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Sensory processing subtypes relate to distinct emotional and behavioral phenotypes in a mixed neurodevelopmental cohort

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Children with autism and other neurodevelopmental concerns (NDC) frequently exhibit an array of sensory processing dysfunction phenotypes, posing a significant challenge their adaptive development. Additionally, these children often encounter difficulties with self-regulation, including emotion dysregulation, anxiety, and symptoms associated with attention and hyperactivity. However, further research is required to comprehend how patterns of sensory processing differences across neurodevelopmental conditions may contribute to regulatory control problems. Adopting a transdiagnostic perspective within the Research Domain Criteria (RDoC) framework, this study examined the relationship between clusters of sensory processing phenotypes and differential patterns of self-regulation behaviors. We recruited a sample of 117 participants (8–12 years) with a diverse range of neurodevelopmental concerns including autism, ADHD, anxiety, and sensory processing differences. This study aimed to (1) establish the prevalence of self-regulation problems in a community-recruited cohort of children with diverse NDCs; (2) construct data-driven sensory processing latent subtypes; (3) investigate group differences in emotion dysregulation, anxiety, and ADHD symptoms. Results showed that 39% of NDC children met clinically concerning thresholds for emotion dysregulation, 19% for anxiety, and 62% for ADHD. Second, latent profile analysis identified five sensory processing subtypes categorized by modality: Typical Processing, Intermediate/Mixed, Sensory Over-Responsive, Sensory Seeking, and Sensory Under-Responsive. Notably, the Sensory Over-Responsive group exhibited distinctively elevated anxiety scores, while the Sensory Seeking and Sensory Under-Responsive groups showed heightened ADHD scores. Intriguingly, the Sensory Over-Responsive, Sensory Under-Responsive, and Sensory Seeking subgroups all demonstrated elevated emotion dysregulation scores, suggesting a potential shared mechanism of emotion dysregulation that might elucidate the connection between sensory processing differences and increased anxiety and ADHD behaviors in children with autism and other NDCs.

Individuals with autism and other neurodevelopmental concerns (NDCs) commonly experience challenges in self-regulation and processing sensory information[1–4]. These difficulties often manifest as problems with emotion dysregulation or clinically as attention deficit hyperactivity (ADHD) and anxiety disorders[4]. Understanding the relationship between emotional dysregulation, sensory processing, and the highly prevalent childhood clinical disorders of ADHD and anxiety is crucial for developing effective interventions and supporting strategies for individuals with NDCs. However, the prevalence of self-regulation problems among children with NDCs in a community clinic population remains understudied. Furthermore, it remains unclear whether transdiagnostic subpopulations characterized by distinct sensory processing profiles relate to the manifestation of maladaptive behaviors specific to common clinical conditions. Consequently, a comprehensive investigation of these factors is needed to address these gaps in the literature.

The terms "sensory processing modulation" or "sensory reactivity" have been used in models to describe individual differences in sensory over-responsivity, sensory under-responsivity, and sensory seeking[5–8]. Sensory

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over-responsivity is characterized by heightened sensitivity and distress reactions to auditory, tactile, visual, vestibular, or olfactory stimuli. Sensory under-responsive involves a hypo-sensitive sensory response, where individuals show minimal or no reaction to sensory stimuli. Sensory seeking, conversely, involves atypical sensory interests or repetitive seeking of sensory stimuli. For instance, a child with sensory seeking may exhibit a strong fascination with bright lights, a preference for deep pressure when being touched, or a persistent seeking of specific sounds. It is clear that children with neurodevelopmental challenges including those with autism, anxiety, and sensory over-responsivity additionally manifest emotional dysregulation[4,9]. It is posited that emotion regulation relies on emotional top-down monitoring, evaluating, and controlling emotional responses and experiences[10]. Consequently, individuals with impaired top-down control mechanisms demonstrate heightened emotional reactions, mood volatility, and lack of impulse control[2]. Interestingly, children with greater sensory over-responsivity have been found to demonstrate a hypervigilance cognitive-emotional response to their environment[11]while individuals with sensory craving or sensory under-responsive demonstrate an under-responsive cognitive-emotion response to their environment. Importantly different sensory processing phenotypes (i.e., over and under or hyper and hypo) are not mutually exclusive. A child may show sensory over-responsive in some contexts or to certain sensory domains but sensory craving in other contexts or to other stimuli[12].

As previously reported, 40% of children with sensory processing differences will also meet research criteria for ADHD[13,14]. However, the frequency of emotional dysregulation was not previously investigated in this SPD cohort, nor has it been explored in a mixed neurodevelopment sample enrolled from a community-based specialty clinic. In the existing literature, anxiety and ADHD are considered distinct disorders, both attributed to aberrant emotion modulation systems[15–18]. Anxiety is marked by an inability to manage heightened emotional arousal resulting in negative emotionality, increased reactivity, and heightened perceived threat[16,19]. Whereas, children with ADHD are reported to show patterns of increased emotion dysregulation resulting in problems with inhibitory control and emotional outbursts[17,18,20]. Understanding the overlap in a single NDC cohort can enhance our grasp of the complex dimensionality arising from diverse biological and environmental factors affecting the perception, processing, and attribution of incoming sensory information, as well as unique attentional abilities and emotional regulation thresholds. Much of the existing research on sensory processing and emotion regulation relies on linear regression approaches which may not fully capture the complex nature of sensory processing abilities and their nuanced relations with various emotion regulation domains.

To extend the existing literature we can leverage an unsupervised machine learning methodology, latent profile analysis (LPA), to identify unobserved subgroups or profiles of children with NDCs based on a set of observed sensory characteristics. LPA has several advantages over traditional non-clustering methods that are applicable to the current project. LPA allows for population heterogeneity to be embraced by recognizing that individuals may have different response patterns or relationships among variables[21,22]. In contrast, traditional regression methods assume a single relationship across the entire population, potentially overlooking important heterogeneity. Because LPA takes a person-centered approach it has been a growing analytic tool for characterizing individual differences in clinical settings[23–25]. LPA is useful for precision intervention and medicine because it characterizes sub-groups based on their phenotypic heterogeneity rather than taking a "one size fits all" approach. LPA approaches are well suited to characterize heterogeneity in sensory processing abilities across clinical populations. By employing LPA, researchers, and clinicians can identify unique subtypes within sensory processing, uncovering groups of individuals that may show unique or overlapping patterns of sensory processing. This classification of sensory subtypes is beneficial as it facilitates a deeper understanding of the differences and similarities between individuals, leading to more targeted interventions and personalized approaches to address the specific needs and challenges associated with each sensory subtype.

Prior research has already begun to explore heterogeneity in the severity of sensory processing differences using LPA approaches[26–30]. For example, past researchers have utilized the Short Sensory Profile (SSP) to characterize heterogeneity in severity and domain-modality of sensory typologies and found that individuals with more severe sensory processing differences across all sensory domains exhibited higher ADHD symptoms, greater social deficits, and lower adaptive behavior scores[27]. Interestingly, the domain modality of sensory processing did not emerge as a key differentiating factor for the sensory clusters, suggesting that subtypes of sensory processing may be driven more by differences in the modulation of processing (over-responsive, under-responsive, seeking) rather than specific sensory modalities (i.e., tactile, auditory, visual). Indeed[31], found that toddlers with under and over-responsivity and seeking were more likely to have depressive/withdrawal symptoms. Understanding this pattern of relations is critical to better understanding and treating neurodevelopmental disorders including children with autism which show a wide range of heterogeneity but an increased prevalence of sensory processing differences, problems with emotion regulation, as well as comorbid autism and ADHD symptoms[4,24,32,33]. Thus, understanding the heterogeneity of sensory processing modalities and their relations to emotion regulation is critical to informing precision-based care for individuals with autism and other neurodevelopmental differences.

Current study

The study aims to classify sensory processing patterns across various neurodevelopmental disorders and investigate their connections with emotion regulation, ADHD, and anxiety symptoms. Using a dimensional approach, the research explores how sensory processing differences may influence emotional, cognitive, and behavioral dysregulation, regardless of clinical labels. By adopting a transdiagnostic perspective within the Research Domain Criteria (RDoC) framework, the study examines the relationships between sensory processing phenotypes, and self-regulation behaviors in children with a range of neurodevelopmental disorders. This investigation provides valuable insights into potential interventions to address sensory processing difficulties and emotional regulation challenges, enhancing the overall well-being of affected individuals.

To achieve this, we adopt a person-centered approach to capture the heterogeneity in sensory processing patterns among children with various neurodevelopmental concerns. Our study has three primary objectives:

1) Characterize emotional and behavioral regulation in a diverse cohort of pediatric neurodevelopmental concerns (NDC).
2) Identify latent clusters of sensory processing typologies, allowing for a comprehensive understanding of the different sensory profiles present in the cohort.
3) Examine the common and distinct associations between sensory typologies and emotion regulation, ADHD behaviors, and anxiety concerns.

This study includes a total of 117 children between the ages of 8–12 years old that were recruited for a collaborative study between the University of California, San Francisco, and Cortica Healthcare, a community-based neurodevelopment clinic and research center in Marin County, California (See Table 1 for Demographic Information). Children eligible for this study were currently seeking treatment at Cortica for a range of neurodevelopmental concerns indicated from the Essence-Q[34], including problems with sensory processing, autism symptoms, mood regulation, or ADHD-like symptoms. By employing a robust person-centered analysis, we aim to shed light on the prevalence, overlap, and unique associations between sensory processing differences, emotion regulation, and attention regulation. The findings from this study will contribute to our understanding of the complex interplay between sensory processing and emotional well-being in children with neurodevelopmental concerns.

Results

A. Prevalence of clinically concerning emotion and behavioral regulation symptoms

We first aimed to evaluate the prevalence of clinically concerning emotion dysregulation, anxiety, and ADHD symptoms among the current NDC cohort (see Table 2). Regarding emotion dysregulation, when considering both at-risk and clinically significant thresholds, over half of the participants were identified as having problems with emotion regulation. In contrast, just under half of the cohort met the criteria for either at-risk or clinically significant levels of anxiety. Notably, ADHD emerged as the most prevalent condition, with 84% of participants exceeding the at-risk or clinically significant thresholds.

Table 3 presents descriptive statistics for parent-reported sensory processing profiles. Parents reported their child's experience of sensory dysregulation behaviors as follows: an average of 3.92 (out of 10) sensory scenarios for sensory over-responsivity (e.g., "wearing certain garments bothers my child", "certain loud sounds bother my child"), 4.7 (out of 13) sensory scenarios for sensory seeking (e.g., "my child has a persistent desire for fast movement", "my child often cannot stop touching things or people"), and 3.7 (out of 11) sensory scenarios for sensory under-responsivity (e.g., "my child often does not respond to what is around him or her", "my child often does not respond to verbal information").

	Mean (SD) [min-max]; *n* (%)
Age	10.1 (1.7) [8.01–12.97]
Sex	
F	29 (25%)
M	88 (75%)
WISC-V	
FSIQ	105 (15) [73–146]
VSI	110 (14) [68–150]
VCI	108 (14) [72–147]
FRI	108 (14) [76–144]
WMI	99 (16) [72–142]
PSI	92 (14) [63–138]
SCQ	10 (7) [1–28]
Elevated autism symptoms	39 (32%)
No elevated autism symptoms	78 (68%)
Race	
Asian	9 (8%)
Mixed	19 (16%)
Other	6 (5%)
White	83 (71%)
Ethnicity	
Hispanic/Latino	10 (9%)
Not Hispanic/Latino	107 (91%)

Table 1. Demographics. *Note. FSIQ, Full Scale IQ; VSI, Visual Spatial Index; VCI, Verbal Comprehension Index; Fluid Reasoning Index FRI; WMI, Working Memory Index; PSI, Processing Speed Index.*

	At-Risk Threshold *N*(%)	Clinically Significant Threshold *N*(%)
Emotion Dysregulation	21 (18%)	46 (39%)
Anxiety	34 (29%)	23 (19%)
ADHD	26 (22%)	72 (62%)

Table 2. Prevalence of clinical self-regulation concerns. *Note. The threshold for at-risk threshold is T-score = 60–69, and the clinically significant threshold is T-score > 69.*

	Mean (SD)
SP-3D: I Sensory OR (max = 10)	3.92 (3.26)
SP-3D: I Sensory Seeking (max = 13)	4.70 (3.26)
SP-3D: I Sensory UR (max = 11)	3.70 (2.84)

Table 3. Descriptive statistics of sensory Processing. *Note. OR = Over-Responsive; UR = Under-Responsive.* .

Class #	BIC	Entropy	Group *N* Min	Group *N* Max
1	-	-	-	-
2	1651	84.0%	34.0%	66.0%
3	1647	83.0%	24.0%	40.0%
4	1654	83.0%	19.0%	36.0%
5	**1643**	**84.0%**	**11.0%**	**30.0%**
6	1674	85.0%	0.05%	30.0%

Table 4. Latent class analysis model comparison.

B. Classification of sensory processing sub-types using latent profile analysis

We compared 5 different latent profile analysis (LPA) models testing the fit of 2–6 latent profiles of sensory processing typologies using the parent-reported scores derived from sensory over-responsivity, sensory seeking, and sensory under-responsive SP-3D: I variable indicators. Conditional latent profiles were modeled, including age and clinical cohort assignment as covariates. The 5-profile model demonstrated the best fit based on BIC, Entropy, and balanced profile membership distribution (see Table 4). Out of the original sample ($N = 117$), 114 children provided usable sensory data required to be included in the LPA analysis.

The latent structures of the profiles are described below, and the estimated standardized sensory processing domain scores for each profile are presented in Fig. 1. The means of the sensory scores were statistically compared between profiles using an analysis of variance (ANOVA), which revealed significant differences among the profiles (see Table 5).

Profile 1 - Typical Sensory Processing. The first and largest identified profile composed 30% of the sample ($N = 34$). This group scored the lowest across each of the sensory processing domains, suggesting that they showed relatively few sensory over-responsive, seeking, or under-responsive behaviors.

Profile 2 - Intermediate/Mixed Sensory Processing. The smallest identified profile accounted for 11% of the sample ($N = 13$). This group had intermediate but mixed scores across each of the sensory processing sub-domains. This group scored relatively low in sensory over-responsivity and seeking but moderately elevated sensory under-responsive behaviors.

Profile 3 - Sensory Over-Responsive. The third identified profile accounted for 19% of the sample ($N = 22$) This group scored differentially higher in the sensory over-responsivity subdomain relative to low-scoring sensory seeking or sensory under-responsive domains.

Profile 4 - Sensory Seeking. The fourth identified profile included 19% of the sample ($N = 22$) and showed the highest scores in the sensory-seeking domain relative to their moderate scores in sensory over-responsivity and sensory under-responsive. Of note, this group also suggesting some overlapping phenotypic behaviors.

Profile 5 - Sensory Under-Responsive. The final identified profile accounted for 20% of the sample ($N = 23$). This group scored the highest in the sensory under-responsive domain compared to the other profiles. As with the previous profile, this group also showed somewhat elevated scores in sensory seeking and sensory over-responsivity. Thus, there is some shared sensory processing typology.

C. Associations between sensory subtypes and emotion regulation, anxiety, and ADHD symptoms

Linear regressions evaluated differences in emotion dysregulation, anxiety, and ADHD symptoms based on sensory processing sub-group membership. Emotional dysregulation, anxiety, and ADHD scores were modeled

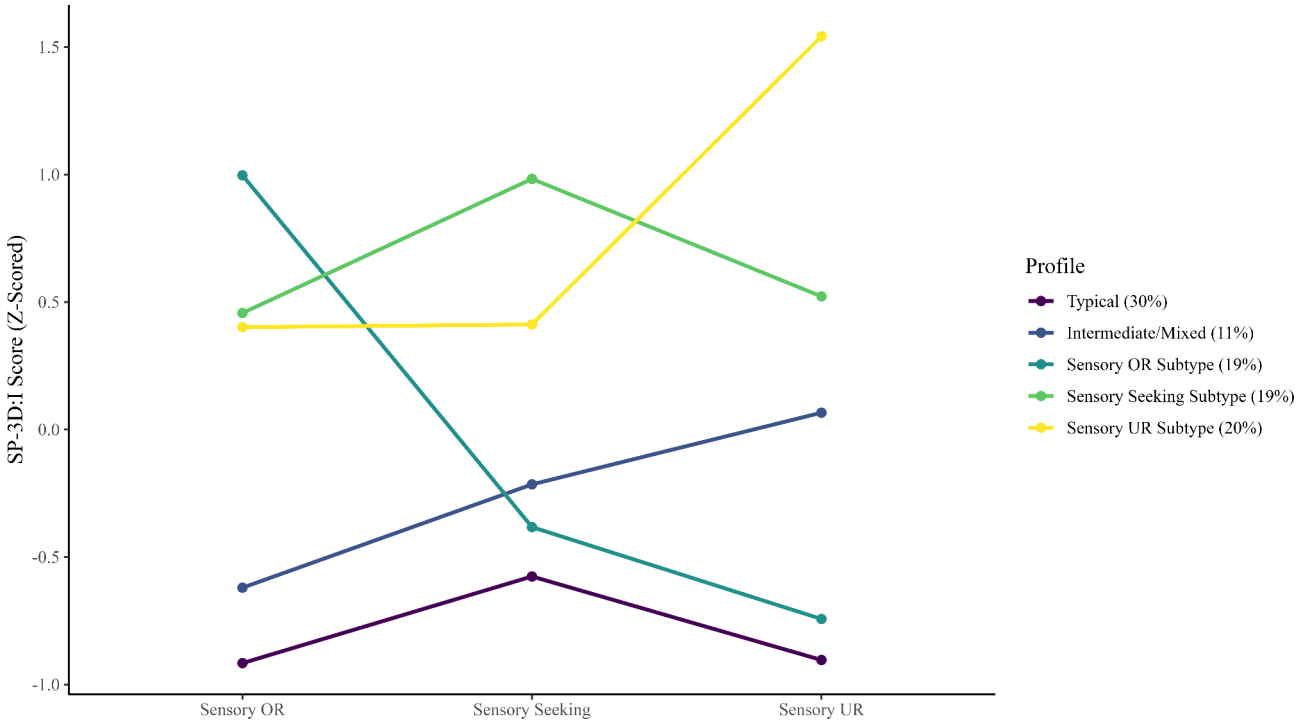

Fig. 1. Latent Class Profiles of Sensory Processing.

	Typical (a)	Intermediate/ Mixed (b)	Sensory OR Subtype (c)	Sensory Seeking Subtype (d)	Sensory UR Subtype (e)	ANOVA Eta Squared
Sensory Over-Response	1.76 (1.50) $^{c, d,e}$	2.46 (1.39)$^{c, d,e}$	6.27 (1.42)$^{a, b,e}$	5.00 (1.79)$^{a, b}$	4.87 (1.94)$^{a, b,c}$	0.55***
Sensory Seeking	2.80 (2.5)$^{d, e}$	4.0 (2.4)^{d}	3.5 (2.3)$^{d, e}$	7.9 (2.6)$^{a, b,c}$	6.0 (3.3)$^{a, c}$	0.35***
Sensory Under-Responsive	1.01 (0.55)$^{b, c,d, e}$	3.85 (0.99)$^{a, c,d, e}$	1.55 (1.06)$^{b, c,d, e}$	5.1 (0.96)$^{a, b,c, e}$	8.0 (1.07)$^{a, b,c, d}$	0.88***

Table 5. Mean comparisons of sensory processing domains between profiles. Note. M(SD); Significant Tukey Mean Honest Difference comparisons are designated with the column superscript at p-value < 0.05.

	Emotional Dysregulation β (95% CI)	Anxiety β (95% CI)	ADHD β (95% CI)
Profile			
Typical	–	—	—
Intermediate/Mixed	4.0 (-3.6, 12)	-0.65 (-7.8, 6.5)	-0.16 (-6.9, 6.6)
Sensory OR Subtype	9.8 (3.4, 16)**	10 (4.3, 16)***	1.0 (-4.5, 6.5)
Sensory Seeking Subtype	8.8 (2.4, 15)**	6.8 (0.72, 13)	13 (7.4, 19)***
Sensory UR Subtype	6.5 (0.23, 13)*	5.8 (-0.08, 12)	5.9 (0.43, 11)*
FSIQ	-0.10 (-0.25, 0.06)	-0.03 (-0.17, 0.11)	-0.11 (-0.24, 0.02)
Standardized Beta (unstandardized beta +/- SD); ***$p < .0001$, **$p < .0$, *$p < .05$			

Table 6. Regression results.

as the dependent variable. All models controlled for full-scale IQ (FSIQ). Results are presented in Table 6 with the "Typical" profile included as the reference level.

With emotion dysregulation modeled as the dependent variable, results indicated that relative to the Typical profile, the Sensory Over-Responsive, Sensory Seeking, and Sensory Under-Responsive showed elevated emotion dysregulation scores. When anxiety was modeled as the dependent variable, results indicated that only children in the Sensory Over-Responsive profile showed significantly higher anxiety levels. When ADHD was modeled as the dependent variable, results showed that children in the Sensory Seeking profile and Sensory Under-Responsive profile reported significantly higher ADHD symptom levels relative to the typical profile. The Intermediate/Mixed or Sensory Over-Responsive subtype profiles did not show differences in ADHD scores,

relative to the Typical profile. See Fig. 2 for complete pairwise comparisons for each profile combination with Sidak adjusted p-value.

Discussion

In this study, our aim was to assess the prevalence and interplay of sensory processing and behavioral phenotypes in children with neurodevelopmental concerns (NDC) drawn from a community sample. Given the intricate nature of sensory processing phenotypes as multidimensional constructs, we utilized latent class analysis to effectively capture the diversity observed in children with various neurodevelopmental concerns (NDCs). Moreover, we demonstrated distinct and shared associations between sensory processing clusters and self-regulation phenotypes, specifically, emotion regulation, anxiety, and ADHD.

This study was driven by an increasing reported prevalence of emotion dysregulation concerns and sensory issues in individuals with autism and other NDCs. We expanded on prior research by assessing the rates of clinically concerning emotion regulation, anxiety, and ADHD within our sampled population[1–4]. Our findings showed that, at the clinically concerning threshold, 39% of participants displayed emotion dysregulation, 19% exhibited anxiety, and 62% showed ADHD symptoms. In relation to sensory processing differences, our analysis using the SPD 3D-I revealed that parents reported, on average, between 4 and 5 sensory processing concerns. This aligns with previous research documenting the prevalence of sensory processing issues in autism populations[13,35–37]. Additionally, our study contributes to the growing body of evidence demonstrating that children with a range of neurodevelopmental concerns also present with atypical sensory processing[5,35,38]. Understanding the comorbid prevalence rates of emotion, behavioral, and sensory dysregulation symptoms that correspond with an array of NDCs is important for clinicians. This knowledge aids in developing targeted intervention strategies and informs best practices for comprehensive care in this population.

Using latent profile analysis, 5 distinct clusters of sensory processing profiles emerged. The first identified cluster was a sensory typical group that accounted for 30% of the sample and showcased the lowest scores across sensory over-responsivity, sensory seeking, and sensory under-responsivity. This identified class supports the sensory literature which suggests that some children with autism and other neurodevelopmental disorders do not present with aberrant sensory processing concerns[27,37,39]. The second and smallest identified profile fit a sensory intermediate/mixed profile, with a balanced distribution of scores across each sensory subdomain which accounted for 11% of our sample. This profile indicates that some children with NDCs show a mixed sensory profile phenotype, experiencing moderate ranges of over-responsivity, under-responsivity, and seeking sensory stimuli. This profile supports the idea that there is generous heterogeneity in the overlap of sensory processing modalities, possibly depending on contextual factors or the domain of the stimuli itself[40].

The remaining profiles clustered our sample by differentiated sensory reactivity experiences. Specifically, the class profile that emerged was a predominately sensory-over responsivity profile accounting for 19% and characterized by distinctly elevated sensory over-responsivity the highest scores resorted in this domain but low scores in the seeking and under-responsive domain. The fourth, the predominantly sensory seeking class, which

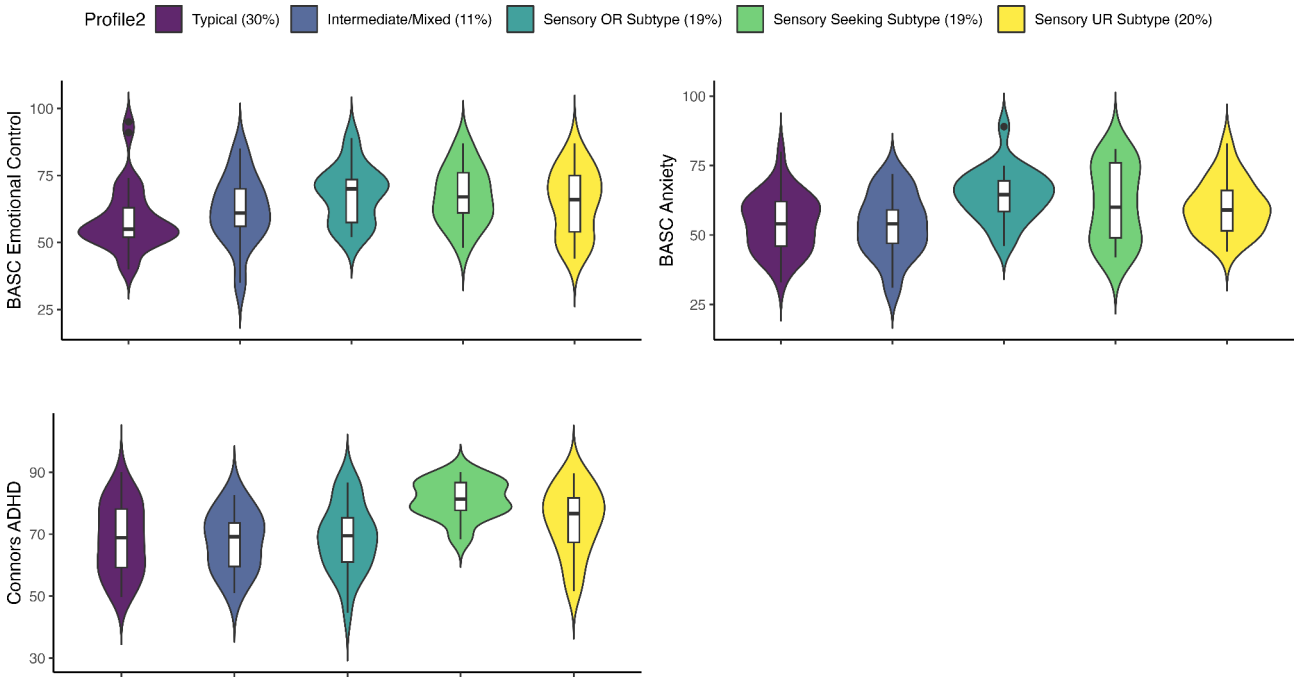

Fig. 2. Differences in Emotion Dysregulation, Anxiety, and ADHD Symptoms Based on Sensory Sub-Group. Note: Violin plots depicting post hoc pairwise comparisons of mean differences in outcomes based on sensory cluster. Lines between violin graphs represent significant mean differences between groups with p-value adjusted for multiple comparisons.

encompassed 19% of the sample exhibited pronounced sensory-seeking tendencies and moderate scores in over-responsivity and under-responsive domains. The final class that emerged was classified as a predominately sensory under-responsive profile represented 20% of the sample and demonstrated the highest scores in sensory under-responsiveness, and moderately elevated sensory seeking and sensory over-responsivity. These findings are in line with past research that has identified clusters of sensory processing patterns among autism populations[27,31,41]. However, we now extend this research by using a different sensory processing assessment tool and generalizing our sample pool to non-autism children in a community clinic cohort.

The results of our LPA analysis differ from the recent work of Kadlaskar and colleagues[27]who predominately showed discrete clusters based on severity (low, moderate, severe) but a high degree of overlap in sensory modality (over-responsive, under-responsive, seeking). While we show a distinct cluster showcasing mixed sensory modality profiles (intermediate/mixed class), we also found three clusters emerge whose distinctness was driven by the modality of sensory processing, namely, primarily over-responsive, under-responsive, and seeking. The findings in this study are reflected on the neurobiological level in research that has demonstrated the unique functional and structural pathways that share common associations between sensory modalities and emotion dysregulation symptoms. For example, research has found that autistic children with sensory over-responsivity demonstrate neural and physiological profiles associated with greater emotional and stress reactivity[42–44]. In general results from this study enrich the sensory literature by highlighting that there is a wide range heterogeneity in sensory experiences among NDC populations with some children experiencing overlap in sensory modality profiles and others showcasing discrete sensory modality experiences[27,31].

To investigate how heterogeneity in sensory processing was associated with self-regulatory outcomes, we evaluated associations between our LPA-driven sensory clusters with anxiety, ADHD, and emotion regulation symptoms. Results indicated that only the sensory over-responsive subtype cluster reported significantly elevated anxiety levels. This is in line with research documenting greater sensory sensitivities among children with anxiety[9,11]. Further, children in the sensory seeking and sensory under-responsive subtypes reported the highest levels of ADHD. This finding is supported by existing research looking at the sensory processing behaviors among children with ADHD[45–48]. Interestingly, all groups demonstrated elevated levels of emotion dysregulation (relative to the typical sensory group), supporting the idea that emotion dysregulation is a common regulatory mechanism involved with both sensory modulation as well as anxiety and ADHD. This finding builds on past research demonstrating that children with sensory concerns and/or an autism diagnosis frequently demonstrate problems with self-regulation which may manifest as anxiety, ADHD, or emotion dysregulation behaviors[4,9]. These profiles may inform clinical differential diagnosis and personalized treatment plans, emphasizing targeted sensory interventions for anxiety in sensory over-responsive subtype children, and specific strategies for managing ADHD symptoms in sensory seeking and sensory under-responsive subtypes while highlighting the importance of emotion regulation across sensory profiles which may also help refine future treatment studies.

Limitations and future directions

While this study substantially expands the sensory processing neurodevelopmental literature, there are several limitations that require acknowledgment. The primary limitation of this study is that both the sensory assessment and self-regulation measures were derived from parent-report questionnaires. While the SP:3D-I, the BASC, and The Connors all demonstrate strong internal validity[49–51] this study would benefit from the inclusion of direct measures of sensory processing, emotion regulation, anxiety, and ADHD. It is important to note that all participants in this study fell within the normal range of the FSIQ, therefore the results of this study do not necessarily generalize to those with low cognitive abilities. Further, the sample used in this study was primarily white and non-Hispanic, limiting the generalizability of these findings to broader demographic populations. Further, specific information on family income and education was not collected, therefore it is unknown how socioeconomic factors may influence these findings. Future research within this field should incorporate diverse populations in their samples and emphasize the importance of context, more broadly, as a contributing factor to individual differences in NDC studies.

Conclusion

This study's outcomes underscore that children with neurodevelopmental issues exhibit a heightened prevalence of challenges in regulating emotions, which are uniquely linked to diverse patterns of sensory processing disparities. Specifically, children primarily exhibiting Sensory Over-Responsivity manifest elevated anxiety symptoms, while those predominantly displaying Sensory Under-Responsivity or Sensory Seeking demonstrate increased indications of ADHD. Intriguingly, irrespective of the sensory modality (over-responsive, under-responsive, seeking), all children exhibiting some form of atypical sensory processing exhibit heightened levels of emotion dysregulation. These findings emphasize the significance of acknowledging the substantial heterogeneity in characterizing sensory and self-regulatory processing within the realm of neurodevelopmental concerns. Moreover, these findings possess the potential to contribute significantly to research focused on interventions, given the intricate interplay between sensory processing disparities and emotion regulation abilities.

Methods

Participants

A total of 117 children between the ages of 8–12 years old were recruited for a collaborative study between the University of California, San Francisco, and Cortica Healthcare, a community-based neurodevelopment clinic and research center in Marin County, California. This project is part of a larger cross-sectional study investigating the neural mechanisms of Sensory Over-responsivity (SOR). This study was approved by the University of California, San Francisco Institutional Review Board (IRB# 19-27681). In accordance with IRB

policy and the Declaration of Helsinki, all methods were performed in accordance with the relevant guidelines and regulations. Informed consent was obtained from each parent and/or legal guardians and assent forms were signed by participants.

Inclusion Criteria.

- 8–12 years of age.
- ESSENCE-Q-REV score indicating high risk for neurodevelopmental concern.

Exclusion Criteria:

- Nonverbal Index ≤ 70 on the Wechsler Intelligence Scale for Children (Fifth Edition).
- Caregiver(s) unable to complete intake forms.
- Parent-reported in-utero toxin exposure.
- Gestational age < 32 weeks or intrauterine growth restriction (birth weight < 1500 g).
- Participant hearing or visual impairment based on medical history review.
- Additional medical/neurologic conditions, including active epilepsy, malignancy, or known brain injury/malformation.

Details on participant demographic information are shown in Table 1.

Measures

Developmental screener measure

The ESSENCE-Q-REV was used to establish the existence of a neurodevelopmental concern (NDC)[34]. The screener includes a list of 12 neurodevelopmental concerns, including autism, attention deficit hyperactivity disorder (ADHD), developmental coordination disorder, specific language impairment, and Tourette's syndrome. The response options are 'No,' 'Maybe / A Little,' or 'Yes.' The threshold for inclusion ("optimal cutoff") for this measure is at least one 'Yes' or at least two 'Maybe / A Little' responses to the listed NDCs.

Autism symptoms measure

Participants are evaluated for research designation of autism using the Social Communication Questionnaire (SCQ)[52]parent report form. Those scoring at or above 12 on the SCQ were then evaluated for autism through the Autism Diagnostic Observation Schedule, Second Edition Module 3 based on the language level (ADOS-2)[53]. Individuals scoring above the autism diagnostic cutoff on the ADOS-2 are included within the 'elevated autism symptoms' cohort for the study.

Cognitive ability

Full-scale IQ, Visual Spatial Index, Verbal Comprehension Index, Fluid Reasoning Index, Working Memory Index, and Processing Speed Index, were derived using the Wechsler Intelligence Scale for Children - Fifth Edition (WISC-V).

Parent report sensory measure

Sensory data was derived from the Sensory Profile Three-Dimension Inventory (SP-3D: I)[54]. The SP-3D: I is a tool for assessing sensory-related behaviors in daily activities, completed by parents or caregivers. The SP-3D: I consist of 69 caregiver questions that evaluate sensory processing modulation modality (over-responsivity, under-responsivity, seeking) within various sensory domains (visual, auditory, tactile, proprioception, vestibular, and gustatory). The SP-3D: I uses a binary scoring system, where each behavior or item is scored as either present (1) or absent or not applicable (0). Previous research validating the SP-3D: I has shown acceptable internal consistency, reliability, and discriminative validity (Schoen et al., 2016). To obtain subscale scores, items within a domain subscale were summed, with higher scores indicating greater impairment. The current study included three modulation subscales to measure sensory over-responsivity, sensory under-responsivity, and sensory seeking behaviors across domains. The maximum scores of sensory over-responsive, sensory under-responsive, and sensory seeking are 10, 11, and 13, respectively.

Emotional regulation measures

Emotional regulation abilities were derived from the parent-reported Behavioral Assessment System for Children, Third Edition (BASC-3)[55] questionnaire. The BASC-3 is a comprehensive tool used to assess children's behavior, emotions, and adaptive behaviors. Composite T-scores of emotional control and anxiety were analyzed for the current study. T-scores are normed based on age and gender (M = 50, SD = 10), where higher scores indicate more difficulty in this area. T-scores 60–69 indicate 1 standard deviation from the norm and are deemed "at-risk" factors; scores greater than 70 are established thresholds for clinically significant concerns, 2 standard deviations from norm. The reliability and validity of the BASC-3 have been well established.

ADHD score

ADHD symptoms were obtained from the Conners 3rd Edition parent report (Conners-3)[49]. The Connors-3 is a reliable and well-validated parent report measure of ADHD behaviors. We analyzed the composite ADHD T-score that was normed based on age and gender (M = 50, SD = 10) where higher scores are indicative of more severe ADHD symptoms. Clinically significant concerns are indicated by an ADHD T-score greater than 70.

Analytic plan

First, we characterize the prevalence of clinically concerning emotion dysregulation, anxiety, and ADHD scores among our NDC cohort. To do so we calculated the proportion of children who scored within the at-risk range (T score of 60–69) and in the clinically concerning range (based on a T-score greater than 70). Next, we used conditional latent profile analysis (LPA) to identify distinct sensory processing profiles based on individual patterns of parent-reported sensory over-responsivity, sensory seeking, and sensory under-responsiveness indicators. We included age and autism cohort assignment as covariates when identifying sensory processing profiles. Autism and age were accounted for in the latent profile analyses to reduce any confounding effects these factors might have on membership in specific sensory processing profiles. All LPA analyses were conducted using Mplus Version 8.1[56]. Each LPA model was initialized 20 times, with 4 iterations for the final stage of optimization. The best-fitting model was selected based on Bayesian information criterion (BIC), and entropy value[57]. Lower BIC reflects better model fit while higher entropy values (closest to 1.0) indicate greater class separation and lower classification error[58].

After identifying sensory processing profiles, we examined whether membership in a particular sensory profile class was associated with elevated emotion dysregulation, anxiety, and ADHD symptoms using linear regression analysis. All regression models included full-scale IQ as a covariate.

Data Availability

All datasets collected and analyzed during the current study are available from the corresponding author on reasonable request.

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Author contributions

A.B.A and R.P. wrote the main manuscript text and prepared figures. A.B.A, J.W., R.C., K.S., P.M., and E.M. contributed to study conceptualization E.M. and P.M directed the study. R.P. and M.S. contributed to study recruitment and executed study procedures. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

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