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EMPIRICAL ARTICLE

CHILD DEVELOPMENT

Developmental trajectories of sensory patterns from infancy to school age in a community sample and associations with autistic traits

Yun-Ju Chen[1] | **John Sideris**[1] | **Linda R. Watson**[2] | **Elizabeth R. Crais**[2] | **Grace T. Baranek**[1]

[1]Mrs. T.H. Chan Division of Occupational Science and Occupational Therapy, University of Southern California, Los Angeles, California, USA

[2]Department of Allied Health Sciences, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina, USA

Correspondence
Yun-Ju (Claire) Chen, Chan Division of Occupational Science and Occupational Therapy, University of Southern California, 1540 Alcazar Street CHP 133, Los Angeles, CA 90089, USA.
Email: chenyunj@usc.edu

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Abstract

This prospective study examined the latent growth trajectories of sensory patterns among a North Carolina birth cohort (N = 1517; 49% boys, 87% White) across infancy (6–19 months), preschool (3–4 years), and school years (6–7 years). Change rates of sensory hyper- and hyporesponsiveness better differentiated children with an autism diagnosis or elevated autistic traits from those with other developmental conditions, including non-autistic children with sensory differences. More sensory hyper- and hyporesponsiveness at infancy followed by steeper increases differentially predicted more autistic traits at school age. Further, children of parents with higher education tended to show stable or improving trajectories. These findings highlight the importance of tracking sensory patterns from infancy for facilitating early identification of associated challenges and tailored support for families.

INTRODUCTION

Atypical behavioral responses to sensory stimuli have been commonly observed in retrospective reports of children with autism spectrum disorder (ASD) (Dawson et al., 2000; Freuler et al., 2012) as well as in prospective studies with high-risk infant siblings within the first years of life, potentially preceding many of the social-communication symptoms associated with ASD (Deconinck et al., 2013; Sacrey et al., 2015; Zwaigenbaum et al., 2005). Past research has commonly characterized these behaviors into three patterns: hyperresponsiveness (HYPER), hyporesponsiveness (HYPO), and sensory interests, repetitions, and seeking behaviors (SIRS) (e.g., Baranek et al., 2006; Ben-Sasson et al., 2009; Liss et al., 2006). Like other autistic traits such as social-communication deficits, the behavioral manifestations of sensory patterns have been reported to vary from one individual to another not only in intensity and modality across these three patterns (Lane et al., 2010; Liss et al., 2006; Little et al., 2017) but also in how they manifest over time (Ausderau et al., 2014; Ben-Sasson et al., 2019). Previous meta-analytic findings regarding sensory patterns in ASD showed that HYPER and SIRS increased

Abbreviations: ANOVA, analysis of variance; ASD, autism spectrum disorder; CFI, comparative fit index; DCQv1.5, Developmental Concerns Questionnaire version 1.5; DIF, differential item functioning; ESF, elevated sensory features; FYIv3.1, First Years Inventory version 3.1; HYPER, hyperresponsiveness; HYPO, hyporesponsiveness; IRT, item response theory; LGCM, latent growth curve modeling; ML, maximum likelihood; NCCDS, North Carolina Child Development Survey; ND, no diagnosis; OD, other diagnosis; RMSEA, root-mean-square error of approximation; RRB, restricted and repetitive behavior; SCI, social communication and interaction; SEQv2.1, Sensory Experiences Questionnaire version 2.1; SIRS, sensory interests, repetitions, and seeking behaviors; SRS-2, Social Responsiveness Scale, 2nd ed.; TLI, Tucker–Lewis index.

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from infancy until 6–9 years of age, and gradually decreased thereafter (Ben-Sasson et al., 2009). HYPER tended to become more prominent as children transition from preschool to school stage (Liss et al., 2006; Talay-Ongan & Wood, 2000). In contrast, the severity of HYPO seemed to decrease as a function of mental age in young children with ASD (Baranek, Watson, Boyd, et al., 2013). A recent study followed up a large sample of children with ASD aged 2–12 years at two time-points separated by around 3 years (Baranek et al., 2019), reporting that the group means of HYPO and SIRS declined over time, while intra-individual differences remained stable. Another longitudinal study on high-risk infant siblings indicated that HYPO and HYPER became more pronounced between 12 and 24 months of age in those with a later diagnosis of ASD (Wolff et al., 2019), while other studies did not find significant changes in overall sensory features over time in children with ASD aged 2–8 years (McCormick et al., 2016; Perez-Repetto et al., 2017).

The interpretation of these findings, however, was often confounded by differences across studies in child's mental or chronological age, study designs (cross-sectional or longitudinal), types of measures (parent-report or observational), theoretical foundations and terminology (Schaaf & Lane, 2015), as well as analytic approaches of modeling changes. Particularly, the existing evidence was mostly based on the "snapshots" of age-heterogeneous samples of children and thus might fail to detect individual deviations from typical trajectories. While there have been a growing number of studies addressing longitudinal variability of ASD symptoms, as summarized in a recent systematic review (Pender et al., 2020), there is currently no evidence on the developmental variability of sensory patterns in children with ASD and other neurodevelopmental conditions. Notably, sensory patterns are also present among non-ASD populations given the estimated 5%–8% prevalence of elevated sensory features among school-aged children (Ahn et al., 2004; Jussila et al., 2020), and appear to be continuously distributed across the general population (Jussila et al., 2020; Little et al., 2017). From a developmental psychopathology perspective, the early disruptions in sensory development may lead to vulnerability for a wide variety of psychopathological conditions (i.e., multifinality; Cicchetti & Rogosch, 1996; Uljarević et al., 2017). In this regard, many questions remain unanswered. For instance, if HYPER was found to increase during early childhood in children with ASD, could a similar pattern be also observed in those with other developmental challenges, such as attention deficit hyperactivity disorder, developmental delay, and non-autistic children with elevated sensory features? That is, is such a pattern unique to ASD? When might we observe divergence of trajectories that lead to various long-term outcomes? These questions highlight the necessity to examine sensory patterns across development beyond ASD populations to better understand commonalities as well as differences that lead to heterogeneous neurodevelopmental outcomes.

Furthermore, it has been hypothesized that altered sensory processing during infancy may cascade into later-emerging traits such as social-communication deficits (Baranek et al., 2018; Robertson & Baron-Cohen, 2017; Thye et al., 2018). This indicates that sensory patterns may be critical behavioral markers for early detection of ASD, which further introduces opportunities for early intervention leading to better outcomes. Despite the existing cross-sectional evidence of linkages between sensory patterns and autism symptoms or risk at both behavioral and neurophysiological levels (Liss et al., 2006; Rogers et al., 2003; Simon et al., 2017; Watson et al., 2011), there is currently a lack of evidence on the longitudinal impact of sensory patterns on later severity of autistic traits. Recently, longitudinal behavioral and electrophysiological studies demonstrated that sensory-seeking behavior by 24 months predicts later social difficulties at 36 months of age (Baranek et al., 2018; Damiano-Goodwin et al., 2018). Another recent study following infants in a community sample with elevated risk of ASD provided longitudinal evidence that early HYPER and HYPO across 14–23 months were associated with autism symptom severity at 3–5 years (Grzadzinski et al., 2020). While these longitudinal findings served as important supporting evidence for the cascading impact of sensory patterns, they tended to focus more on average changes or associations without sufficiently addressing individual differences. Conventional approaches of analyzing change over time, such as repeated-measures analysis of variance (ANOVA) and multivariate ANOVA, are limited in accounting for measurement errors of predictors or outcome variables as well as variations in intra-individual change (Curran et al., 2010), which may thus affect the interpretation of findings. Also, they are less flexible in exploring more complex developmental processes (e.g., continuity or discontinuity in development, multivariate growth processes with multiple covariates and distal outcomes) which may underlie the longitudinal association between sensory patterns and autistic traits.

Given these empirical gaps, the current study aimed to examine the developmental variability of sensory patterns prospectively from infancy through school age, and to determine their associations with later autistic traits and various neurodevelopmental outcomes in a large community sample. We used latent growth curve modeling (LGCM), an analytic method that allows for estimating between-person differences in within-person patterns of change over time (Curran et al., 2010), to explore the trajectories of sensory patterns. The specific research questions were as follows: (1) Are the developmental trajectories of sensory patterns, including HYER, HYPO, and SIRS, stable and linear from infancy to school age across a community sample? (2) Are there

significant between-person differences among these trajectories? If so, to what extent could such variability be explained by demographics, such as child's sex, race, and parent education? (3) Do children later classified into different developmental outcome groups show distinct sensory pattern trajectories? (4) Are the latent growth factors of sensory pattern trajectories able to predict levels of autistic traits at school age? Although we expected that children who were reported to have an ASD diagnosis or elevated autistic traits in our sample would show more elevated sensory features across this period than those in the other outcome groups given the widely reported sensory challenges among autistic populations, the current latent trajectory analyses were exploratory as no previous evidence had been derived from a similar community sample and prospective cohort design.

METHOD

Participants and procedure

This study followed a large cohort of families with infants born between January 1 and December 31, 2013, in the state of North Carolina, who were previously recruited for the North Carolina Child Development Survey (NCCDS) project, and collected new outcome measures at school age. Families were initially ascertained from birth registries, with recruitment of infants (N = 6454) at the age of 6–19 months (T1) for completing the First Years Inventory version 3.1 (FYIv3.1; Baranek, Watson, Crais, et al., 2013) in 2014. Families with Hispanic or Latino ethnicity, based on information available in the state vital records, were excluded from recruitment because a large proportion (~80%) of these families spoke primarily Spanish at home (Tippett, 2014) and the FYIv3.1 had not yet been translated into Spanish with a valid cultural adaptation (particularly concerning the language-related items; DuBay et al., 2021) at the time of the study in 2014. Those who returned their responses at T1 were re-contacted at 3–4 years (T2) between 2016 and 2017 to assess their child's developmental outcomes; measures at T2 included the Developmental Concerns Questionnaire version 1.5 (DCQv1.5; Reznick et al., 2005), Sensory Experiences Questionnaire version 2.1 (SEQv2.1; Baranek, 1999), and Social Responsiveness Scale 2nd edition (SRS-2; Constantino & Gruber, 2012). In this study, the 2236 families who returned their responses at T2 (response rate = 35%) were re-contacted in 2019 via email to complete new questionnaires regarding their child's current diagnostic status or any parent-report concerns (DCQv1.5), as well as sensory patterns (SEQv2.1) at 6–7 years of age (T3, Phase-1).

At T3 Phase-1, we received 1508 complete sets of responses (response rate = 67%). The second phase of data collection (T3, Phase-2) took place approximately 5 months after T3 Phase-1 responses were returned. Invitations were sent to all families who reported any diagnosis or concerns at previous time-points, as well as a random sample of families whose responses did not indicate any concerns. A total of 465 families (N = 359 with diagnoses or concerns, and N = 106 without diagnoses or concerns) were asked to complete SRS-2 (school-age version). The response rate at T3 Phase-2 was 84% (389 out of 465). All procedures were approved by the University of North Carolina at Chapel Hill (IRB #13-2648) and University of Southern California Institutional Review Boards (IRB #HS-19–00651).

The measures collected across time-points are summarized in Table S1. The longitudinal responses of FYIv3.1 and SEQv2.1 (no missingness for at least two time-points) from a total of 1517 participants and their outcome data were used for further analysis. The demographics of the full sample (N = 1517) at T3 Phase-1, and subsample with T3 Phase-2 responses (N = 389) are shown in Table 1.

Measures

First Years Inventory, Version 3.1 (FYIv3.1)

The FYIv3.1 is a newly revised parent-report measure (69 items in total) designed to identify infants aged 6–16 months at elevated risk for a later diagnosis of ASD or related neurodevelopmental conditions. It measures the frequency of behaviors across social-communication, sensory-regulatory functions, and motor development with a 5-point Likert scale. Its previous version FYIv2.0 has been validated (Reznick et al., 2007) and used in several studies including both community samples and high-risk samples (e.g., Meera et al., 2020; Turner-Brown et al., 2013). The FYIv3.1 data were collected at T1, with each participant randomly receiving either an A or B form to reduce response time burden (each form with 48 FYI items, 27 items in common). For this study, fourteen items related to sensory patterns were extracted from the FYIv3.1 to comprise constructs of HYPER, HYPO, and SIRS (see Table S2 for a list of items).

Sensory Experiences Questionnaire, Version 2.1 (SEQv2.1)

The SEQv2.1 is a parent questionnaire designed to measure the frequency of behavioral responses to daily sensory experiences for children ages 1–12 years. It includes 37 items using a 5-point Likert scale, with higher scores indicating endorsement of more sensory features. It has excellent internal consistency (α = .80) and test–retest reliability (ICC = .92) (Little et al., 2011), along with good discriminative validity (Baranek et al., 2006), and has been used extensively in the literature, including studies of young children with ASD and high-risk infant siblings (Boyd et al., 2010; Wolff et al., 2019). The SEQ data were collected

TABLE 1 Sample demographics and descriptive statistics

	Full sample w/complete sensory data (*N* = 1517)	Subset sample w/age-6 SRS-2 data (*N* = 389)
Sex (male)	742 (49%)	233 (60%)
Race		
White	1315 (87%)	341 (88%)
Black	65 (4%)	11 (3%)
Asian	16 (1%)	4 (1%)
American Indian/Hawaiian	11 (1%)	4 (1%)
Multi-racial/Other	110 (7%)	29 (7%)
Parent education[a] (5% missing)		
Two parents had a college degree (or beyond)	896 (59%)	205 (53%)
One parent had a college degree (or beyond)	328 (22%)	95 (24%)
None of the parents had a college degree (or beyond)	209 (14%)	69 (18%)
SRS-2 *T*-score at T3 [*M* (*SD*)]		
Total	—	52.95 (11.20)
Social communication/interaction	—	52.80 (11.14)
Restricted/repetitive behavior	—	53.21 (11.46)

[a]Categorization was based on the reported mother's and father's education at T1.

at T2 and T3. Fourteen items in common with those in the FYIv3.1 (see Table S2) were extracted to establish sensory construct scores for HYPO, HYPER, and SIRS.

Developmental Concerns Questionnaire, Version 1.5 (DCQv1.5)

The DCQv1.5 is a parent-report measure with open-ended questions about whether a parent or professional has been concerned about the child's development and whether the child has received any clinical diagnoses. The DCQ data at T2 and T3 were used for clinical outcome classification, as previously validated in a study by Turner-Brown et al. (2013). Responses were coded to determine whether the child has had a diagnosed developmental disability, including ASD and other developmental diagnoses or concerns.

Social Responsiveness Scale, 2nd Edition (SRS-2)

The SRS-2 is a parent-report measure of levels of autistic traits; it provides general population norms and has good discriminative validity (sensitivity = 0.83–0.91, specificity = 0.53–0.88) among clinical and non-clinical samples of young children with diverse demographics (Moody et al., 2017). The SRS data were collected at T2 (preschool-age version) and T3 Phase-2 (school-age version). The total T-scores at T2 and T3 were used for outcome group classification (see the next section for details). The Social Communication and Interaction (SCI) and Restricted and Repetitive Behavior (RRB) domain T-scores at T3 Phase-2 were used as distal outcome variables in the analysis.

Classification of outcome groups

Based on all the available parent-report data collected at T2 and T3, including SEQv2.1, DCQv1.5, and SRS-2, children's neurodevelopmental outcomes were classified into either of the following groups (see Figure 1 for the classification flow): (1) ASD or elevated autistic traits (ASD-AT): parental report of an ASD diagnosis from clinicians or elevated autistic traits as measured by the SRS-2 (total *T*-score ≥60); (2) elevated sensory features (ESF): parental report of sensory-related diagnoses or concerns or elevated SEQv2.1 scores (total score >1 *SD* above the mean) and SRS-2 total *T*-score <60; (3) other diagnosis or concerns (OD): parental report of other developmental diagnoses or concerns, SRS-2 total *T*-score <60, and SEQv2.1 total score ≤1 *SD* above the mean; (4) no diagnosis or concerns (ND): absence of any parent-report developmental diagnosis or concerns and not meeting any of the conditions above. It should be noted that given the potential shifts of ASD and other developmental diagnoses during early childhood (e.g., children may "age-in" to an ASD diagnosis at T3), we adopted an "EVER" criterion for the grouping. The validity of a similar approach has been demonstrated in previous population-based research using parent-report measures of autistic traits (e.g., the lifetime Social Communication Questionnaire; Marvin et al., 2017; Wei et al., 2015). Among the 101 children who were classified to the ASD-AT group, a subset of 31 children were reported

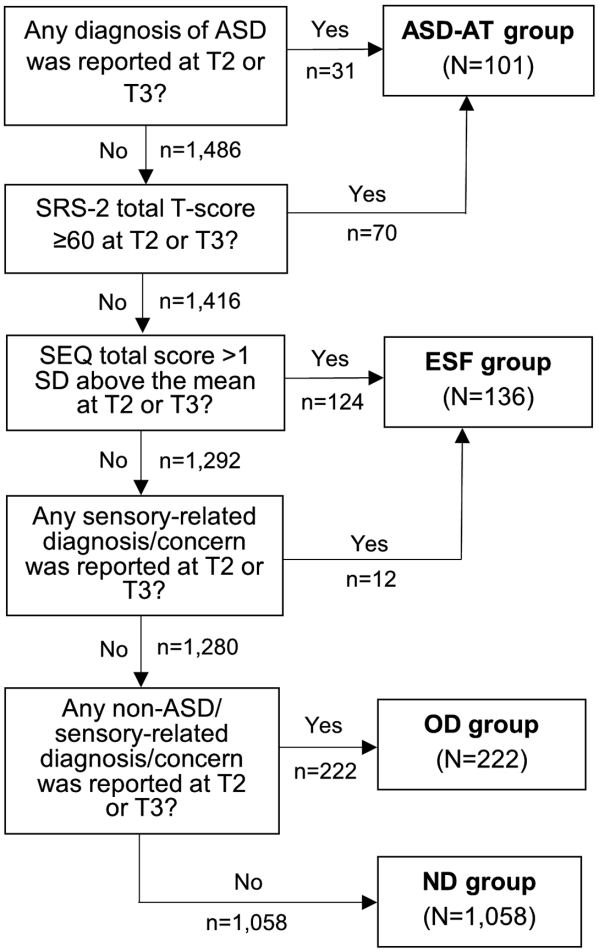

FIGURE 1 Flow chart of outcome classification based on parent reports ($N = 1517$)

by parents to have an official diagnosis of ASD from licensed clinicians ($N = 30$) or based on IEP classification ($N = 1$), and 23 of the 31 children in the "diagnosed" subset concurrently met the SRS-2 cutoff. The remaining subset of 70 children met the SRS-2 cutoff but were not reported by parents to have an ASD diagnosis. Among these 70 children, 63% ($N = 44$) of them were reported to have other developmental diagnoses from clinicians, and 99% ($N = 69$) of them had concerns from parents or elevated SEQv2.1 scores at T2 or T3. The demographics and descriptive statistics by outcome group can be found in Table S3.

Data analyses

Establish longitudinally comparable scores of sensory patterns

As the 14 sensory items were extracted from two different measures (FYIv.3.1 and SEQv.2.1) administered at their respective time-points, we followed a series of procedures to compute comparable scores before conducting the LGCM. We first tested whether measurement invariance held at the configural level across measures over time, followed by metric and scalar invariance tests for each of the three sensory constructs (Millsap, 2012). Full-information maximum likelihood (ML) estimation was used in Mplus 8.4 (Muthén & Muthén, 2018) to account for the split-form missingness at T1, which was not associated with child's sex, race, or parent education based on the non-significant Little's missing completely at random test results (Little, 1988). We ensured that there were <50% of the items missing for each construct at each time-point so that the item-response-theory (IRT) trait scores would be constructed upon enough items. Differences in fit indices between models were evaluated to determine whether invariance held at different levels. A decrease in comparative fit index (CFI) or Tucker–Lewis index (TLI) >.01, or an increase in root-mean-square error of approximation (RMSEA) >.01 indicates measurement non-invariance (Cheung & Rensvold, 2002). The purpose of invariance testing in the current study was to ensure that at least configural invariance was met before constructing trait scores that adjust for differential item functioning (DIF). Next, DIF was evaluated to determine which non-DIF items could be used as anchor items for Stocking and Lord's (1983) scale equating method. A relatively conservative criterion (McFadden's pseudo-R^2 change ≥.02 between nested logistic regression DIF models) was used to detect meaningful DIF (Paz et al., 2013; Wong et al., 2015). It has been recommended to have one anchor item for about every four non-common items to avoid construct drift (Kolen & Brennan, 2004). By recalibrating group-specific item parameter estimates (i.e., estimates specific to each time-point) for the DIF items, IRT trait scores of HYPER, HYPO, and SIRS that accounted for DIF across time-points were generated (Choi et al., 2011). The DIF detection and trait score computation were implemented with R package lordif (Choi et al., 2016).

Latent growth curve modeling of sensory patterns

First of all, univariate LGCMs were performed separately on the three sensory patterns (i.e., HYPER, HYPO, and SIRS) to determine their functional forms over the three time-points. For such models, a CFI or TLI ≥.95 and an RMSEA <.06 indicate a good fit (Hu & Bentler, 1999). Upon confirming that the three univariate trajectories were consistent in their functional forms (e.g., all linear), a multivariate LGCM was conducted by estimating them simultaneously given the potential co-occurrence of the three sensory constructs (Ausderau et al., 2014; Baranek et al., 2006). Latent growth factor covariances were specified to examine the interrelations among intercepts and slopes across sensory constructs. Next, three demographic variables (child's sex, child's race, and parent education)

were included as time-invariant covariates to examine their effects on the slopes and intercepts in a conditional multivariate LGCM. It should be noted that we combined children of non-White races (Black, Asian, American Indian, Hawaiian, and multi-racial) into one group given their small numbers for analysis purposes. Also, three categories of parent education were created based on the reported mother's and father's education at T1 (see Table 1 for the categories). As a post-hoc analysis, the latent growth factor estimates derived from the conditional LGCM were compared across the four clinical outcome groups (ASD-AT, ESF, OD, and ND) using one-way ANOVA with Bonferroni corrections. Finally, SRS-2 domain scores (SCI and RRB) at T3 were regressed on the latent growth factors of sensory patterns as well as demographic covariates to examine the impacts of sensory pattern trajectories on autistic traits as distal outcomes. The participants without SRS-2 data collected at T3 were treated as missing. All the LGCM analyses were performed with robust ML estimation in Mplus 8.4.

RESULTS

Measurement invariance testing and DIF adjustment

Longitudinal invariance testing on each of the constructs demonstrated invariance at least at the configural level (see Table S4 for the model fits), indicating that the constructs to be measured by the selected items held constant across time-points. To resolve the scalar non-invariance, DIF detection process was implemented to identify the non-DIF items for scale equating. Four out of fourteen items (2 in HYPER, 1 in HYPO, and 1 in SIRS; see Table S2) were identified as anchor items (McFadden's pseudo-R^2 change = .003–.013) for producing DIF-adjusted scores. Given the expected split-form missingness of FYI items resulting from the study design, we examined whether the derived scores were influenced by which form the parent filled out. As a result, no significant difference was found between those who filled out A-form or B-form in their HYPER, HYPO, and SIRS scores at T1 (F =0.03–0.38, p all >.50). The descriptive statistics of the trait scores for HYPER, HYPO, and SIRS at each time-point were shown in Table S5. The concurrent validity between the average raw scores of all available items from the full measures and trait scores derived from the common items was moderate to strong (r = .50–.87; see Table S6).

Sensory pattern trajectories for HYPER, HYPO, and SIRS

Univariate linear LGCMs for each of the three sensory patterns indicated excellent model fit: $\chi^2(1)$ =0.41–0.70, all CFIs and TLIs = 1.00, RMSEAs < .001. The unconditional multivariate LGCM also demonstrated a good fit: $\chi^2(15) = 27.44$, CFI = .995, TLI = .988, RMSEA = .023. These results indicate that these trajectories can be sufficiently described as linear. Given that three time-points of data require imposing constraints on some parameters for identification purposes when testing nonlinear changes and are thus not ideal for capturing the full picture of variability (Bollen & Curran, 2006), we did not further explore nonlinear models. The unconditional model indicated the intercepts of HYPER and SIRS significantly different from zero (M = .22 and .49, SE = .04, p < .001). The slope estimates indicated a significant increase in HYPO (M = .15, SE = .04, p < .001) and significant decreases in HYPER and SIRS (M = −.26 and −.32, SE = .04, p < .001). Significant variances were found for the intercepts and slopes across trajectories (all p < .001), suggesting the presence of significant individual differences in the initial levels and change rates across sensory patterns.

Latent growth factor associations

Strong correlations were found between the intercepts of HYPER and HYPO (r = .72, SE = .08, p < .001), and HYPER and SIRS (r = .54, SE = .06, p < .001). Medium correlations were observed between the slopes of HYPER and HYPO (r = .50, SE = .05, p < .001), as well as HYPER and SIRS (r = .42, SE = .05, p < .001), indicating that these trajectories traveled together in the same direction over time. Most of the significant intercept-slope correlations were weak and negative (r = −.26 to −.17, SE = .05–.09, p < .05). The only positive correlation was found between the intercept of SIRS and the slope of HYPO (r = .14, SE = .05, p = .009). The correlation results were visualized in Figure S1.

Impact of demographic variables on sensory pattern trajectories

The conditional multivariate model demonstrated a satisfactory model fit: $\chi^2(24) = 66.05$, CFI = .984, TLI = .958, RMSEA = .035 (the fit statistics of all the unconditional and conditional LGCMs are shown in Table S7). The three demographic covariates explained the variability of the latent growth factors to various extents (see Figure 2). Child's sex was a significant predictor of the intercept of HYPO (β = −.12, SE = .05, p = .007). That is, boys tended to have higher HYPO scores at baseline. Child's race only predicted the intercept of SIRS (β = .17, SE = .04, p < .001), indicating that families of non-White (i.e., Black, Asian, American Indian, Hawaiian, and multi-racial) children tended to report more frequent SIRS behaviors at baseline. Parent education levels predicted the intercepts of HYPO (β = .12, SE = .05, p = .011) and SIRS (β = −.15,

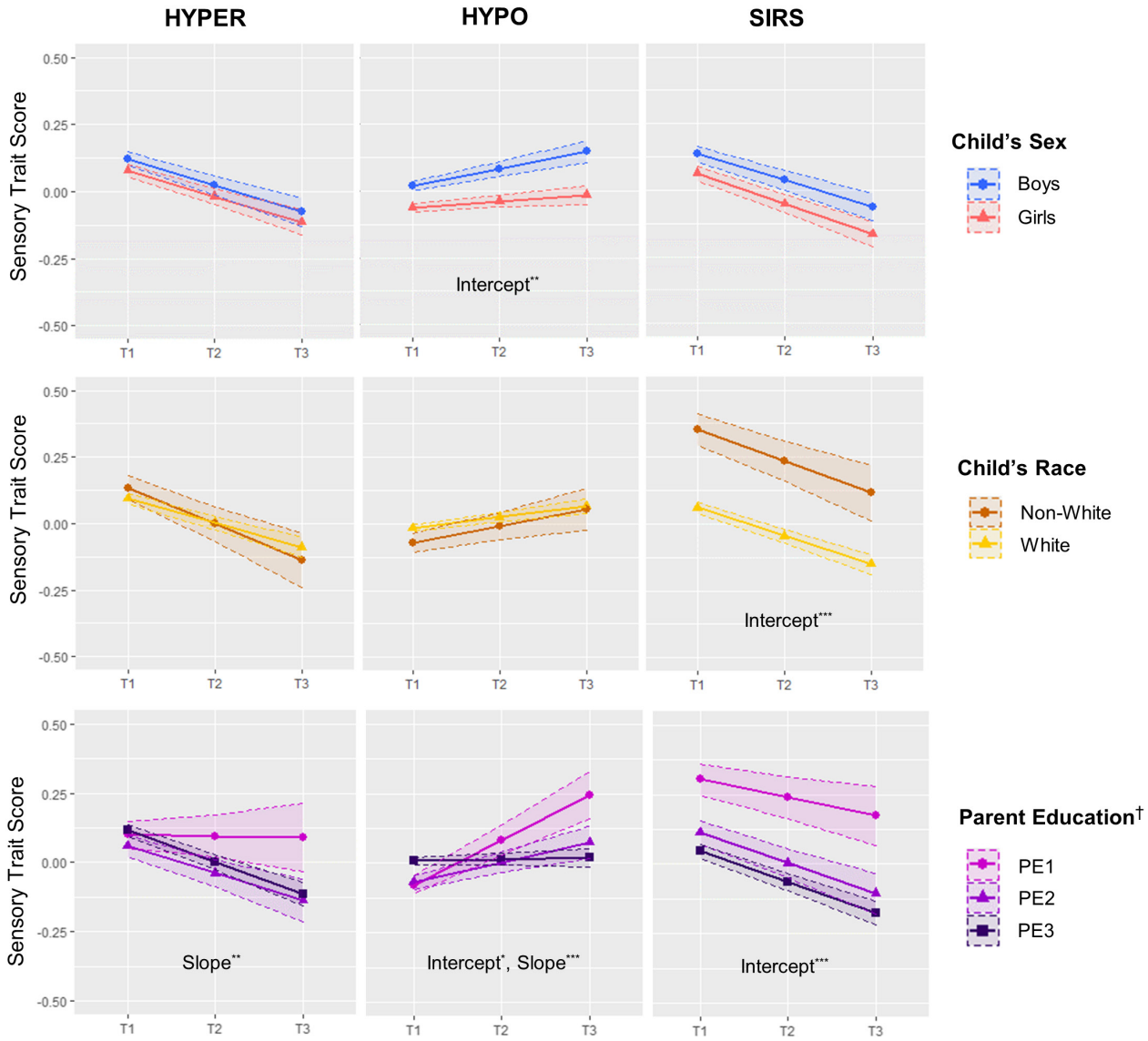

FIGURE 2 Trajectories of sensory patterns by child's sex, race, and parent education levels (estimated means with 95% confidence intervals). †Parent Education: PE1 = none of the parents had college degrees (or beyond); PE2 = one parent had college degree (or beyond); PE3 = two parents had college degrees (or beyond). *$p < .05$; **$p < .01$; ***$p < .001$ (two-tailed)

SE = .04, $p < .001$), and the slopes of HYPER ($\beta = -.10$, *SE* = .04, $p = .007$) and HYPO ($\beta = -.19$, *SE* = .04, $p < .001$). These results indicated that children of parents with higher education levels tended to have lower SIRS but higher HYPO scores at baseline, followed by decreases in HYPER and HYPO over time.

Sensory pattern trajectories by outcome groups

Figure 3 shows the individual sensory pattern trajectories by outcome group membership. As shown in Table 2, significant group differences were observed across all latent growth factors [$F(3, 1513) = 49.1–113.4$, p all <.001; see Table S8 for detailed post-hoc group comparison results]. Children classified to ASD-AT and ESF groups on average scored significantly higher than their OD and ND counterparts at baseline and showed worsening patterns across sensory constructs ($|t| = 4.42–17.05$, all <.001). The ASD-AT group tended to show steeper increases in HYPER and HYPO than the other groups ($|t| = 6.51–17.05$, p all <.001) but did not differ from the ESF group in the slope of SIRS. The OD group differed from the ND group only in the slope of HYPER and HYPO as well as the intercept of HYPO ($|t| = 2.60–3.47$, p all <.05). Overall, all the latent growth factors were able to differentiate ASD-AT and ESF from OD and ND, while the slopes of HYPER and HYPO were able to further differentiate ASD-AT from ESF ($|t| = 7.76$ and 6.51, p both <.001). Additionally, we compared the latent growth factor estimates across children classified to the ASD-AT group, including those who were only reported

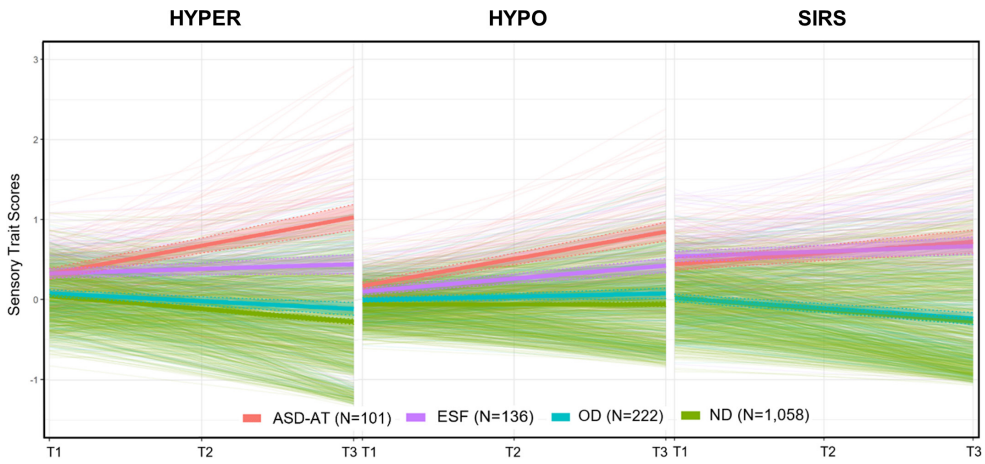

FIGURE 3 Trajectories of sensory patterns by outcome group. *Note*: Bolded lines indicate the estimated mean trajectories of each group with 95% confidence intervals

TABLE 2 Latent growth factor estimates by clinical outcome group [*M* (*SE*)]

	ASD-AT [1] (*N* = 101)	ESF [2] (*N* = 136)	OD [3] (*N* = 222)	ND [4] (*N* = 1058)	*F* test (3, 1513)	Post-hoc group comparisons[a]
HYPER						
INT	0.33 (0.03)	0.33 (0.03)	0.09 (0.02)	0.05 (0.01)	49.1***	1 > 3***, 1 > 4***, 2 > 3***, 2 > 4*** (1 = 2, 3 = 4)
SLP	0.35 (0.04)	0.06 (0.03)	−0.10 (0.02)	−0.16 (0.01)	111.6***	1 > 2***, 1 > 3***, 1 > 4***, 2 > 3***, 2 > 4***, 3 > 4*
HYPO						
INT	0.17 (0.02)	0.10 (0.02)	−0.00 (0.01)	−0.06 (0.01)	51.3***	1 > 3***, 1 > 4***, 2 > 3***, 2 > 4***, 3 > 4** (1 = 2)
SLP	0.34 (0.03)	0.16 (0.02)	0.04 (0.01)	0.00 (0.01)	98.0***	1 > 2***, 1 > 3***, 1 > 4***, 2 > 3***, 2 > 4***, 3 > 4*
SIRS						
INT	0.45 (0.04)	0.54 (0.03)	0.02 (0.02)	0.03 (0.01)	113.4***	1 > 3***, 1 > 4***, 2 > 3***, 2 > 4*** (1 = 2, 3 = 4)
SLP	0.14 (0.03)	0.07 (0.02)	−0.13 (0.02)	−0.15 (0.01)	67.4***	1 > 3***, 1 > 4***, 2 > 3***, 2 > 4*** (1 = 2, 3 = 4)

Abbreviations: ASD-AT, autism spectrum disorder autistic traits; ESF, elevated sensory features; HYPER, hyperresponsiveness; HYPO, hyporesponsiveness; INT, intercept; ND, no diagnosis; OD, other diagnosis; SIRS, sensory interests, repetitions, and seeking behaviors; SLP, slope.

[a]See Table S8 for detailed group comparison results.

* $p < .05$; ** $p < .01$; *** $p < .001$ (two-tailed; Bonferroni adjusted for multiple comparisons).

to have an ASD diagnosis ($N = 8$), only met the SRS-2 cutoff ($N = 70$), or met both criteria ($N = 23$), and did not find significant differences across the three subsets of children under these conditions.

Associations of sensory pattern trajectories with autistic traits at age 6

The conditional LGCM with distal outcomes (autistic traits measured by SRS-2) demonstrated good model fit: $\chi^2(34) = 76.40$, CFI = .987, TLI = .966, RMSEA = .033. The standardized estimates of the significant paths are shown in Figure 4. The steeper slopes of HYPER and HYPO predicted higher SCI and RRB scores at school age ($\beta = .25$–.34, $SE = .06$–.07, p all <.01). SCI was additionally predicted by the intercept of HYPO ($\beta = .25$, $SE = .10$, $p = .01$), while RRB was predicted by the intercept of HYPER ($\beta = .28$, $SE = .08$, $p = .001$). The effects of the slope and intercept of SIRS on RRB appeared to be marginally significant (both $\beta = .14$, $SE = .08$, $p < .10$). Regarding the demographic covariates, children of parents with higher education tended to have lower SCI and RRB scores ($\beta = -.18$ and $-.10$, both $SE = .04$, $p < .05$). Regarding the demographic covariates, boys tended to have higher RRB scores ($\beta = -.09$, $SE = .04$, $p = .04$), and non-White children showed higher SCI scores ($\beta = .11$, $SE = .03$, $p < .001$). The pseudo-R^2 statistics revealed that 48.8% and 43.3% of the variances in SCI and RRB were explained by the latent growth factors along with demographic covariates.

DISCUSSION

This study was the first to investigate the developmental trajectories of three common sensory patterns in a

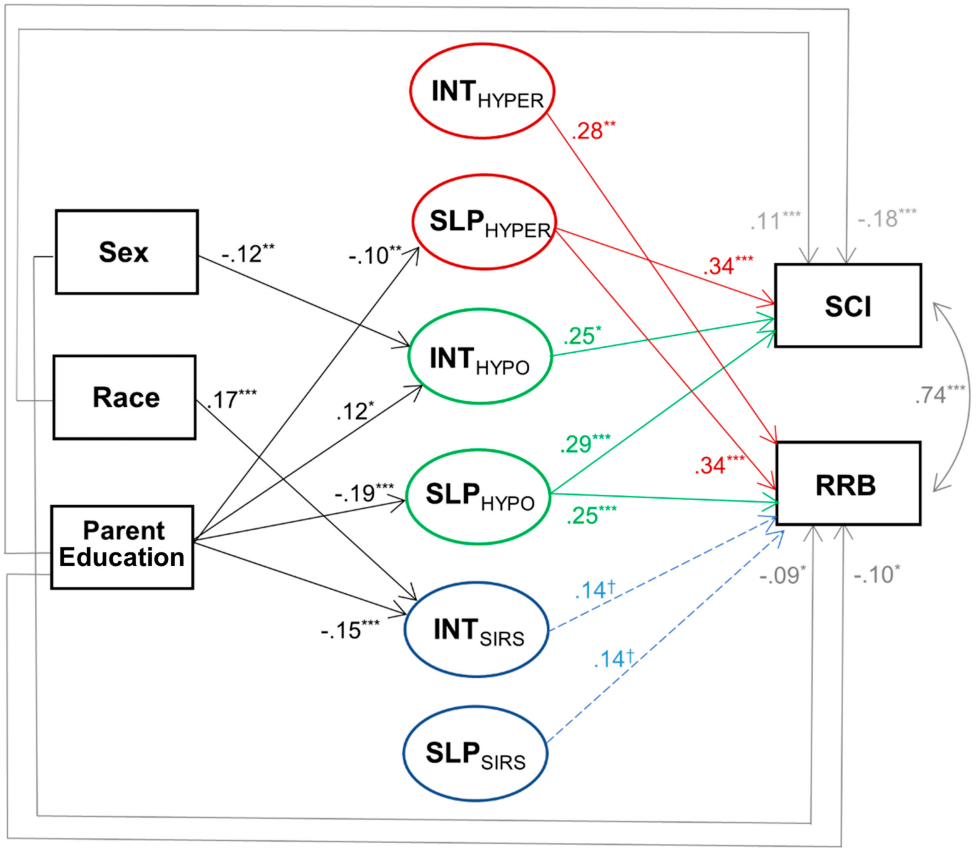

FIGURE 4 Prediction effects (standardized beta coefficients) of latent growth factors and demographic covariates on autistic traits at age 6. *Note*: Non-significant paths ($p > .10$) and covariances between latent growth factors are not shown in the figure. $^{\dagger}p < .10$; $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$ (two-tailed). INT, intercept; RRB, restricted/repetitive behavior on the SRS-2; SCI, social communication/interaction on the SRS-2; SLP, slope

community sample spanning infancy and early childhood. There were several important and novel findings. First, we demonstrated developmental heterogeneity by identifying highly variable individual trajectories of sensory patterns among this sample of children with various neurodevelopmental outcomes. It should be noted that the overall decreases in HYPER and SIRS patterns as well as an increase in the HYPO pattern were *averages* across diverse individual trajectories. Children characterized by different demographics and outcome statuses could show very different sensory pattern trajectories, as shown in Figures 2 and 3. This highlights the importance of examining within-person change prospectively over time at the individual level, as cross-sectional differences related to age or time may fail to capture sources of longitudinal variability across a diverse population (MacDonald & Stawski, 2016). Past evidence on the developmental changes of sensory patterns (as well as other ASD-related behavioral traits) was often limited to subgroup analyses within ASD, or comparisons of ASD to typically developing children, and thereby did not sufficiently represent the broader continuum of behavioral manifestations. Our findings revealed significant increases in trajectories over time across all three sensory patterns among children in the ASD-AT group, in contrast to the overall stable or decreasing trajectories evidenced in their non-autistic counterparts. These results were generally consistent with the previous evidence on high-risk siblings later diagnosed with ASD versus non-ASD controls, where significant group differences across sensory patterns were observed at baseline, followed by a larger increase in HYPO among those with a later diagnosis with ASD during the first 2 years of life (Wolff et al., 2019). However, the ASD-AT outcome group in the current study includes a subset of children with a reported clinical diagnosis of ASD (~2% of our total sample), as well as a subset of children with elevated autistic traits as measured by the SRS-2 (~6% of our total sample) who may or may not go on to receive a later diagnosis; therefore the findings for this outcome group need to be interpreted carefully and may be an underestimate of sensory patterns in a fully clinically ascertained ASD population.

The current study also included children who were reported to have elevated sensory features but without an ASD diagnosis or elevated autistic traits (i.e., the ESF group) to understand the utility of the three sensory patterns in differentiating these two groups. The ASD-AT and ESF groups both showed elevated sensory scores across this period with similar levels in the beginning.

However, ASD-AT versus ESF distinctions became more obvious over time, as children in the ESF group showed less dramatic increases in these two constructs as early as by age three. This indicated that the *change rates* of sensory patterns might be a useful predictor (especially as compared to absolute levels of sensory features at any given point in time) of a later ASD-related outcome, with good differentiability from non-ASD conditions also present with significant sensory differences. The utility of HYPER in differentiating ASD from non-ASD conditions demonstrated in our study was consistent with the recent meta-analytic results of Ben-Sasson et al. (2019) showing that HYPER generally demonstrated larger effect sizes across studies when comparing ASD with other groups. Further, our findings partially align with previous comparisons of sensory features in children aged 2–15 years with ASD versus sensory processing disorder, where Tavassoli et al. (2018) found a significant group difference in HYPO, but not in HYPER and SIRS. Thus, expanding upon the previous cross-sectional findings (Ben-Sasson et al., 2019; Tavassoli et al., 2018), our current longitudinal study showed that sensory patterns differed between ASD-AT and ESF not only in intensity but also in how much they change over time. Nevertheless, it is noteworthy that trajectories varied *within* each of the clinical outcome groups. For instance, in the ASD-AT group, sensory patterns tended to be elevated and to increase over time, but there were children in this group who deviated from that pattern. Similarly, there were cases in other outcome groups that did display the characteristic pattern of the ASD-AT group. Future research should incorporate subtyping methods such as latent class growth analysis to further parse individual differences in longitudinal variability.

As further support of the potential cascading impact of sensory patterns across early development, we demonstrated that sensory patterns beginning at infancy and their changes over time predicted the level of autistic traits at school age in this population-based sample. Particularly, the *change rates* of HYPER and HYPO patterns were the most robust predictors of both RRB and SCI domains of autistic traits. Interestingly, higher *initial levels* of HYPO and HYPER respectively predicted more social-communication deficits and RRBs at school age. These findings are partially consistent with the previous longitudinal evidence from community samples of toddlers with elevated risk for ASD, that HYPO at 20–24 months predicted later social impairments (Nowell et al., 2020), while HYPER at 14 months was associated with higher autism severity in the RRB domain at 3–5 years (Grzadzinski et al., 2020). We note that studies have shown that HYPO is linked to language and joint-attention deficits in children diagnosed with ASD (Baranek, Watson, Boyd, et al., 2013), potentially because directing another person's attention to objects or events of interest requires that a young child first register and orient to salient sensory stimuli themselves. In contrast, HYPER has been proposed to associate with a cognitive style of strong systemizing skills (e.g., increased attention to detail) and the need to keep things constant and predictable, which might be an underlying mechanism of RRBs (Baron-Cohen et al., 2009). Also, our findings are consistent with the notion that elevated sensory features at early ages may cascade to later social-communication deficits in children who go on to be diagnosed with ASD (Baranek et al., 2018; Thye et al., 2018). The differential associations between HYPO and HYPER at infancy and later social communication and RRBs respectively, as observed in the current study, may have important implications for more targeted early intervention to mitigate such cascading effects and eventually improve long-term ASD-related outcomes.

Aside from child's outcome status, demographics such as child's sex, race, and parent education levels also explained the developmental variability of sensory patterns. Specifically, boys seemed to show more HYPO than girls across time, while no sex differences were found in HYPER and SIRS. A previous population-based study has reported more overall sensory symptoms in boys (Jussila et al., 2020) and our study added to this by showing that sex differences might be more evident in HYPO. Thus, investigations of sensory patterns within the general population may be particularly useful in reducing potential biases associated with populations, such as ASD, that are overrepresented by male participants (Pender et al., 2020). Regarding the potential sensory differences associated with race (i.e., non-White children were reported to have more SIRS on average), we note that our findings should be held tentatively given the heterogeneous nature of the non-White group in these analyses. Further research that deliberately samples for racial and ethnic diversity is needed to determine whether the race-related differences in SIRS could be associated with cultural differences in proxy ratings of children's problem behaviors (Harvey et al., 2013).

Interestingly, parent education seemed to have greater impacts on sensory pattern trajectories relative to child's sex and race. The finding that higher parent education levels predicted fewer increases in children's HYPER and HYPO patterns from infancy through school age warrants further research. This may indicate that parents who are more educated tend to be intervening more effectively with their children's sensory challenges over time, or perhaps they have access to different resources or strategies for coping with such challenges and thus are less apt to endorse high levels of these challenges. Our study also showed that the effect of parent education was not unidirectional—for example, in families where both parents had college degrees or beyond, children were scored to have *more* (not less) HYPO behaviors at infancy. Parents with higher education levels may tend to be more sensitive to noticing the absence of typical responses to sensory stimuli (i.e., hyporeactivity) in very young and less verbal children, whereas parents with

lower education levels may be picking up on these atypicalities more as children age and become more verbally capable. We also note that the presence of overt atypical responses (as often manifested in HYPER and SIRS) may be more easily observed by parents than the absence of typical behaviors (as often manifested in HYPO) in young children (Jones et al., 2015). Given the discrepancies between parent-report and clinician-observed sensory behaviors reported in previous studies (Baranek et al., 2008; Zwaigenbaum et al., 2005), further research is needed to examine potential informant biases related to parent education and other family or socioeconomic factors affecting trajectories of sensory patterns in the early years. Overall, our findings highlight the critical role of caregivers in their child's sensory reactivity patterns (i.e., HYPER and HYPO), which have been reported to be associated with parent responsiveness in parent-child dyads (Jaegermann & Klein, 2010; Kinard et al., 2017).

Finally, the significant associations observed among the latent growth factors of sensory pattern trajectories support the notion that the three sensory patterns are not mutually exclusive: individual children may exhibit behaviors indexed by one or more sensory patterns across contexts and developmental stages (Uljarević et al., 2017). The strong correlations our study found between HYPER and HYPO (in both intercepts and slopes) suggest some shared variance in these constructs, perhaps because both patterns are linked to a dynamic process of up- and down-regulation of sensory input during early development that supports optimal engagement (Baranek et al., 2001; Jao Keehn et al., 2017). More research is needed to clarify the underlying etiology of such cross-construct relations for developing more effective intervention strategies and supports for children and their caregivers.

Limitations

One of the limitations of this study is the use of two different measures of sensory patterns across time-points with a portion of items extracted from full measures. Although efforts were made to construct equivalent scores across measures and time-points, measurement biases may not have been completely avoided. Future replications with more comprehensively equated scales may help reduce these biases. Another key limitation is the use of parent-report measures for characterizing sensory patterns as well as classifying outcome groups. Given the large size of our community sample, not previously attempted by other researchers studying sensory patterns, we were limited in our ability to collect observational measures or validate parent-reported diagnoses with gold-standard tests used in clinic environments. While the main purpose of this study was tracking developmental trajectories of sensory patterns and not predicting ASD per se, we note that several population-based studies have used similar outcome ascertainment methods (e.g., Kogan et al., 2018; Turner-Brown et al., 2013), and that previous studies have reported high reliability (96%–98%) between parent reports of whether or not their child had an ASD diagnosis and the actual clinical diagnosis based on clinician reports (Daniels et al., 2012; Warnell et al., 2015). Moreover, the outcome group classification was based on all available developmental and diagnostic information at T2 and T3, with the caveat that there were some shifts in status from T2 to T3, and missing SRS-2 scores for some participants at T3. Thus, caution is advised in terms of generalizing the findings to populations with fully clinically confirmed diagnoses. The exclusion of Hispanic populations at recruitment and the necessity to aggregate small numbers of disparate racial groups into one larger "non-White" group for analyses, combined with the likely higher attrition rate for parents with lower education levels, also limit the generalizability of our findings to under-represented groups. Future studies may benefit from the addition of data collected from multiple sources including observational measures to cross-validate with parent reports, and purposive sampling for more diverse and representative populations.

CONCLUSION

This study provided the first longitudinal evidence on the early trajectories of sensory patterns among a large community sample with diverse developmental outcomes using latent growth modeling to better address their developmentally variable nature. Notably, the latent growth factors, such as the change rates of sensory hyper- and hyporesponsiveness from infancy through school age, were associated with the level of autistic traits manifested at school age, and further differentiated children with an ASD diagnosis or elevated autistic traits from their non-autistic counterparts with sensory challenges. These findings support the potential utility of measuring sensory patterns at infancy and their change over time in the quest for early markers of ASD and related neurodevelopmental outcomes. Also, parent education (relative to child's sex and race) accounted for more of the variability in sensory pattern trajectories, suggesting a need to further investigate diverse parental understandings and approaches to addressing these behaviors across children's development, particularly for those who may be at-risk for ASD or related neurodevelopmental conditions.

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ORCID

Yun-Ju Chen https://orcid.org/0000-0002-0659-2110
Linda R. Watson https://orcid.org/0000-0001-7722-406X
Grace T. Baranek https://orcid.org/0000-0002-5321-6353

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