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Linking Sensory Processing Patterns and Somatosensory Thresholds to Behavioural and Emotional Symptoms in Adolescents with ADHD

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Abstract

Sensory difficulties in attention deficit hyperactivity disorder (ADHD) exacerbate behavioural and emotional challenges. Despite their clinical prevalence, objective psychophysical assessments of sensory performance in ADHD patients remain scarce, leaving a critical gap in our neurobiological understanding. This study multimodally investigated sensory processing via the Adult/Adolescent Sensory Profile (AASP), Somatosensory Detection (SDT) and Temporal Discrimination Thresholds (STDT) in 26 adolescents with ADHD and 29 comparison adolescents. The link between sensory processing and ADHD-related behavioural and emotional symptoms was assessed via the Strengths and Difficulties Questionnaire (SDQ). Significant differences emerged in AASP tactile sensitivity ($p=0.016$) and avoidance ($p=0.008$), although objective thresholds (SDT/STDT) did not reach statistical significance between the groups. Tactile sensory seeking was correlated with externalizing symptoms ($r=0.444$). Tactile low registration was correlated with externalizing ($r=0.443$) and hyperactivity symptoms ($r=0.517$). While subjective sensory processing behaviours differ significantly in ADHD, the accompanying statistical trends in objective detection thresholds warrant caution, as they may point to subtle psychophysical variations that require larger cohorts to evaluate conclusively.

1. Introduction

Attention deficit hyperactivity disorder (ADHD) is the most common neurodevelopmental disorder in children and adolescents and is accompanied by symptoms of inattention, hyperactivity, and impulsivity [1-3]. In addition to core symptoms, impairments, such as emotional, social, and sensory processing, may also be observed at the neurophysiological level [4]. The literature suggests that approximately 50–60% of children with ADHD present with sensory processing difficulties [5,6]. Sensory processing problems can impair daily functioning, cognitive functions, emotion regulation and psychosocial development [7-10].

Sensory processing is defined as the recognition, interpretation, and organization of sensations in order to generate appropriate responses [11,12]. Sensory processing facilitates adaptive behaviour by enabling individuals to respond appropriately to situations and contributes to their overall functioning and psychophysical well-being [5]. Sensory processing problems can affect children's behaviour, cognitive functions, learning difficulties, emotions and attention regulation, psychosocial development and participation in social relationship in their daily lives [7-10]. There are various types of atypical sensory processing, such as hyporeactivity, which is associated with a low neurological threshold, and hyperreactivity, which is associated with a high neurological threshold, sensory seeking and sensory discrimination difficulties [13,14]. Dunn's sensory processing model explains the nervous system's stimulus perception thresholds and the response tendencies to these stimuli. This is closely related to habituation (reduced neural transmission once the stimulus becomes familiar) and sensitization (enhanced neural response when the stimulus is perceived as salient) in the central nervous system. When the balance between habituation and sensitivity is impaired, individuals exhibit maladaptive behaviours such as being overly excitable or hyperactive (too sensitive, low thresholds) or excessively lethargic and inattentive (excessive habituation, high thresholds). Sensory processing patterns are classified into four quadrants based on the interaction between individuals' neurological threshold level and their behavioural response to stimuli. These quadrants are defined as: sensory sensitivity (associated with a low threshold and passive response), sensation avoiding (associated with a low threshold and active response), sensation seeking (associated with a high threshold and active response), and low registration (associated with a high threshold and passive response) [15,16]. Atypical sensory processing can be observed in children with ADHD in various levels [17,18]. Several studies have reported that individuals with ADHD exhibit at least clinically/subclinically detectable hyposensitivity/hypersensitivity to auditory, visual, and tactile stimuli [19,20]. Accordingly, atypical sensory processing has been suggested as a possible phenotype of ADHD [21]. Behavioural and emotional problems have been linked to sensory processing difficulties in ADHD. Sensory processing abnormalities were found to be associated with internalizing and externalizing problems in children with

ADHD [18,22,23]. Since sensory processing difficulties can affect many areas of an individual's life, assessing sensory processing is important in evaluating and improving a patient's functionality [18].

A growing body of literature has examined sensory processing problems. A recent meta-analysis examining the dimensions of sensory processing patterns revealed that individuals with ADHD have greater sensory sensitivity, sensory avoidance, sensory seeking, and low sensory registration. Additionally, greater difficulties in tactile, visual, oral, and auditory sensory discrimination have been reported in children with ADHD than in comparison children. Furthermore, ADHD increases the risk of hypersensitivity in children and adolescents [24]. In a study conducted with adults, self-reported ADHD symptoms were associated with atypical sensory processing, such as low registration, sensation seeking, and sensory sensitivity [20]. A similar study revealed that individuals with ADHD had an atypical sensory profile, with significant changes in low registration, sensory seeking, sensory sensitivity, and sensory avoidance, as well as differences across sensory modalities such as taste/smell, movement, vision, touch, and hearing [25].

One of the sensory abnormalities highlighted in the literature is atypical tactile processing. Tactile sense is the earliest sensory system to develop and plays a critical role in learning about both the environment and one's own body and social development [26,27]. Tactile processing abnormalities have been reported in both ASD and ADHD. However, the extent to which these abnormalities are disorder-specific and how they are related to the clinical features of these disorders are not yet fully understood [28-31]. However, tactile processing abnormalities may influence the clinical features of ADHD. A study of adults with ADHD demonstrated that touch sensitivity was significantly elevated and positively correlated with self-reported symptom severity [32]. In addition, it is known that oppositional defiant disorder symptoms in individuals with ADHD predict tactile hypersensitivity [33]. Research has demonstrated that children with ADHD exhibit altered responses to tactile stimuli and perform worse on simple and choice reaction time tasks, frequency discrimination, and temporal order judgment [34]. This finding is noteworthy, as tactile discrimination contributes to the development of body schema and enables the planning of new actions [35]. Moreover, tactile discrimination plays important roles in learning processes, daily living activities, and the ability to sustain activities [36]. Although tactile processing has been evaluated in previous studies using different neurophysiological and psychophysical methods, such as somatosensory evoked potentials (SEPs) and somatosensory discrimination thresholds [31,32], studies evaluating tactile impairments in ADHD usually rely on clinical observations and scales [37]. Most studies attempting to examine sensory processing in children with ADHD have been conducted through surveys administered to parents, teachers, or children themselves via self-report measures [6,18,25,38]. Objective, psychophysical evaluations of the somatosensory pathway remain scarce, leaving a critical gap regarding whether these clinical complaints stem from baseline sensory thresholds.

This study combines questionnaire-based measures with two distinct psychophysical metrics, Somatosensory Detection Thresholds (SDT) and Somatosensory Temporal Discrimination Thresholds (STDT). While SDT evaluates primary somatosensory cortical acuity, STDT indexes the central nervous system's fine temporal gating and resolution capacity. Investigating STDT specifically in adolescents with ADHD, which has not been previously explored, allows us to mechanistically test whether real-world tactile challenges co-occur with underlying central temporal resolution deficits. Furthermore, evaluating these objective thresholds alongside the Adult/Adolescent Sensory Profile (AASP) and the Strengths and Difficulties Questionnaire (SDQ) provides a precise multi-informant framework to clarify how neurophysiological thresholds relate to behavioural and emotional phenotypes.

2. Methods

2.1. Participants

The ADHD group was recruited from the Child and Adolescent Psychiatry Outpatient Clinic of a University Hospital. The inclusion criteria for the ADHD group were as follows: 1) age between 11 and 18 years; 2) diagnosis of ADHD according to the DSM-5 criteria; 3) no additional psychiatric disorders, including intellectual disability, on the basis of the Schedule for Affective Disorders and Schizophrenia for School-Age Children-Present and Lifetime Version (K-SADS-PL 2013) screening and clinical evaluation [39]; 4) no chronic physical diseases; 5) no use of daily medication; and 6) cooperation with the tests and voluntary participation. The control group consisted of comparison adolescents aged between 11 and 18 years who were admitted to the child and adolescent psychiatry outpatient clinic for mild counselling needs (e.g., school adaptation, family relationships) but were not diagnosed with any psychiatric

disorders or chronic diseases. The screening process actively evaluated both comorbid disorders and clinically elevated, subthreshold symptoms that could confound the somatosensory data.

A total of 40 adolescents with a clinical diagnosis of ADHD were initially screened. Of these, 14 individuals were excluded for the following reasons: 1) presence of comorbid psychiatric disorders or subthreshold symptoms discovered during structured interviews (e.g., anxiety disorders, autistic traits) ($n=9$) 2) current or recent daily medication use ($n=2$), and 3) inability to cooperate with the practice trials or maintain task compliance during psychophysical evaluation ($n=3$). Consequently, 26 medication-free adolescents with ADHD were included in the final analysis. The control group initially consisted of 35 adolescents. To ensure diagnostic accuracy and rule out any underlying psychopathologies, all participants and parents in the control group underwent the exact same systematic clinical evaluation and screening via the Turkish version of the K-SADS-PL 2013 as the ADHD group. From this pool, 5 individuals were excluded due to meeting the criteria for a subclinical or clinical psychiatric diagnosis during the K-SADS-PL interview or due to chronic diseases, and 1 individual due to inability to maintain task compliance during psychophysical evaluation. This resulted in a final control sample of 29 comparison adolescents. Informed written consent was obtained from all participants and parents. All participants were evaluated by two experienced child and adolescent psychiatrists to ensure diagnostic accuracy. The study was approved by the Clinical Research Ethics Committee and conformed to the Declaration of Helsinki.

2.2. Clinical evaluation and questionnaires

K-SADS-PL (2013 DSM-5 Version): The Turkish adaptation and validation study of the K-SADS-PL DSM-5 version was conducted by Ünal et al. specifically within child and adolescent psychiatry outpatient clinics, including large cohorts of adolescents diagnosed with ADHD. It demonstrated excellent inter-rater reliability and high test-retest reliability for establishing clean, non-comorbid ADHD phenotypes in Turkish clinical settings [40].

Strengths and Difficulties Questionnaire (SDQ): Emotional and behavioural difficulties were evaluated via the self- and parent-rated SDQ, which includes five categories: emotional problems; conduct problems; hyperactivity; peer problems; prosocial behaviours; and a sum of internalizing and externalizing problems [41]. The Turkish validity and reliability studies for the SDQ (both parent and self-report forms) were validated in both community and extensive clinical samples, including children and adolescents with ADHD [42,43]. The Hyperactivity/Inattention subscale and the Externalizing Problems composite scale have consistently demonstrated high internal consistency, strong test-retest reliability, and exceptional discriminative validity in separating adolescents with ADHD from controls. Written permission for the use of the SDQ in this study was obtained from Youth in Mind, the copyright holder of the questionnaire.

Adult/Adolescent Sensory Profile (AASP): Sensory processing patterns were assessed via the AASP, a 60-item self-report questionnaire. The AASP evaluates responses to sensory stimuli across four patterns: low registration (high threshold, passive regulation), sensation seeking (high threshold, active regulation), sensory sensitivity (low threshold, passive regulation), and sensation avoidance (low threshold, active regulation) [16,44]. The Turkish psychometric adaptation by Üçgül et al. demonstrated good internal consistency and strong construct validity across healthy and clinical adolescent/young adult cohorts[45].

2.3. Psychophysical evaluation

Psychophysical measurements were performed at the dorsum of the hand (C7 dermatome) bilaterally via Ag-AgCl skin electrodes (10 mm diameter) placed 1 cm apart. The stimulation order always began with the dominant hand and only the dominant hand's data were analysed and reported in this study.

SDT: Square wave electrical pulses (0.2 ms duration) were delivered via a constant current stimulator (Keypoint EMG Unit). The intensity started at 0.4 mA and increased by 0.2 mA until the participant consistently perceived the stimulus across three consecutive trials.

STDT: The stimulation intensity was set at 1.5 times the detection threshold. Paired stimuli started with an interstimulus interval (ISI) of 5 ms and increased in 5 ms increments. The ISI at which the participant perceived two distinct stimuli on three separate trials was recorded as the ascending STDT (aSTDT). To determine the descending STDT (dSTDT), stimuli were presented starting at an ISI 20 ms longer than the aSTDT and decreased by 5 ms until a single stimulus was perceived. The overall STDT for each hand was calculated as the arithmetic mean of the aSTDT

and dSTDT. The ascending and descending series for STDT were performed in a fixed order (ascending series followed by the descending series).

The examiners performing the psychophysical measurements were blinded to the diagnostic groups. All participants received identical, scripted verbal instructions prior to testing. To ensure task comprehension and compliance, a brief session of 3 practice trials was conducted for the stimuli before official data logging began. To monitor for false alarms, premature impulsive responses, or lapses in attention, catch trials (trials with zero intensity or no change in interstimulus interval) were randomly interjected throughout the protocol. If a participant provided inconsistent responses or triggered multiple false alarms during catch trials, the block was paused, the instructions were re-explained, and the session was restarted. Participants who demonstrated persistent poor task compliance, excessive movement, or an inability to maintain focus after re-instruction were excluded. Testing was uniformly conducted in a quiet, temperature-controlled laboratory between 9:00 AM and 12:00 AM. Participants and their families were instructed to ensure normal sleep the night before and to avoid caffeine intake for at least 4 hours prior to the evaluation.

2.4. Statistical analysis

Data analysis was performed via SPSS version 31.0. A post-hoc sensitivity analysis was conducted using G*Power 3.1 [46] to determine the minimum effect sizes detectable with the present sample ($\alpha = .05$, two-tailed, power = .80): $d = 0.76$ for independent-samples t-tests ($n_1 = 29$, $n_2 = 26$), $d = 0.77$ for ANCOVA with one covariate, and $r = 0.53$ for within-group correlations ($n = 26$; $r = 0.54$ for partial correlations). These thresholds indicate that the study was adequately powered to detect only large effects. Skewness and kurtosis statistics were reported to assess the distribution of the variables, adhering to the conventional criteria of skewness and kurtosis $<|1|$, which indicates a "very good" normal distribution [47].

Independent samples t tests were used for normally distributed variables, with Cohen's d and 95% confidence intervals reported as effect size measures (JASP v0.19). The Mann–Whitney U test was used for nonnormally distributed data, with the rank-biserial correlation coefficient (r) reported as the effect size. The chi-square test was used to compare categorical data between the two groups. Findings for continuous variables are expressed as the mean $\pm$ standard deviation or median (min–max), as appropriate. To control the false discovery rate (FDR) the Benjamini–Hochberg procedure was applied separately within each conceptually defined family of group comparisons, objective somatosensory measures ($k = 2$), self-reported SDQ core subscales ($k = 5$), parent-reported SDQ core subscales ($k = 5$), AASP quadrants ($k = 4$), and AASP tactile subdomains ($k = 4$); adjusted q-values are reported alongside uncorrected p-values in Table 1. The composite SDQ indices (internalizing, externalizing, and total difficulties) are derived from the core subscales and were therefore reported without inclusion in the FDR families. To examine whether age confounded group differences in objective somatosensory measures, analyses of covariance (ANCOVA) were conducted with age (in months) as a covariate; the homogeneity-of-regression-slopes assumption was assessed prior to each ANCOVA by testing the Group $\times$ Age interaction term. Spearman's Rho correlation coefficients were calculated ($r \leq 0.30$: mild; 0.30 – 0.50 : moderate; ≥ 0.50 : strong relationship). The Benjamini–Hochberg FDR adjustment was computed directly from the test-wise p-values obtained from the primary analyses. Confidence intervals for Spearman correlations were estimated using Fisher's r -to- z transformation. To examine whether associations between STDT and behavioural measures were independent of age, partial correlations (Pearson-based) controlling for age were computed within the ADHD group; sex was additionally included alongside age as a covariate in a sensitivity model, and the robustness of these associations was further evaluated using bootstrap bias-corrected and accelerated (BCa) 95% confidence intervals (1000 resamples). Within-group correlations are treated as exploratory and interpreted on the basis of effect size and confidence interval width. Sex was additionally examined as a sensitivity covariate in ANCOVA models for the objective somatosensory measures. Statistical significance was set at $p < 0.05$.

3. Results

3.1. Demographic and Psychopathological Measures

Statistical analysis revealed no significant differences between the ADHD group ($n=26$) and the control group ($n=29$) regarding age, sex, or dominant hand distribution ($p > 0.05$) (Table 1). Within the ADHD group, 13 participants (50.0%) presented with the predominantly inattentive subtype, 11 (42.3%) with the combined subtype, and 2 (7.7%) with the predominantly hyperactive subtype. Regarding treatment history, all patients were completely medication-free at the time of the study. Specifically, 11 patients were completely drug-naïve, while 15 patients had a history of past stimulant/non-stimulant exposure but had undergone a minimum washout period of 1 month prior to enrolment.

Throughout the Results, non-normally distributed variables were compared using the Mann–Whitney U test (reported with the U statistic and rank-biserial r), whereas normally distributed variables were compared using independent-samples t -tests; the test applied to each variable is indicated in Table 1. The SDQ results indicated significant clinical differences between groups across both the self-reported and parent-reported versions (Table 1). Compared with the control group, the ADHD group reported significantly higher scores for hyperactivity ($t(53) = 4.87, p < .001$, Cohen's $d = 1.31$, 95% CI [0.72, 1.89]), externalizing problems ($t(53) = 4.45, p < .001$, $d = 1.20$, 95% CI [0.62, 1.77]), and total difficulties ($t(53) = 3.14, p = .003$, $d = 0.85$, 95% CI [0.29, 1.40]), and significantly lower prosocial behaviour scores ($t(53) = -2.27, p = .027$, $d = 0.61$, 95% CI [0.07, 1.15]). Parent-rated evaluations similarly showed significantly elevated scores in the ADHD group across all problem domains: emotional problems ($t(53) = -3.81, p < .001$, $d = 1.03$), conduct problems ($U = 178.0, p = .001, r = 0.528$), hyperactivity ($t(53) = -5.18, p < .001$, $d = 1.40$), peer problems ($U = 199.0, p = .002, r = 0.472$), internalizing composite ($t(53) = -4.51, p < .001$, $d = 1.22$), and total difficulties ($t(53) = -5.91, p < .001$, $d = 1.60$); the five parent-reported core subscales survived Benjamini–Hochberg correction (all $q \leq .002$), whereas the composite indices were reported without FDR adjustment (all $p < .001$). Externalizing composite scores were also significantly elevated ($U = 118.5, p < .001, r = 0.686$; reported without FDR adjustment as a derived composite). Prosocial behaviour scores were lower in the ADHD group on both self-report ($t(53) = 2.27, p = .027, d = 0.61$) and parent-report ($t(53) = 3.39, p = .001, d = 0.92$) versions, although only the parent-report difference survived FDR correction ($q = .002$; self-report $q = .069$).

3.2. Sensory profile and tactile processing

Data from the AASP highlighted distinct sensory processing patterns in adolescents with ADHD (Table 1). Compared with controls, the ADHD group scored higher in sensory sensitivity ($p = 0.026$) and sensory avoidance ($p = 0.036$). However, neither difference survived Benjamini–Hochberg correction within the AASP-quadrant (both $q = .074$). No significant differences were found for low registration or sensory seeking (Fig 1).

Within the tactile domain, adolescents with ADHD demonstrated significantly greater levels of sensory sensitivity (10.50 ± 3.57 vs 8.52 ± 2.23 ; $p = 0.016$) and sensory avoidance (8.46 ± 2.79 vs 6.48 ± 2.56 ; $p = 0.008$); both differences remained significant after Benjamini–Hochberg correction (both $q = .031$). Differences in tactile low registration and sensory seeking were not statistically significant. In terms of objective psychophysical measures, the SDT was numerically higher in the ADHD group than in the control group (1.62 ± 0.72 vs 1.30 ± 0.51), this difference did not reach statistical significance ($t(53) = 1.91$, Cohen's $d = 0.52$, 95% CI [0.02, 1.05], $p = 0.061$). ANCOVA with age as a covariate confirmed the absence of a significant group difference after adjustment ($F(1,52) = 3.72, p = .059$, partial $\eta^2 = .067$); the homogeneity-of-slopes assumption was met ($F(1,51) = 0.45, p = .507$). No significant group difference was detected for STDT (Cohen's $d = 0.06$, 95% CI [0.00, 0.59]; $p = 0.832$) (Table 1). However, a significant Group $\times$ Age interaction was observed for STDT ($F(1,51) = 13.59, p = .001$, partial $\eta^2 = .210$), indicating that the relationship between age and STDT differed markedly between groups: in the ADHD group, older adolescents demonstrated shorter STDT values ($r = -.60$), whereas the opposite pattern was observed in the control group ($r = +.27$). Accordingly, a simple age-adjusted group comparison for STDT was not performed. A sensitivity analysis including sex as an additional covariate confirmed that sex was non-significant ($F \leq 0.094, p \geq .761$) and the Group $\times$ Age interaction remained virtually unchanged ($F(1,50) = 13.247, p = .001$, partial $\eta^2 = .209$).

3.3. Correlation Analyses in the ADHD Group

Correlation analyses within the ADHD group revealed several significant associations between age, somatosensory measures, and clinical symptoms (Fig 2).

- 3.3.1. Age and Sensory Measures:** A significant and strong negative correlation was observed between age and STDT ($r = -0.558, p = 0.003$), indicating that temporal discrimination improves (thresholds decrease) as age increases. However, no significant correlations were found between age and sensory profile scores (Table 2).
- 3.3.2. Tactile Processing and Behavioural Symptoms:** Specific tactile processing patterns were significantly positively correlated with behavioural outcomes. Tactile low registration was positively correlated with both self-reported externalizing symptoms ($r = 0.443, p = 0.023$) and parent-reported hyperactivity ($r = 0.517, p = 0.007$). Tactile sensory seeking was also positively correlated with self-reported externalizing symptoms ($r = 0.444, p = 0.023$) (Table 2).

3.3.3. STDT and Clinical/Sensory Symptoms: In unadjusted analyses, STDT values were negatively correlated with sensory seeking behaviour ($r=-0.441$, $p=0.024$), and positively correlated with parent-reported hyperactivity symptoms ($r=0.395$, $p=0.046$) (Table 3). However, after controlling for age via partial correlation, both associations were attenuated to non-significance (sensory seeking: $r_p=-.309$, $p=.133$; parent hyperactivity: $r_p=.335$, $p=.101$), indicating that age was a confounding variable in these associations. Findings were unchanged when sex was included alongside age as a covariate (sensory seeking: $r_p=-.32$, $p=.128$; parent hyperactivity: $r_p=.34$, $p=.107$), and bootstrap bias-corrected and accelerated (BCa) 95% confidence intervals (1000 resamples) for these age- and sex-adjusted associations both included zero (sensory seeking: $[-.72, .14]$; parent hyperactivity: $[-.10, .66]$), confirming their non-significance. These findings are consistent with the significant Group $\times$ Age interaction observed for STDT and should be regarded as exploratory.

4. Discussion

In the present study, we examined SDT and STDT and their relationships with clinical sensory symptoms in adolescents with ADHD. Although sensory processing difficulties (specifically, sensory sensitivity and sensory avoidance) were detected in the AASP in adolescents with ADHD, the SDT and STDT did not differ significantly from those in the control group. We also found positive correlations between low tactile registration and externalizing symptoms, as well as between tactile sensory seeking and externalizing symptoms, in adolescents with ADHD.

While we found differences in AASP scores, the objective evaluations did not reach a significant difference between groups. This situation may be explained by the overlap between the symptoms of ADHD and difficulties in sensory processing. High AASP scores may reflect sensory manifestations of ADHD symptoms. Sensory seeking patterns and ADHD hyperactivity symptoms can manifest as similar behaviours, such as difficulty with impulse control, inappropriate movement, and touch [24]. The attention deficit symptoms of ADHD overlap with the distractibility and difficulty in focusing that are also observed in the overresponsive pattern and with the lack of awareness when being spoken to or following directions observed in the underresponsive pattern [48,49]. A recent review examining sensory modulation difficulties in ADHD revealed that the prevalence of sensory modulation difficulties accompanying ADHD may be affected by the measurement tool used in the study; studies using physiological measurements had a lower prevalence of sensory modulation difficulties than studies based on caregiver reports [50]. For example, approximately 35% of sensory profile items are associated with behaviours that more closely resemble those in the ADHD population, which may create challenges in assessing the use of the sensory profile [48]. In summary, the overlap of symptoms may complicate differential diagnosis [49]. All of these factors may explain the discrepancy between the thresholds and the AASP scores in our study. In addition to overlapping symptoms, IQ may also be a contributing factor to the absence of differences in thresholds. Puts et al. reported a negative correlation between IQ and tactile detection thresholds, suggesting that the worse tactile thresholds observed in ADHD may be due to differences in IQ rather than ADHD itself. Since our study included adolescents with ADHD performing typical intellectual functioning, the absence of significant differences in threshold measures between the groups is consistent with the study by Puts et al. [34]. Furthermore, our results showing that age has a negative correlation with the STDT support the relationship between IQ and the tactile detection threshold. As age increases, the maturation of cognitive functions and skills may contribute to a decrease in STDT. Furthermore, a significant Group $\times$ Age interaction for STDT suggests divergent developmental trajectories for somatosensory temporal discrimination.

The discrepancy between self-reported sensory patterns and psychophysical metrics highlights that sensory thresholds do not linearly map onto everyday behavioural manifestations. SDT and STDT capture narrow, neurophysiological thresholds under highly structured, low-distraction laboratory conditions. In contrast, questionnaire scores like the AASP capture sensory modulation and sensory reactivity operating in real-world environments [16,49]. Therefore, the lack of significant differences in thresholds does not imply that real-world sensory complaints are merely an artifact of ADHD symptom overlap. Rather, sensory difficulties in adolescents with ADHD appear to be fundamentally context-dependent, affective, and regulatory rather than threshold-based [51]. While an adolescent with ADHD may possess intact peripheral and intermediate sensory tracks to detect a stimulus under optimal lab settings, they may exhibit heightened attentional capture by sensory stimuli and poor behavioural regulation in sensory contexts when encountered in daily life [52]. This executive mismatch drives the high real-world sensitivity and avoidance reported in questionnaires. Finally, psychophysical task performance itself can be confounded by response bias and impulsive responding, further widening the gap between laboratory threshold estimation and actual ecological sensory

regulation. Together, these distinctions highlight that sensory differences in ADHD may represent a complex failure of multimodal regulation rather than a basic impairment in raw sensory acuity [34].

On the other hand, our finding regarding the SDT showed a numerical trend toward higher thresholds in the ADHD group ($p = 0.061$). This suggests that the lack of statistical significance may be due to our relatively modest sample size being underpowered to detect medium-sized effects, rather than a true neurobiological equivalence or 'preservation' of tactile function. This trend aligns with previous literature indicating subtle tactile processing abnormalities in neurodevelopmental conditions and highlights the need for larger replication studies [32]. However, the absence of a significant difference in the thresholds of ADHD group may support the distinction between ASD and ADHD in terms of sensory-related diagnostic criteria. Sensory-related criteria are included in the DSM-5 diagnostic criteria for ASD but not for ADHD [3]. Compared with the control group, the adolescents with ASD had worse SDT and STDT, indicating that they were less able to perceive and temporally discriminate tactile stimuli [31]. In contrast, such a finding was not observed in our ADHD sample. These results are consistent with the fact that the clinical presentation of sensory symptoms in ADHD is not as pronounced as that in ASD.

Our findings revealed significant differences in sensory sensitivity and avoidance in the ADHD group, whereas no differences were found for low registration and seeking. Sensation avoidance is related to individuals being more overwhelmed or disturbed by stimuli and less aware of how sensory information affects their daily lives [25]. Additionally, sensory sensitivity is associated with responding quickly to low-threshold stimuli, which can lead to individuals being easily distracted [16,53]. The literature contains studies with variable results regarding changes in these four quadrants in the ADHD group. While some studies reported significant changes in all quadrants [18,25], other studies reported no significant changes in sensory avoidance [24,54]. This variability across studies likely reflects the substantial methodological heterogeneity reported in previous meta-analytic research. Hypersensitivity and hyposensitivity differ across specific sensory modalities in individuals with ADHD; furthermore, a single individual may exhibit multiple sensory differences simultaneously. Because these difficulties are not uniformly distributed, the results across studies remain variable. This heterogeneous sensory profile is reflected in the clinical presentation as a combination of strengths and weaknesses across different sensory modalities [24].

In our study, we also examined the relationship between the sensory profile and the clinical presentation of ADHD. In line with our findings, a relationship between sensory seeking, touch processing difficulties and externalizing symptoms was reported in individuals with ADHD [18]. Additionally, difficulties with sensory processing are also associated with an increase in behavioural problems [18,55]. This finding can be explained by Dunn's model, which suggests that seeking behaviour with a high neurological threshold, along with aggressive, hyperactive, and risky behaviours, can be associated with externalizing symptoms [16]. While we suggest that sensory seeking, which is generally characterized by hyporesponsiveness, is associated with externalizing symptoms, Ghanizadeh et al. reported that individuals with ADHD and sensory hypersensitivity also exhibit oppositional behaviours [28]. We also found a positive correlation between low-tactile registration and adolescent-reported externalizing symptoms and parental-reported hyperactivity symptoms. Low registration may lead to children having difficulty noticing stimuli and missing environmental cues for behavioural regulation, resulting in externalizing symptoms. Overall, the capacity to process sensory information, which may influence individual differences in self-regulation, may also help explain externalizing symptoms [56]. On the other hand, we did not find a relationship between internalizing symptoms and sensory quadrants, in contrast to a study in adults [54]. The discrepancy between studies may be because sensory processing problems vary in extent and characteristics across ADHD subtypes [22].

This study has several notable strengths. First, to our knowledge, this is the first study investigating the STDT specifically in adolescents with ADHD, providing valuable insights into the neurophysiological basis of sensory processing in this group. Second, the use of a multi-informant approach (self- and parent-rated SDQ forms) alongside standardized clinical interviews (K-SADS-PL) ensures a comprehensive evaluation of symptoms. Furthermore, the inclusion of a specialized sensory measure (AASP) allows for an exploration of the relationship between psychophysical thresholds and subjective sensory experiences. Finally, the exclusion of comorbid psychiatric disorders and the recruitment of a medication-free sample minimize potential confounding factors on sensory measures. Despite its strengths, several limitations should be acknowledged. First, the sample size is relatively small, which may limit the generalizability of the findings and detecting medium-sized effects. As the G*Power sensitivity analysis indicated, the study was adequately powered to detect only large effects (group comparisons: $d \approx 0.76$; within-group correlations: $r \approx 0.53$); accordingly, small-to-moderate group differences and associations may have gone

undetected, and both the significant and the non-significant findings, including the non-significant group differences in the objective somatosensory measures, should be interpreted in light of this limited statistical power. Second, while intellectual disability was strictly excluded through clinical history and school performance, standardized IQ scores were not available for our participants. Likewise, we did not collect standardized quantitative measures of subclinical autistic traits, although ASD diagnoses and subclinical autistic traits were systematically excluded via structured clinical interviews (K-SADS-PL). Because previous literature suggests a relationship between cognitive performance, autistic traits, and tactile thresholds, the absence of these measures as a continuous covariate limits our ability to completely isolate pure somatosensory processing. Finally, while the SDQ is a well-validated multi-informant screening metric, it is not a direct substitute for dedicated ADHD symptom severity instruments. The absence of quantitative parameters tracking diagnostic severity, functional impairment indexes, and exact age at diagnosis limits our capacity to map sensory processing variances directly onto incremental core symptom dimensions.

In conclusion, the symptoms of ADHD and sensory processing difficulties may be associated in adolescents. High tactile sensory sensitivity and sensory avoidance behaviours, as reported in questionnaires, may serve as clinical reflections of underlying ADHD symptoms. Alternatively, objective assessments of somatosensory processing may fail to detect existing impairments owing to the confounding effect of impulsivity-driven response errors typical of ADHD. Furthermore, sensory processing challenges appear to be associated with the externalizing symptoms of ADHD. Ultimately, the pathophysiological and clinical links between neurodevelopmental disorders and sensory processing require further investigation.

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Data availability: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

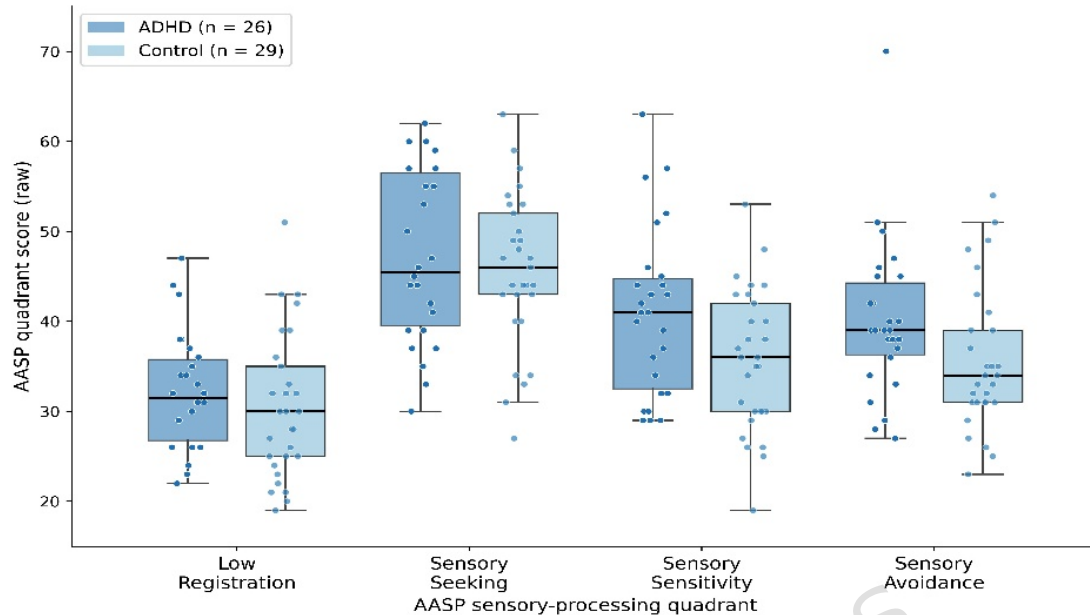
Author contributions: DB, EG, EI, ZG, and BC conceptualized and designed the work. DB and IAS wrote the main manuscript text. DB and ZKK made the investigation and data curation. AO analyzed and interpreted the data. All authors reviewed the manuscript.

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Consent to participate: Informed consent was obtained from all participants and parents.

Figure 1. Comparison of Adult/Adolescent Sensory Profile (AASP) Scores between the ADHD and control groups

Boxes show the median and interquartile range, whiskers the range, and overlaid dots individual participants. Sensory sensitivity ($p = .026$) and sensory avoidance ($p = .036$) differed at the uncorrected level; neither survived Benjamini–Hochberg correction within the AASP-quadrant family (both $q = .074$).

Table 1. Comparison of demographic characteristics, somatosensory measures, and clinical scales between the ADHD and control groups

		ADHD (n=26)	Control (n=29)	$t/U/\chi^2$	p	Cohen's d [95% CI]	q (FDR)
Age (months) (mean±SD)		165.69±26.51	161.10±24.88	0.662	0.511	-	-
Sex (male, %)		17 (65%)	18 (62%)	0.065	0.799	-	-
Dominant Hand (Right, %)		22 (85%)	27 (93%)	1.016	0.406	-	-
Dominant Hand SDT (mA)		1.62±0.72	1.30±0.51	1.911	0.061	0.52 [0.02, 1.05]	0.123
Dominant Hand STDT (ms)		92.60±44.82	94.91±35.75	-0.213	0.832	0.06 [0.00, 0.59]	0.832
SDQ_Self	Emotional problems	2.81±2.65	2.34±1.99	0.737	0.464	0.20 [0.00, 0.73]	0.464
	Conduct problems	2.96±1.61	2.03±1.88	1.952	0.056	0.53 [0.00, 1.06]	0.094
	Hyperactivity	6.15±2.20	3.38±2.02	4.866	<0.001	1.31 [0.72, 1.89]	<0.001*
	Peer problems	3.19±1.50	2.52±1.55	1.639	0.107	0.44 [0.00, 0.98]	0.134
	Prosocial	7.50±1.90	8.62±1.76	-2.269	0.027	0.61 [0.07, 1.15]	0.069
	Internalizing Problems	5.85±3.09	4.86±2.90	1.217	0.229	0.33 [0.00, 0.86]	-
	Externalizing Problems	9.08±3.16	5.48±2.84	4.445	<0.001	1.20 [0.62, 1.77]	-
	Total	14.46±5.24	10.34±4.50	3.135	0.003	0.85 [0.29, 1.40]	-
SDQ_Parent	Emotional problems	3.58±2.10	1.66±1.63	3.810	<0.001	1.03 [0.46, 1.59]	0.001*
	Conduct problems ¹	3 (0-7)	1 (0-5)	178.000	<0.001	$r = 0.528$	0.001*
	Hyperactivity	5.81±2.24	2.62±2.30	5.182	<0.001	1.40 [0.80, 1.99]	<0.001*
	Peer problems ¹	3 (0-14)	1 (0-6)	199.000	0.002	$r = 0.472$	0.002*
	Prosocial	7.27±1.95	8.86±1.53	-3.388	0.001	0.92 [0.35, 1.47]	0.002*
	Internalizing Problems	6.62±3.10	3.10±2.68	4.509	<0.001	1.22 [0.64, 1.79]	-

		SDT	STDT	Low Registration		Sensory Seeking		Sensory Sensitivity		Sensory Avoidance		
				Gen.	Tactile	Gen.	Tactile	Gen.	Tactile	Gen.	Tactile	
Age		.006	-.558**	.012	-.114	.225	.197	.238	.083	.175	.122	
SDQ Self	Emotional problems	-.185	.165	.100	.083	-.099	.157	.217	-.014	.330	.072	
	Conduct problems	-.219	.194	-.018	.345	.311	.275	.107	.274	-.322	.065	
	Hyperactivity	-.030	.213	.251	.382	-.160	.345	.135	.093	-.013	-.068	
	Peer problems	.027	.077	-.306	-.215	-.059	-.004	-.197	-.106	-.194	-.329	
	Prosocial	.237	.118	-.164	.149	-.166	-.348	.008	.111	.046	-.175	
	Internalizing Problems	-.137	.191	-.086	-.078	-.096	.060	.050	-.055	.145	-.081	
	Externalizing Problems	-.111	.245	.190	.443*	.084	.444*	.127	.177	-.149	-.050	
Total		-.101	.221	.025	.128	.016	.203	-.009	.021	-.145	-.165	
SDQ Parent	Emotional problems	-.046	.200	-.009	.126	-.136	.059	-.011	-.100	.263	.307	
	Conduct problems	-.169	.240	-.116	.243	-.148	-.090	-.157	-.150	-.068	.309	
	Hyperactivity	.043	.395*	.050	.517**	-.382	-.150	-.133	-.164	-.151	.019	
	Peer problems	.082	.045	-.117	-.005	-.133	-.101	-.240	-.344	.003	.137	
	Prosocial	-.091	-.079	-.343	-.247	-.045	-.163	-.153	.085	.155	.040	
	Internalizing Problems	.012	.014	-.120	.047	-.093	.036	-.138	-.256	.115	.273	
	Externalizing Problems	-.040	.300	-.019	.371	-.266	-.088	-.167	-.171	-.052	.177	
Total		.018	.201	-.071	.270	-.217	-.025	-.196	-.249	-.008	.214	
		Externalizing Problems ¹		7 (3-17)		4 (0-13)		118.500	<0.001	r = 0.686		-
		Total		15.19±6.18		6.72±4.37		5.914	<0.001	1.60 [0.98, 2.20]		-
AASP	Low registration		32.19±6.49		30.38±8.02		0.914	0.365	0.25 [0.00, 0.78]		0.486	
	Sensory seeking		47.23±9.44		45.72±8.56		0.621	0.538	0.17 [0.00, 0.70]		0.538	
	Sensory sensitivity		40.96±9.35		35.66±7.86		2.286	0.026	0.62 [0.07, 1.16]		0.074	
	Sensory avoidance ¹		39 (27-70)		34 (23-54)		253.000	0.036	r = 0.329		0.074	
AASP_Tactile	Low registration ¹		6 (3-10)		5 (3-15)		342.500	0.556	r = 0.092		0.658	
	Sensory seeking		8.23±2.75		7.90±2.81		0.445	0.658	0.12 [0.00, 0.65]		0.658	
	Sensory sensitivity		10.50±3.57		8.52±2.23		2.498	0.016	0.68 [0.13, 1.22]		0.031*	
	Sensory avoidance		8.46±2.79		6.48±2.56		2.745	0.008	0.74 [0.19, 1.29]		0.031*	

Significance after false discovery rate (FDR) correction is indicated in the q column. q = Benjamini–Hochberg FDR-adjusted p-value, computed within conceptually defined families (objective measures, k = 2; SDQ self-report core subscales, k = 5; SDQ parent-report core subscales, k = 5; AASP quadrants, k = 4; AASP tactile subdomains, k = 4); bold q-values denote significance after correction (q < .05). Bold p-values denote uncorrected significance (p < .05). Composite SDQ indices (internalizing, externalizing, total difficulties) and demographic comparisons were not included in the FDR families (-). SDT: somatosensory detection threshold (mA); STDT: somatosensory temporal discrimination threshold (ms); SDQ: Strengths and Difficulties Questionnaire; AASP: Adult/Adolescent Sensory Profile, ADHD: attention deficit hyperactivity disorder; SD: standard deviation. Values are mean ± SD or median (min–max). Effect sizes: Cohen's d [95% CI] for t-tests (absolute values; JASP v0.19); rank-biserial r for Mann–Whitney U tests; 1: non-parametric variables that were analysed by Mann-Whitney U *: Survived FDR correction.

Table 2. Spearman correlations among age, somatosensory measures (SDT and STDT), AASP sensory-profile quadrants, and Strengths and Difficulties Questionnaire scores in the ADHD group

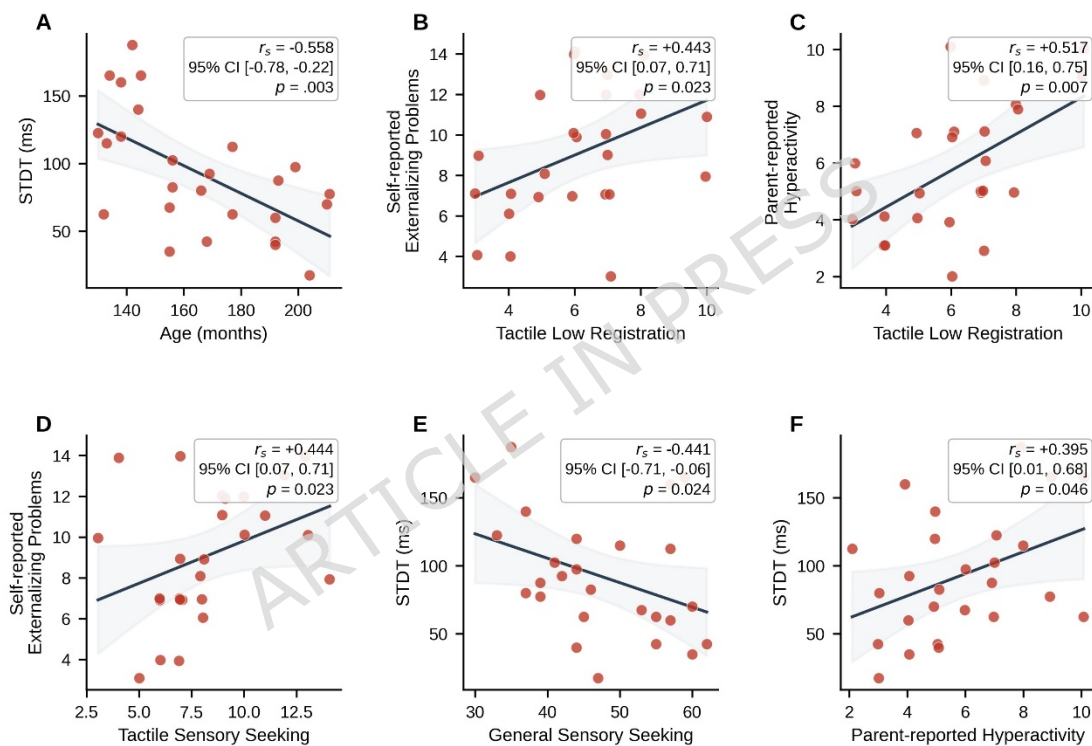
Bold values indicate significant correlations (p < .05). Spearman's rho; n = 26. 95% CIs based on Fisher's r-to-z transformation: Age × STDT: r = -.558 [-.78, -.22]; Tactile Low Registration × Externalizing: r = .443 [.07, .71]; Tactile Seeking × Externalizing: r = .444 [.07, .71]; Tactile Low Registration × Parent Hyperactivity: r = .517 [.16, .75]; STDT × Parent Hyperactivity: r = .395 [.01, .68]. ADHD: attention deficit hyperactivity disorder; SDT: somatosensory detection threshold; STDT: somatosensory temporal discrimination threshold; SDQ: strengths and difficulties questionnaire; AASP: adult/adolescent sensory profile; *: p<0.05 **: p<0.01

Table 3. Correlations between sensory profiles and somatosensory detection and temporal discrimination thresholds in the ADHD group

		SDT	STDT	95% CI (SDT)	95% CI (STDT)
General Sensory	Low Registration	-.072	.274	-.45, .33	-.04, .57
	Seeking	.098	-.441	-.31, .48	-.71, -.07
	Sensitivity	.106	-.140	-.29, .47	-.49, .23
	Avoidance	.078	-.007	-.33, .44	-.40, .38
Tactile Sensory	Low Registration	.081	.345	-.32, .46	-.06, .65
	Seeking	.141	-.217	-.26, .51	-.57, .19
	Sensitivity	.155	-.177	-.26, .52	-.52, .22
	Avoidance	.088	-.070	-.32, .45	-.40, .27

Spearman's rho; $n = 26$. Bold values indicate significant correlations ($p < .05$). 95% CIs (Fisher's r -to- z): Partial correlations (Pearson-based) controlling for age within the ADHD group: STDT $\times$ General Sensory Seeking: $r_p = -.309$, $p = .133$; STDT $\times$ Parent Hyperactivity: $r_p = .335$, $p = .101$ (both attenuated to non-significance). Results were unchanged with age and sex as joint covariates (STDT $\times$ Seeking: $r_p = -.32$; STDT $\times$ Parent Hyperactivity: $r_p = .34$), and bootstrap BCa 95% confidence intervals for these adjusted associations both included zero (see Results). SDT: somatosensory detection threshold (mA); STDT: somatosensory temporal discrimination threshold (ms), ADHD: attention deficit hyperactivity disorder

Figure 2. Scatterplots of Significant Correlations in the ADHD Group



Scatterplots with linear regression lines and 95% confidence bands for the six significant correlations observed within the ADHD group ($n = 26$). Spearman's rho is reported; 95% CIs are based on Fisher's r -to- z transformation. STDT $\times$ sensory seeking and STDT $\times$ parent-reported hyperactivity reflect unadjusted associations; both were attenuated to non-significance after controlling for age via partial correlation (see Results, Section 3.3).