autism (Feldman et al., 2021; Wolff et al., 2019), though most longitudinal studies to date on infants at an increased likelihood for later autism diagnosis, notably, have not assessed all patterns of sensory responsiveness (i.e., Baranek et al., 2018; Damiano-Goodwin et al., 2018; Grzadzinski et al., 2021; Narvekar et al., 2022). Additionally, most studies on sensory responsiveness in infants have only utilized one type of measure (i.e., caregiver report or observational) or have not attempted to aggregate caregiver report and observational measures.

Though there is limited evidence for associations between observational and caregiver-report measures of the same patterns of sensory responsiveness in prior work (i.e., Boyd et al., 2010), it is notable that the caregiver-report and observational measures purported to tap the same patterns of sensory responsiveness were not sufficiently intercorrelated in this sample to warrant aggregation. We suspect that the lack of strong covariation may be attributable to the fact that the various measures differ in the extent to which they tap patterns of sensory responsiveness within specific sensory modalities. The caregiver reports index infants' behavioral responses to sensory stimuli from a broad range of modalities (i.e., auditory, visual, tactile, gustatory, olfactory, vestibular, proprioceptive, multisensory) encountered in everyday settings. In contrast, variables derived from the SPA index infants' observed responses to sensory stimuli in primarily auditory, visual, and tactile modalities, and variables derived from the TSFI index infants' observed responses to predominantly visual, tactile, and vestibular stimuli. Emerging work suggests that considerable variance is accounted for by modality-specific response patterns versus supra-modal response patterns (Ausderau et al., 2014; Tillmann et al., 2020). Given our differential findings for theorized links with later communication, we recommend that future studies employ multiple measures with at least some prior psychometric support for tapping all patterns of sensory responsiveness across the broadest possible range of sensory modalities in infants and/or autistic children (e.g., Eeles et al., 2013; Schaaf & Lane, 2015; Yeung & Thomacos, 2020). Doing so will further our understanding of which sensory responsiveness scores have the highest validity or clinical utility for predicting communication outcomes.

Only one of the associations tested in this study varied according to sibling group: the relation between caregiver reported sensory seeking and later expressive communication. In this case, the association was stronger in Sibs-NA relative to Sibs-autism and only in the anticipated direction for the Sibs-NA. It is unclear why these associations were not present or in the hypothesized direction in the Sibs-autism group. Notably, this interaction was not robust to controlling for other factors, such as entry-level communication and chronological age; however, the present study was somewhat underpowered to include additional covariates in regression models. Additionally, this study is already at an increased risk of making a type I error due to the number of analyses run. Thus, our findings may be best considered preliminary and beg for replication in future studies testing more complex moderation models with larger samples.

It is also possible that relations of interest may differ between Sibs-autism-dx, Sibs-autism-nodx, and Sibs-NA. Although our prospective design allowed us to follow infants over the course of their early development and to assess whether the relations between sensory differences and communication skill were moderated by preliminary diagnostic outcome, we did not find evidence for differences between infants diagnosed with autism (Sibs-autism-dx) compared to the other infants (Sibs-autism-nodx and Sibs-NA). Our relatively small number of six participants diagnosed with autism in the present sample, though consistent with published literature on diagnostic rates in Sibs-autism (Ozonoff et al., 2011), is arguably not sufficient to comprehensively assess moderation according to diagnostic outcome, thus limiting our ability to draw firm conclusions regarding the extent to which longitudinal relations of interest vary according to this factor. Additionally, because some of the Sibs-autism who were not diagnosed with autism at this time may still receive a diagnosis later in life (e.g., around their fifth or eighth birthday; Ozonoff et al., 2018), we may need to follow a larger sample of infants for a more extended period of time to more fully evaluate the degree to which these relations differ according to outcome status.

Although we did find evidence for moderated longitudinal associations between early sensory responsiveness and later communication in the present study, the predictive relations of interest were not significantly moderated by chronological age. This result is somewhat surprising, given that our prior work on Sibs-autism suggested that concurrent relations between sensory responsiveness and communication did vary according to age (Feldman et al., 2021), such that concurrent correlations trended in the anticipated (negative) direction and were stronger in older infants. In the previous report, we noted that at least some of the previously observed moderated associations may have been driven by reduced variance (i.e., a truncated range) in communication when measured concurrently, in particular at younger ages (i.e., before 13 months). Alternatively, it is still possible that, at younger ages, certain patterns of sensory responsiveness may be adaptive (or at least not maladaptive) in the short-term.

A notable limitation of this study was that our sample was largely white and non-Hispanic or Latino, which may limit our ability to generalize our results to the entire autistic population. Thus, future research recruiting samples of infants from more diverse racial and ethnic backgrounds is needed.

It is also important to note that our study does not permit conclusions regarding *how* sensory responsiveness as measured early in life may influence later communication. Theory and past research, however, point towards factors that may mediate the relations that we have observed. Specifically, theory suggests that early disruptions in sensory function may influence downstream developmental skills by interfering with an infant's engagement with their environment (e.g., Baranek et al., 2018). Santapuram et al. (2022) provided some empirical support for this theorized mechanism, by demonstrating that an early multisensory milestone (looking to audiovisual speech) influenced communication via higher-order supported joint engagement in infants at both high and low likelihood for autism (see Bottema-Beutel et al., 2014, 2019). In a related study of infants identified as being at high likelihood for autism via community screening, Grzadzinski et al. (2021) found that a transactional construct (i.e., caregiver responsivity) mediated selected associations between early indices of sensory responsiveness and communication outcomes. These findings, collectively, suggest that hyporesponsiveness, hyperresponsiveness, and/or sensory seeking may interfere with typical dyadic interactions, thus decreasing the opportunities that caregivers have to engage with and respond to their child during play interactions and thereby indirectly influencing later communication. Further research, employing larger samples, longitudinal designs, and advanced analytic approaches such as moderation and mediation will provide additional insights into precisely *when*, *for whom*, and *by what mechanisms* early sensory responsiveness is useful for predicting communication development in infants at high and low likelihood for a future diagnosis of autism.

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Author Contributions JIF, CJC, and TGW posed the research questions. JIF, VG, KD,JEM, SMB, AJG, CD, SK, NM, SR, PS, ES, AEA, AM, BKK, and TGW collected and scoredthe data. KLW and AVK scored the data. JIF and TGW analyzed the data. JIF, VG, and TGW-drafted the manuscript and interpreted the results. All authors read and approved the finalmanuscript.

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Declarations

Conflict of interest The authors declare no competing interests.

Ethical Approval All procedures were performed in accordance with the ethicalstandards of the Vanderbilt University Institutional Review Board and with the 1964 Declarationof Helsinki and its later amendments.

Informed Consent All participants or their parents provided written informed consent.All minor participants provided written assent prior to their participation.

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