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Atypical sensory processing in adolescents with Attention Deficit Hyperactivity Disorder: A comparative study

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ABSTRACT

Atypical sensory processing is common in Attention Deficit Hyperactivity Disorder (ADHD). Despite growing evidence that ADHD symptoms persist into adolescence, the sensory processing of individuals with ADHD in this age group is limited. The aim of this study was to assess differences in self-reported sensory experiences between adolescents with and without ADHD. One hundred thirty-eight Italian adolescents aged between 14 and 18 years (M=16.20; SD= ± 1.90) participated in the study. Sixty-nine participants with ADHD were matched by gender, age, and IQ to 69 typically developing individuals. The sensory processing of all participants was assessed using the Adolescent Sensory Profile (ASP) on the components: low registration, sensation seeking, sensory sensitivity, and sensation avoiding. Moreover, the modalities of ASP were measured: movement, vision, touch, activity level, hearing, and taste/smell. Results show that the ADHD group consistently displayed higher scores across all four components of the sensory profile compared to the control group. The subjects with ADHD also reported higher scores than the control group in all the modalities of ASP. These results confirming the presence of atypical sensory processing in adolescents with ADHD were discussed considering the Cumulative and Emergent Automatic Deficit model (CEAD).

1. Introduction

Through the senses, individuals are able to perceive and process a significant amount of information from the external world (Marshall et al., 2022). The process by which the nervous system receives, modulates, integrates, organizes, and responds to stimuli is known as sensory processing (Miller & Lane, 2000; Miller et al., 2007). Sensory processing is crucial for adaptive behavior, as it enables individuals to produce appropriate responses to specific situations (Dellapiazza et al., 2020) and influences their overall functioning and psychophysical well-being (Kojovic et al., 2019).

Dunn's model (1999) explains how reactivity to sensory processing can vary based on the neurological threshold and individual behavioral self-regulation responses, both of which exist on a continuum. At the extremes of the neurological threshold continuum, two types of atypical sensory processing can be observed: hypo-reactivity to sensory stimulation associated with a low neurological threshold, and hyper-reactivity characterized by a high neurological threshold. Similarly, the extremes of the behavioral response

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continuum encompass passive self-regulation strategies, which involve allowing sensory stimuli to occur without interference, and active self-regulation strategies that entail engaging in behaviors to manage sensory input. The interplay between these continua gives rise to four components of sensory processing: sensation seeking, sensory avoidance, sensory sensitivity, and low registration (Rogers et al., 2011). Each component pertains to specific sensory modalities, including taste/smell, movement, vision, touch, activity level, and auditory processing. While the prevalence of atypical sensory processing in typically developing children is reported to be 12% (Adams et al., 2015), several studies have focused on investigating sensory processing in clinical populations and examining how it differs from that of the general population (Balasco et al., 2020; MacLean et al., 2022; Griffin et al., 2022; Isralowitz et al., 2023; Mohammadhsani et al., 2020).

Attention Deficit Hyperactivity Disorder (ADHD) is one clinical condition frequently associated with unusual responses to sensory stimulation (Little, Dean, Tomchek, & Dunn, 2018; Varbanov, Overton, & Stafford, 2023). ADHD is a neurodevelopmental disorder characterized by persistent and pervasive patterns of inattention, hyperactivity, and impulsivity. It can be categorized into three subtypes based on symptomatology: predominantly inattentive (ADHD-I), predominantly hyperactive/impulsive (ADHD-H), or combined (ADHD-C) (American Psychological Association, 2013). Individuals with ADHD experience adverse academic, social, emotional, and physical outcomes, leading to impairments across multiple domains of life (Kooij et al., 2019; Caprì et al., 2020, 2021; Fabio & Urso, 2014; Yüksel et al., 2023). Extensive research on ADHD has demonstrated the relationship between core symptoms and deficits in executive functioning (Bos et al., 2017; Fabio & Caprì, 2019a; 2019b; Nikolas & Nigg, 2013; Sonuga-Barke, Bitsakou, & Thompson, 2010). More recently, studies have also indicated the impairment of automatic processes in individuals with ADHD (Fabio, 2017; Fabio et al., 2019, 2020), suggesting that ADHD symptoms may arise from selective disruptions in automatic processing, leading to an increased demand for attentional resources (Ullman & Pullman, 2015). This could be attributed to atypical sensory processing, which impairs the ability to automate behaviors and process information rapidly and efficiently without conscious effort. In more detail, the Cumulative and Emergent Automatic Deficit model (CEAD) proposes that deficits in sensory processing contribute to deficits in automatization. If basic knowledge is not well automatized, it leads to a high cognitive load. Consequently, automatic deficits can result in deficits in controlled processes, potentially explaining the symptoms of ADHD. In other words, variations in the brain structures underlying controlled processes, such as automatic-subcortical functions (Fabio, 2017), can account for the core deficits observed in the disorder. Specifically, variations in the frontal/basal-ganglia circuits and the cerebellum can potentially explain deficits in both controlled and automatic processes in ADHD, as these networks regulate both types of processes. Several studies have demonstrated that early sensory processing is linked to cortical and subcortical systems (Happel et al., 2022). Johnson's theory (2015a; 2015b; 2017) provides a more detailed analysis of how these integrations can occur. Johnson (2017) proposes that autism and other disorders such as ADHD might result from adaptive processes activated during sensitive periods, like how the brain adapts to its individual social and physical environment during ontogenetic development. Early perception and environmental sampling depend closely on the specific characteristics of the brain involved in their processing. Consequently, the effective environment experienced by infants with certain limitations in their neural processing may differ from that experienced by others. Inferior quality in the processing of early sensory signals, due to mediated sensory processing atypicality through synaptic connections, can lead to an adaptive developmental trajectory that results in autism (Johnson et al., 2015; Carrozza et al., 2020). For example, variations in attentional styles observed in some developmental disorders, such as autism and ADHD, can be viewed as adaptive brain strategies in response to its limitations and capacities. Excessively focused attention may arise from limitations in parallel processing, making it advantageous to concentrate on a single channel or area of external space. These examples reflect the general principle of developmental pathways (Waddington, 1966), which suggests that predefined developmental trajectories tend to be quite resilient to minor or temporary disruptions (mild NE). However, when more substantial and prolonged disruptions occur during sensitive periods, the development process can deviate toward alternative directions, giving rise to distinct profiles of abilities, disabilities, and behaviors (moderate NE) (Steinmetz et al., 2021).

A systematic review based on 11 studies showed that atypical sensory processing was more frequently reported among individuals with ADHD compared to those with typical development (Ghanizadeh, 2011), across all sensory modalities (Shimizu et al., 2014). Experimental studies have found atypical sensory processing in samples of children (Lane & Reynolds, 2019) and adults with ADHD (Bijlenga et al., 2017). Another study found that ADHD traits predict sensory processing in the general population, suggesting that atypical sensory processing may be part of the ADHD phenotype (Panagiotidi et al., 2018). Mimouni-Bloch et al. (2018) measured sensory processing in a sample of children with ADHD using the Sensory Profile questionnaire. The results suggest that almost 50% of children with ADHD exhibit atypical sensory processing. In the studies conducted by Clince et al. (2016), individuals diagnosed with ADHD scored significantly higher in relation to all sensory components. Bijlenga et al. (2017) examined sensory processing in 116 adults diagnosed with ADHD. The findings revealed that self-reported ADHD symptoms were associated with atypical sensory processing in relation to three sensory components: low registration, sensation seeking, and sensory sensitivity. In contrast, there were no significant differences in the avoidance component.

However, previous work that used the Sensory Profile for sensory processing assessment did not include a control group of non-ADHD individuals. The obtained data were compared to normative elements provided in the Adolescent/Adult Sensory Profile (AASP) manual. The interpretation of the data regarding each sensory modality reported in Bijlenga et al. (2017) is also limited by the lack of normative data for modality scores. Only the research conducted by Kamath et al. (2020) determined sensory processing in adults with and without ADHD, reporting greater hypersensitivity and hyposensitivity in the experimental group compared to the control group. Differences between the groups were found for low registration, sensation seeking, and sensory sensitivity, but not for sensory avoidance and specific sensory modalities.

Furthermore, recent studies have demonstrated the variation of ADHD symptoms in adolescence and changes in the developmental trajectory from childhood to adolescence (Becker et al., 2020; Dekkers et al., 2022). Specifically, during this period, hyperactivity tends to attenuate, while impulsivity and symptoms of inattention intensify (Sibley et al., 2022; Marten et al., 2023). ADHD is prevalent in individuals at a rate of 7.2% (Thomas et al., 2015), with approximately 65% of cases persisting into adulthood (Turgay et al., 2012). However, we are not aware of any study that has investigated sensory processing experiences in a sample of adolescents with ADHD.

Therefore, the overall objective of this study was to evaluate differences in self-reported sensory experiences between adolescents with and without ADHD. Specifically, the aims were to:

Investigate whether adolescents with ADHD exhibit an atypical sensory profile compared to individuals with typical development.

Determine if the above-mentioned differences are particularly significant in certain sensory components (low registration, sensation seeking, sensory sensitivity, sensory avoidance), and if so, which ones.

Finally, understand if there are significant differences in sensory processing between individuals with and without ADHD in relation to different sensory modalities (taste/smell processing, movement processing, visual processing, touch processing, activity level, auditory processing).

By examining these objectives, we aim to contribute to the existing literature on sensory processing in ADHD and provide insights into the potential sensory differences experienced by adolescents with ADHD compared to their typically developing peers. Understanding these differences can have important implications for the development of targeted interventions and support strategies that address sensory processing difficulties in individuals with ADHD.

Based on the results of previous studies that have investigated sensory processing in adults and children with ADHD, it has been hypothesized that (a) individuals with ADHD would show higher levels of sensory processing than their peers without ADHD, more in detail (b) individuals with ADHD demonstrate higher levels in the three sensory components (low registration, sensation seeking, sensory sensitivity) than individuals without ADHD, and (c) individuals with ADHD exhibit atypical sensory processing not only in a specific sensory modality but also across all sensory modalities.

2. Materials and methods

2.1. Participants

The participants were selected from a sample of 1230 adolescents, consisting of 715 males and 515 females, aged between 14 and 18 years (M=16.20; SD= ± 1.90). All participants were Italian and attended public secondary schools in Calabria, a region in Southern Italy. Each participant completed the Adult Self-Report Scale (ASRS) to assess ADHD symptoms and the Raven Progressive Matrices Test (Raven, 1962, 2000) for intelligence assessment.

2.1.1. ADHD group

The initial screening for ADHD symptoms was based on the scores of the Adult Self-Report Scale (ASRS). For inclusion in the ADHD group, participants needed to have ASRS scores between 17 and 24 and undergo evaluation by a clinical psychologist. The presence of other disorders was ruled out based on normal ASRS scores (0 to 17), normal scores on Raven's Progressive Matrices, and a clinical interview. The clinical interview DIVA-5 (Kooij et al., 2010; 2019) was used, available at the link https://www.divacenter.eu/DIVA.aspx?id= 523 (accessed in September 2022). The interview lasted approximately 1 h and was based on the DSM-V (APA, 2013) guidelines. It covered various aspects related to general medical status, daily and school functioning, and difficulties associated with ADHD (Mohammadhasani et al., 2020; Shorey et al., 2022; van den Broek et al., 2023). Participants were given the freedom to respond in their own words, and prompts were used when necessary to obtain more detailed responses. Behavioral observations during the interview also contributed to the description and evaluation of the adolescents' symptoms and diagnoses. None of the participants had a history of brain injury, epilepsy, psychosis, or anxiety disorders. Among the initial 86 participants who met symptomatic criteria for ADHD based on the questionnaire, the diagnosis was confirmed by a clinical psychologist for 69 participants, forming the final ADHD group.

2.1.2. Control group

The control group consisted of 69 children selected from the initial sample of 1230 participants who scored within the normal range on the ASRS (0 to 17) and did not present any clinical disorders (as confirmed through a clinical interview conducted by a psychologist). The selection of participants for the control group took into consideration gender, age, and IQ to approximately match the male/female ratio, average age, and average IQ with the characteristics of the ADHD group. The matching process was carried out in

Table 1
Score distribution of adolescents with (N = 69) and without (N = 69) ADHD in each quadrant of the ASP.

	Much Less Than Most People		Less Than Most People		Similar To Most People		More Than Most People		Much More Than Most People		
Quadrant	Control	ADHD	Control	ADHD	Control	ADHD	Control	ADHD	Control	ADHD	χ^2
Low Registration	33 (48)	16 (23)	34 (49)	9 (13)	2 (3)	14 (20)	0	22 (32)	0	8 (12)	12.89 * *
Sensation Seeking	7 (10)	4 (6)	16 (23)	4 (6)	36 (52)	18 (26)	5 (7)	36 (52)	5 (7)	7 (10)	9.32 * *
Sensory Sensitivity	42 (61)	20 (29)	14 (20)	7 (10)	8 (12)	12 (17)	2 (3)	10 (14)	3 (4)	20 (29)	7.99 * *
Sensation Avoiding	25 (36)	18 (26)	26 (38)	18 (26)	18 (26)	8 (12)	0	13 (19)	0	12 (17)	13.01 * *

accordance with the rules outlined by Kover & Atwood (2013).

The final sample consisted of 69 children with ADHD and 69 children without ADHD (control group). Table 1 provides a summary of the descriptive statistics (mean and standard deviation) for each variable characterizing the sample. Each group consisted of 45 males and 24 females; thus, there were no significant differences in gender distribution between the experimental group and the control group. The results showed that there were no significant differences in age between the control group and the ADHD group ($t = 0.7$, $p = .21$). Similarly, there were no significant differences in intelligence, as measured by Raven's matrices, between the two groups ($t = 0.75$, $p = .23$). However, significant differences were observed in grades in humanities, grades in science, inattention, and hyperactivity between the ADHD and control groups. The control group had significantly higher mean grades in humanities and science compared to the ADHD group, with t-values of 2.57 ($p < .01$) and 4.43 ($p < .001$), respectively. Additionally, symptoms of inattention and hyperactivity were significantly more prevalent in the ADHD group than in the control group, with t-values of 34.68 ($p < .0001$) and 28.58 ($p < .001$), respectively.

2.2. Instruments

2.2.1. Adult Self-report Scale (ASRS)

Adult Self-Report Scale (ASRS) is a tool used to measure ADHD symptoms developed by the World Health Organization (WHO, 1992) and the Adult ADHD Working Group (Kessler et al., 2005; 2007). The scale has been translated and validated in Italy by Somma et al. (2019). The validity and reliability of this instrument have been demonstrated in clinical and population-based samples (Adler et al., 2006; Glind et al., 2013; Gray et al., 2014). The internal consistency, assessed using Cronbach's alpha, was found to be $\alpha = 0.88$ (Doğan et al., 2009). Additionally, Adler et al. (2011) confirmed that symptom checklists were internally consistent self-report scales for assessing adolescent ADHD. The ASRS includes 18 items (6 in the short form) that assess the symptoms of inattention, hyperactivity, and impulsivity associated with ADHD, in accordance with the DSM-V criteria (American Psychiatric Association, 2013). Participants responded to the items using a 5-point Likert scale ranging from 0 (never) to 4 (very often). Two additional items were added in this study: one item assessed the frequency of engaging in aggressive behaviors, and the other item asked participants to describe themselves during childhood and pre-adolescence (4–14 years) using adjectives such as inattentive, hyperactive, and impulsive.

2.2.2. Adolescent Sensory Profile (ASP)

To assess sensory problems, an Italian adaptation of the Adolescent Sensory Profile (ASP), derived from Dunn's sensory processing model (1997), was administered. It provides a framework for understanding the nervous system thresholds for stimulus detection and propensity for response. The thresholds and responsivity exist on a continuum and are anchored by the four outermost points of each scale, giving rise to four quadrants (Brown et al., 2002). The four quadrants arise from the interaction between neurological threshold and stimuli on the behavioral response continuum. Specifically, "Low Registration" is the anchor for high thresholds with a passive response, while "Sensation Seeking" is the anchor for high thresholds and an active response (Christakou et al., 2013). "Sensory Sensitivity" is the center for low thresholds with a passive response, and "Sensation Avoiding" is the point for low thresholds for an active response. Each individual experiences these thresholds to varying degrees, resulting in an individual score in each quadrant. The Sensory Profile includes six sensory modalities: taste/smell, movement, vision, touch, activity level, and auditory processing. Therefore, in addition to the four overall quadrant scores, quadrant scores can be obtained for each sensory modality (Licciardi et al., 2021). The questionnaire consists of 60 items, with a 5-point Likert scale response format (from 1 = almost never to 5 = almost always). Cronbach's alpha found good internal consistency for each of the ASP quadrants, with coefficient alpha values of 0.692 for Low Registration, 0.639 for Sensation Seeking, 0.657 for Sensory Sensitivity, and 0.699 for Sensation Avoiding (Pohl et al., 2003; Engel-Yeger, 2012). In the current study, Cronbach's Alpha was calculated for each sensory component and modality of the questionnaire. For sensory components, the coefficient alpha values were 0.83 for Low Registration, 0.84 for Sensation Seeking, 0.87 for Sensory Sensitivity, and 0.79 for Sensation Avoiding. For sensory modalities, the alpha coefficients were 0.81 for taste/smell, 0.87 for movement, 0.82 for vision, 0.87 for touch, 0.86 for activity level, and 0.83 for hearing. The robust internal consistency confirmed by these results reflects the questionnaire's reliability.

2.2.3. Raven's Progressive Matrices (RPM)

The Raven's Progressive Matrices test is a widely used tool for assessing cognitive abilities, primarily focused on measuring fluid intelligence. Its utility stems from its relative insensitivity to socio-cultural factors, such as environmental contexts and educational levels. The test's structure consists of a sequence of diagrams or matrices composed of abstract geometric figures, with the absence of a specific element. The standard version is divided into five sets (from A to E), characterized by various levels of complexity, totaling 60 items distributed across 12 questions for each set. Participants are required to identify the underlying pattern or rule in the arrangement of figures and to select the appropriate figure, among the provided options, to complete the series.

2.2.4. Assessment of Grades in Humanities and Science

Teachers of the participantsTeachers were asked to write their performance using a numeric scale from 1 to 10. Within the Italian educational system, a grade of 10 signifies an excellent mastery of the subject, while a grade of 1 indicates a very poor performance. Teachers were required to provide the average of their grades up to that point in the school year, allowing for a concise evaluation of their overall performance in both humanities and sciences.

Inizio modulo.

2.3. Procedure

The procedures implemented in the present study are consistent with the Declaration of Helsinki. After obtaining informed consent from the parents/guardians of each participant, the research was initiated. Data collection lasted for a total of three months, from December 2022 to February 2023. Self-report questionnaires were used, specifically the Adolescent Sensory Profile (ASP), to examine sensory experiences. All tests were administered by an experimental psychologists during school hours, between 9:00 AM and 12:00 PM in the morning.

3. Statistical analysis

Statistical analysis was performed using SPSS 24.0 software (SPSS Inc., Chicago, IL, USA). The measured parameters were the components of the sensory profile (Low Registration, Sensation Seeking, Sensory Sensitivity, Sensation Avoiding) and the sensory modalities (Taste/Smell Processing, Movement Processing, Visual Processing, Touch Processing, Activity Level, Auditory Processing) for each experimental condition (ADHD subjects, control).

To compare the scores of the four quadrants of the Sensory Profile between the experimental group and the control group, a multivariate analysis of variance (MANOVA) was conducted, with one between-subject factor (2 groups: ADHD subjects vs control subjects) and one within-subject factor (4 Profile Components: Low Registration, Sensation Seeking, Sensory Sensitivity, Sensation Avoiding).

To examine whether significant differences in sensory processing emerge between subjects with and without ADHD across different sensory modalities, a MANOVA was conducted, with 2 groups (ADHD subjects vs control subjects) and 6 Sensory Modalities (Taste/Smell Processing, Movement Processing, Visual Processing, Touch Processing, Activity Level, Auditory Processing). Finally, post-hoc analyses were conducted using t-tests with Cohen's d effect size (Cohen, 1988) to assess group differences. To address the issue of multiple comparisons, a post hoc analysis was conducted by applying Bonferroni's correction when comparing both the scores of the four quadrants of the Sensory Profile and the scores across different sensory modalities between the ADHD and control groups. In both cases, significance was attributed solely to the level $p < .005$.

4. Results

Fig. 1 shows the means and standard deviations for each component of the sensory profile: low registration, sensation seeking, sensory sensitivity, and sensation avoiding. The Group exhibited significant effects, $F(1, 124) = 87.64$, $p < .001$, $d = 0.98$. The ADHD group consistently displayed higher scores across all four components of the sensory profile compared to the control group. Specifically, the ADHD group had significantly higher scores in low registration, $t = 9.78$, $p < .001$; sensation seeking, $t = 5.70$, $p < .001$; sensory sensitivity, $t = 8.73$, $p < .001$; and sensation avoiding, $t = 7.79$, $p < .001$. Results indicate significant effects of sensory modalities, $F(5, 620) = 161.931$, $p < .001$, but no significant interaction between groups and sensory modalities.

These findings are further confirmed by the prevalence results. As shown in Table 1, individuals with ADHD have a higher prevalence of scoring higher in all sensory components compared to most people, which is higher than the control group.

Regarding sensory modalities, Fig. 2 displays the means and standard deviations for taste/smell processing, movement processing, visual processing, touch processing, activity level, and auditory processing. The Group exhibited significant effects, $F(1, 124) = 57.89$,

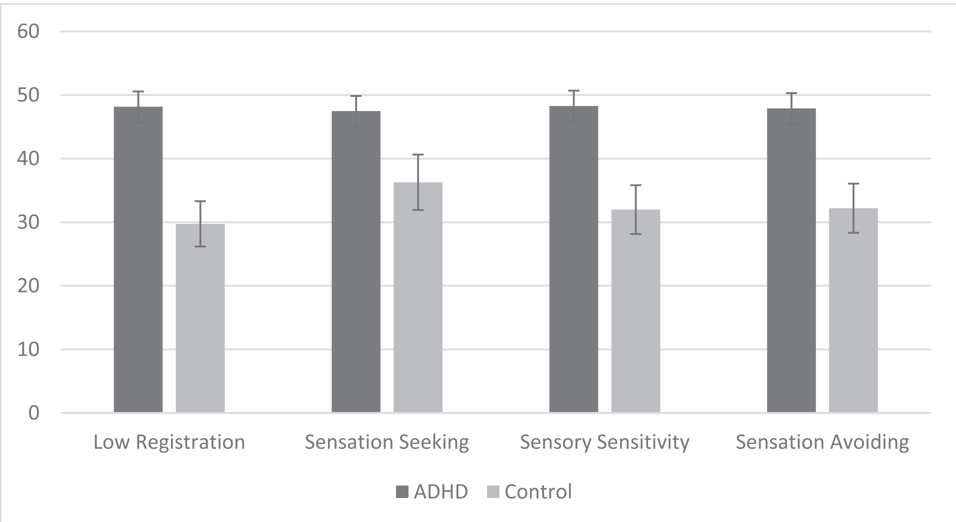

Fig. 1. Means and standard deviations for each component of the sensory profile measured with ASP: low registration, sensation seeking, sensory sensitivity, sensation avoiding.

$p < .001$, $d = 0.97$. Significant group differences were observed for each variable across all sensory modalities. Specifically, the ADHD group reported significant higher scores than control group in taste/smell processing, $t = 6.37$, $p < .001$; movement processing, $t = 6.99$, $p < .001$; visual processing, $t = 6.95$, $p < .001$; touch processing, $t = 6.28$, $p < .001$; activity level, $t = 9.20$, $p < .001$; and auditory processing, $t = 10.31$, $p < .001$.Fig. 3.

5. Discussion

The aim of this study was to assess differences in self-reported sensory experiences, investigating for sensory processing components and modalities, in subjects with and without ADHD matched for gender, age and IQ.

Three significant findings emerged from this research. Firstly, it was demonstrated that individuals with ADHD exhibit an atypical sensory profile compared to those with typical development. Secondly, significant differences were found in all sensory components (low registration, sensation seeking, sensory sensitivity, sensation avoiding). Thirdly, significant differences were observed in sensory processing between individuals with and without ADHD across different sensory modalities (taste/smell, movement, vision, touch, activity level, hearing).

5.1. *Sensory components in ADHD*

Consistent with the findings of Clince et al. (2016), individuals with ADHD obtained significant scores on all four sensory components of the Adolescent Sensory Profile (ASP) (Dunn, 1999). It is important to note that the results of this study seem to indicate that adolescents occupy high positions in every quadrant of the model, even though theoretically these quadrants should be orthogonal and independent of each other. This apparent inconsistency with Dunn's model could be explained by the possibility that adolescents might be placed in different positions within each quadrant depending on the sensory modality involved. However, the sample size was not sufficiently large to conduct a detailed statistical analysis of all possible combinations of quadrants and sensory modalities. The scores obtained in the low registration component highlight difficulties in quickly responding to stimuli, especially those that are less salient or weak. Although this characteristic may be considered advantageous in terms of maintaining good concentration, it is possible that important stimuli may be missed. Individuals who score high in sensory sensitivity have difficulty in rapidly responding to low-threshold stimuli, resulting in a propensity to be easily distracted (Dunn et al., 2022; Sanchis-Asensi et al., 2022). The combination of high scores in both the low registration and sensory sensitivity components suggests that individuals with ADHD may simultaneously notice and miss stimuli. Consequently, they may exhibit seemingly irregular and unpredictable behavioral responses or, in some cases, may not be able to modulate their environment. Consistent with the findings of Bijlenga et al. (2017), individuals with ADHD obtained high scores in the sensation seeking component. This indicates a tendency to seek opportunities to enhance sensory experiences that are perceived as pleasurable. However, these individuals easily become bored in unstimulating environments and tend to seek stimuli that may be distracting to others (Ohta et al., 2020; Schulz et al., 2023). Contrary to the findings of Kamath et al. (2020), individuals with ADHD also reported high scores in the sensation avoiding component. This discovery suggests that individuals with ADHD may be more overwhelmed or bothered by stimuli compared to individuals with typical development, and they may be less aware of how sensory information influences their daily lives.

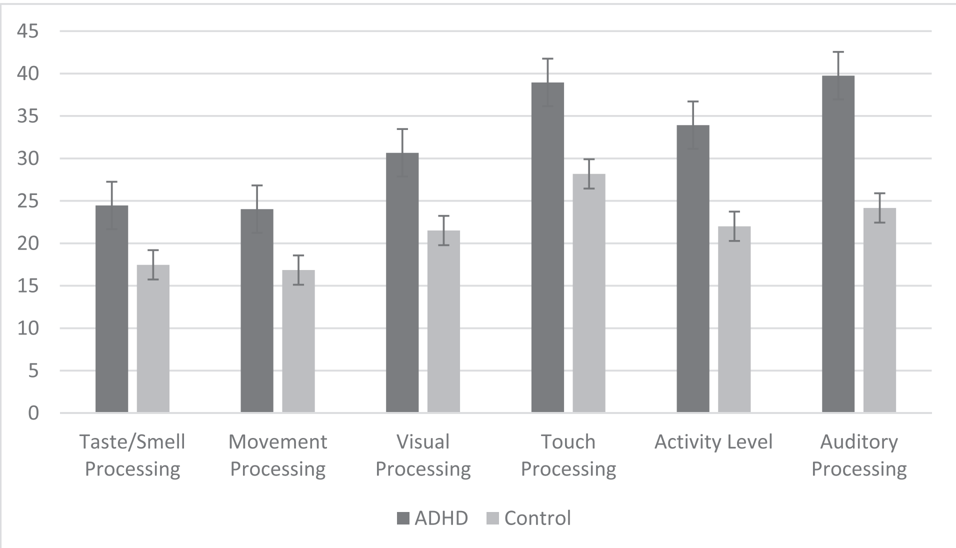

Fig. 2. Means and standard deviations for each sensory modality measured with ASP: taste/smell processing, movement processing, visual processing, touch processing, activity level, auditory processing.

Fig. 3. Sequential breakdown illustrates how sensory alterations can have cascading effects on cognitive processes. [1]*Atypical sensory processing in individuals with ADHD.* [2]*Resulting from sensory alterations, individuals may experience an overwhelming amount or insufficient sensory information from various sources.* [3]*Sensory overload disrupts the ability to automate behaviors and process information efficiently without conscious effort.* [4]*Due to deficits in automatization, controlled cognitive functions in cortical areas must work harder to compensate.* [5]*The increased cognitive effort and compensation can lead to deficits in various cognitive abilities, including attention, memory, and impulse control.*

5.1.1. Sensory modalities in ADHD

In addition to the sensory components, the current study found significant differences between individuals with and without ADHD in relation to all the sensory mode indices. The literature examining specific sensory modes in individuals with ADHD is ambiguous and difficult to summarize due to widely varying methods, samples, and outcome measures. To our knowledge, only one previous study has examined mode indices with a non-ADHD control group for comparison, and it found no significant differences in taste/smell processing (Kamatha et al., 2020). In our study, significant differences in taste/smell processing also emerged. The current results suggest that individuals with ADHD may process stimuli differently than those without ADHD across all sensory modes.

5.1.2. Theoretical explanations

Based on the Cumulative and Emergent Automatic Deficit (CEAD) model, the results of this study on sensory processing in ADHD and control groups can be interpreted in the context of deficits in automation and sensory processing. The CEAD model suggests that atypical sensory processing in individuals with ADHD hinders their ability to automate behaviors and efficiently process information without conscious effort. The findings of this study indicate that individuals with ADHD exhibit variations in sensory processing, as evidenced by higher scores in sensory sensitivity and sensation avoiding compared to the control group. These sensory processing difficulties can disrupt the automatization of basic knowledge, leading to increased cognitive load and impairments in controlled processes. The deficits in automatic-subcortical functions, specifically within frontal/basal-ganglia circuits and the cerebellum, contribute to both automatic and controlled process deficits in ADHD. The observed group differences in sensory modalities, including taste/smell processing, movement processing, visual processing. touch processing, activity level, and auditory processing, align with the CEAD model's predictions regarding variations in brain structures involved in sensory and automatic processing and confirm the atypical coding pattern (Fabio, 2017; Mohammadhasani et al., 2020). Additionally, Johnson's theory (2017) suggests that early sensory experiences influence brain development and can give rise to distinct profiles of abilities, disabilities, and behaviors. In this context, it is plausible to infer that atypical sensory experiences in adolescents with ADHD may exert different influences on brain development compared to their non-ADHD peers.

The CEAD model and Johnson's theory together can better explain the results: sensory alterations in individuals with ADHD can lead to atypical reception and processing of information from the surrounding environment. In simple terms, their senses may perceive things differently than those without ADHD. This can lead to a kind of "sensory overload" where the individual receives too much or too little sensory information from different sources. When sensory information is not processed correctly due to sensory alterations, the input reaching the brain can be distorted or less reliable. This makes it difficult for the individual to create accurate mental representations of the world around them. In the context of automating information automation refers to the ability to perform tasks or processes without having to dedicate much conscious attention to them. This ability is often based on experience and repeated learning. However, if sensory input is distorted or unreliable due to sensory alterations, automating this information becomes more challenging. Controlled cognitive functions, involving the cortical areas of the brain responsible for processing more complex information, must therefore work harder to compensate for this lack of automation. This can result in increased mental fatigue, influencing cognitive abilities such as attention, memory, and impulse control.

In short, sensory alterations directly impact the input reaching the brain, making the automation of information difficult and putting pressure on controlled cognitive functions, thereby affecting cognitive abilities and the cortical areas involved in such processes.

5.1.3. Strengths and limitations of the present study

There are several strengths of the present research. Firstly, our study is noteworthy as it is the first to assess differences in sensory processing among adolescents with and without ADHD. Secondly, various aspects of sensory processing, such as sensory components and modalities, were evaluated. Lastly, the sensory processing scores of individuals with ADHD were compared to scores obtained from a control group consisting of individuals with typical development.

The present study also has some limitations. The obtained results were interpreted using the ASP Manual as a guide; however, the interpretation is based on group data. This approach may not fully capture individual nuances in sensory processing. The ideal use of the ASP is to interpret scores on an individual basis and in accordance with a clinical history. In future studies, it could be useful to integrate group data analysis with individual assessments based on comprehensive clinical histories. A second limitation is due to the sample size, which prevented the assessment of gender differences and could affect the generalizability of the results. Future studies could address this issue by increasing the sample size and carefully assessing potential gender differences in sensory processing, enabling better representativeness, and understanding of the data. Additionally, the lack of adequate matching between the experimental and control groups in terms of age and intelligence quotient (IQ) scores could impact the comparability of the groups. Although the group with ADHD was selected through the administration of the ARSR scale and the presence of symptoms was further confirmed through a clinical interview, it should be noted that the fact that the ADHD sample had not received a formal diagnosis previously represents another limitation of our study. In future studies, it is suggested to include a formal clinical assessment to confirm the presence of ADHD, thus ensuring greater validity of the results. Research findings highlight high levels of comorbidity between Attention Deficit Hyperactivity Disorder (ADHD) and various other disorders, including Learning Disorders, Anxiety and Mood Disorders, Behavioral Disorders, Aggression, and Autism (Hours et al., 2022; Koyuncu et al., 2022). However, co-occurring conditions with other disorders were not evaluated in the present study. Considering the current findings, the research field should be further explored through investigations of sensory processing in individuals with ADHD, studying individual ADHD symptoms as well as the presence of any co-occurring disorders.

6. Conclusion

In summary, this study provides substantial evidence of the association between ADHD and atypical sensory processing in adolescents. These findings lend support to the theoretical perspectives of CEAD and Johnson, highlighting the significant role of sensory experiences in the development and manifestation of ADHD symptoms. This is important because sensory processing influences daily functioning and participation in academic environments, leisure activities, and social interactions (Harrison et al., 2019; Fabio et al., 2020; Kerley et al., 2023). These findings also have significant implications in the educational field. Atypical sensory processing contributes to explaining the discrepancies between intellectual abilities and academic performance in students with ADHD. Understanding strengths and weaknesses in sensory processing and attention is necessary to design better classroom environments and develop more effective accommodations and interventions to support optimal success (Wood, 2020; Panagiotidi et al., 2020). Understanding the interplay between sensory processing, automatization, and ADHD symptoms can inform the development of targeted interventions and therapeutic strategies. By addressing sensory processing difficulties and promoting automatization of basic knowledge, it may be possible to alleviate cognitive load and improve cognitive functioning in individuals with ADHD, ultimately enhancing their daily functioning and quality of life.

Ethics approval

Approval was obtained from the ethics committee of University of Messina. The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Consent

Informed consent was obtained from all individual participants included in the study.

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CRediT authorship contribution statement

Fabio Rosa Angela: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Suriano Rossella:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing. **Levante Annalisa:** Data curation, Investigation, Resources. **Lecciso Flavia:** Data curation, Investigation, Resources. **Orsino Caterina:** Investigation.

Declaration of Competing Interest

The authors declare no conflict of interest. The authors have no financial or proprietary interests in any material discussed in this article.

Data Availability

Data will be made available on request.

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