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EDITED BY
Valentina Parma,
Monell Chemical Senses Center, United States

REVIEWED BY
Antonia Cascales-Martinez,
University of Murcia, Spain
Ángel Freddy Rodríguez Torres,
Central University of Ecuador, Ecuador
Elisa Dal Bò,
University of Padua, Italy

*CORRESPONDENCE
David Pérez-Jorge
✉ dpjorge@ull.edu.es

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Electrodermal response to olfactory stimuli in children with autism spectrum disorder: a systematic review of emotional and cognitive regulation

David Pérez-Jorge[1]*, Elena Olmos-Raya[1], Isabel Alonso-Rodríguez[1] and Itahisa Pérez-Pérez[2]

[1]Department of Didactics and Educational Research, DISAE Research Group, University of La Laguna, San Cristóbal de La Laguna, Spain, [2]Department of History and Philosophy of Science, Education, and Language, DISAE Research Group, University of La Laguna, San Cristóbal de La Laguna, Spain

Introduction: The study of electrodermal activity (EDA) in individuals with Autism Spectrum Disorder (ASD) is gaining scientific interest as a potential source of physiological biomarkers that can objectively improve the diagnosis of this condition. Despite significant research into responses to visual and auditory stimuli, the response to olfactory stimuli has not been extensively explored.

Methods: This research involved a systematic literature review of studies on EDA responses to olfactory stimuli in ASD populations, published between 2000 and 2024. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a rigorous and transparent methodology. From the selected scientific databases, such as Scopus and Web of Science, 20 publications met the inclusion and exclusion criteria for detailed analysis.

Results: The analysis revealed that individuals with ASD display distinct electrodermal patterns compared to the typically developing population, especially in response to intense and emotionally evocative odors, which elicited the highest electrodermal reactivity.

Discussion: The pronounced electrodermal response to specific odors suggests that EDA could serve as a reliable physiological measure for predicting emotional states in individuals with ASD. This capability provides educators with valuable insights, allowing them to tailor educational strategies to the unique emotional needs of each moment, thereby optimizing the teaching and learning process.

KEYWORDS

electrodermal activity, autism spectrum disorder, sensory processing, sympathetic nervous system, galvanic skin response, learning processes, sensory modulation

1 Introduction

Autism Spectrum Disorder (ASD) is a condition linked to the so-called Neurodevelopmental Disorders with the presence of difficulties in social interactions, communication skills, imagination, and the presence of repetitive or stereotyped behaviors (Wing and Gould, 1979), as well as the presence of dysregulation of sensory channels (O'Neill and Jones, 1997), which allows the needs of those affected to be classified according to the severity of the symptomatology. This helps professionals who care for this group have a guide to specify each person's support (American Psychiatric Association, 2013). Implicit measures such as electrodermal activity (EDA) establish markers well suited to complete diagnosis, improve therapeutic intervention, and adapt educational

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settings (Lieberman, 2010). In the framework of studies on students with ASD, in recent years, there has been growing interest in analyzing the so-called implicit measures. This interest is due to new perspectives considering ASD as a spectrum with greater variability between individuals than had been considered until now (Del Valle Rubido et al., 2018). These new approaches suggest that these measurements may suggest quantitative markers that allow the identification of these students according to different biological subtypes (Loth et al., 2017; Yan and Jia, 2022). Physiological signals such as EDA (Schupak, 2014), heart rate (Billeci et al., 2018), and eye tracking have been applied to look for a link between ASD symptomatology and these measures. However, there is no consensus on the link between the two in the case of EDA (Lydon et al., 2014).

EDA, also known as Galvanic Skin Response (GSR), is the body's unconscious electrodermal response in the form of sweating, a measure provided by constant variations in the electrical characteristics of the skin (Benedek and Kaernbach, 2010). This response occurs in emotionally charged situations or the presence of an external stimulus (Fagius and Wallin, 1980). It is an indicator of the sympathetic nervous system (SNS) activity, and its activation involves an increase in the metabolic system, which is associated with both internal and external stimuli (Critchley, 2002). EDA can reflect boredom, fear, or surprise in addition to other emotions (Jang et al., 2019). The EDA measure is elicited in two phases: (a) the Tonic Phase (SCL) and (b) the Phasic Phase (SCR). The first is slow and is not associated with an external stimulus. It indicates the degree of general arousal of a person. The second is faster and is associated with an external stimulus (Venables and Christie, 1980). In addition to the SCL and SCR phases, the Ratio can be calculated, which is a way of controlling for baseline values, which show the level or response as a function of the task (Olmos-Raya et al., 2023) and non-specific skin conductance responses (NS-SCR), which reflect discrete, spontaneous increases in skin conductance in the absence of any external stimulus (Dawson et al., 2017).

Understanding the type of analysis (Li et al., 2022) of how the different phases of EDA (SCL and SCR) and the Ratio measure relate to ASD symptomatology may provide a clearer and more quantifiable view of the autism spectrum, thus allowing for better matching of interaction and relational patterns.

2 Response to olfactory stimuli in children with ASD

The sense of smell is active from an early age, alerting to stimuli that can harm the person. With experience, we learn to discriminate noxious odors from those that are not, giving them meaning (Stockhorst and Pietrowsky, 2004). In the case of people with ASD, the development of the sense of smell is little studied, despite the relationship that this sense has with brain areas responsible for social behavior and emotion management. These aspects are altered in people with ASD (Boudjarane et al., 2017).

Few research studies have included the sense of smell in analyzing electrodermal measurements. Only one study has specifically included olfaction, finding significant differences between experimental and control groups (Legiša et al., 2013), despite a discrepancy between subjective perception and physiological and behavioral responses in children with ASD. The study highlights the importance of using multiple methods to assess emotional reactions in this population, given that self-assessment itself may not fully reflect their emotional experiences.

While Legiša et al. (2013) provided a comprehensive approach to emotional responses to odors, the studies by Ashwin et al. (2014) and Wicker et al. (2016) focused more on the perception and neurobiology of olfactory processing in individuals with ASD.

Other studies combined visual, auditory, olfactory, tactile, and vestibular sensory channels under the common denominator of being investigations conducted in laboratory settings, where participants were exposed to visual (flashes of light), auditory (tones or sirens), olfactory (wintergreen oil), tactile (feathers), and vestibular (rocking on the edge of a chair) sensory cues (Legiša et al., 2013; McCormick et al., 2016; Schoen et al., 2008, 2009). Although these studies presented low ecological validity derived from experimental control in laboratory settings (Loomis et al., 1999), they were pioneering in looking for a relationship between ASD symptomatology and electrodermal activity using SCL, finding no significant differences or correlations with sensory-based diagnostic batteries (McCormick et al., 2016).

The findings of McCormick et al. (2016) were replicated by Fenning et al. (2017) and Prince et al. (2017) using similar sensory tasks. These studies reported greater electrodermal activation in the presence of greater ASD symptomatology, such as increased anxiety and stress and repetitive and stereotyped behaviors. Fenning et al. (2017) observed that children with more severe symptoms had more pronounced variations in their electrodermal activity, suggesting a correlation between symptom severity and physiological response. Prince et al. (2017) also found that a greater presence of repetitive and stereotyped behaviors was associated with greater electrodermal activation. However, both studies excluded the sense of smell in their assessments, focusing on other types of sensory stimuli. This underscores the need to investigate further the specific impact of olfactory stimuli on electrodermal and emotional responsiveness in children with ASD.

Generally, the study of the sense of smell in people with ASD has been measured through questionnaires. Few studies have used AEDs to measure reactions to olfactory stimuli. Instead, this physiological measure has been studied with auditory and olfactory stimulation (Thye et al., 2018). This is a gap in the literature, as the sense of smell is critical for discriminating the odors we are exposed to daily. In the case of people with ASD, it would provide insight into the reaction to these stimuli, which could help to interpret emotional reactions to them (Chen et al., 2025; Boudjarane et al., 2017).

These alterations affect emotional regulation, sensory perception, and learning, so studying the electrodermal response to olfactory stimuli is necessary to understand better this group's sensory particularities (Thye et al., 2018).

Rozenkrantz et al. (2015) discovered a possible marker for ASD diagnosis based on olfactory processing. While neurotypical children adjust their sniffing according to odor valence within milliseconds, children with ASD do not show this adaptation. This difference in response made it possible to predict the diagnosis of ASD with 81% accuracy. Furthermore, the severity of the disorder was correlated with more significant impairment in the sniffing pattern, particularly in social domain scores.

Recent contributions have focused on using virtual contexts where various odors were included but measured only by direct observation of the therapists (behavioral and motor response). They have left aside electrodermal measurement and concluded that olfactory stimuli helped to create a more immersive and ecologically valid environment (Minissi et al., 2024).

3 Importance of EDA for improving learning processes in children with ASD: response to smells

Recent research has begun to explore further the impact of olfactory stimuli on the emotional and physiological state of children with ASD. These studies have revealed that certain odors can have a significant impact on the modulation of emotional and physiological states; this is especially relevant in the educational context of children with ASD. Laohakangvalvit et al. (2023) found that certain odors significantly affect the modulation of emotional and physiological states. In the case of children with ASD, understanding the impact of odors on their emotional and physiological state can be crucial for designing effective educational strategies (Greco et al., 2021). For example, calming odors could help reduce anxiety and improve concentration during school activities. It can predict classroom performance (Yu et al., 2024) and even influence difficulties such as language development (Lorang, 2022).

In addition, Shikha et al. (2024) claimed that citrus odor could improve responsiveness and cognitive performance. Incorporating pleasant aromas such as citrus in the learning environment could help children with ASD better manage cognitive loads and improve their performance on academic tasks. These findings support the idea that creating sensory-enriched environments can facilitate better educational responsiveness and enhance the learning experience for students with ASD. Fekri Azgomi et al. (2023) showed that auditory, gustatory, and olfactory stimulation affect cognitive processes in the brain. The results showed that each type of sensory stimulation can significantly influence cognitive states, reflected in measurable changes in brain activity and physiological responses. Modulating cognitive states through sensory stimuli could be a valuable tool in educational settings to improve these students' attention and academic performance. This is particularly relevant for children with ASD, who often face challenges with sensory regulation. Educators could create more inclusive and optimized learning environments by identifying and applying each child's most effective sensory stimuli.

In an educational setting, applying specific scents could be a strategy to regulate emotions and improve attention in children with ASD (Berčík et al., 2021). Careful manipulation of olfactory stimuli could help to create a more comfortable environment conducive to learning.

Ezzameli and Mahersia (2023) highlighted the importance of multimodal analysis for emotion recognition. In the educational setting, implementing emotional recognition systems can help teachers better understand the emotional state of students with ASD in real time. This understanding can enable more accurate and timely interventions, adapting the learning environment better to meet these students' emotional and cognitive needs.

3.1 Visual and auditory vs. olfactory stimuli: previous studies

Visual and auditory processing in the ASD population has been extensively studied using EDA as a measure. Suppose we review the previous literature on EDA and its relationship with visual stimulation. In that case, we can see that since 1999–2000, studies on EDA reactivity to the presence of images have begun to be published. We found studies focused on monitoring EDA in the presence of faces or emotional images (Blair, 1999; Cohen et al., 2013; Hirstein et al., 2001; Riby et al., 2012; Shalom et al., 2006). The results were not unanimous. On the one hand, the ASD population was found to be more reactive to threatening images (Blair, 1999; Cohen et al., 2013) and less reactive to faces (Hirstein et al., 2001). In contrast, Riby et al. (2012) and Shalom et al. (2006) found no differences.

Electrodermal activity has also been studied in the presence of images with faces with direct or avoidant gaze (Kaartinen et al., 2012; Kylliäinen and Hietanen, 2006; Joseph et al., 2008; Kylliäinen et al., 2012). While Kylliäinen and Hietanen (2006) found that electrodermal reactivity increased as eye opening increased, authors such as Kaartinen et al. (2012) did not.

If we focus on auditory stimulation and ASD, there are many studies on auditory processing (Palkovitz and Wiesenfeld, 1980; Stevens and Gruzelier, 1984; Van Engeland, 1984), and its relationship to attention and cognition (Zahn et al., 1987), auditory sensitivity (Chang et al., 2012) and emotional response to musical stimuli (Allen et al., 2013). Studies showed varying results; Palkovitz and Wiesenfeld (1980) observed that children with ASD showed a higher electrodermal response at the first baseline compared to the control group, but no significant differences were observed in response to different auditory stimuli presented, including standard tones and phrases with social content. Similarly, Chang et al. (2012) stated that children with ASD had a higher SCR at baseline and in response to standard tone, suggesting greater basal autonomic activation in this group.

On the other hand, Stevens and Gruzelier (1984) found that people with ASD had delayed signal registration and increased activation in response to the first tone, which may reflect difficulties in modulating the sensory response. Van Engeland (1984) also reported a delayed response to acoustic stimulation, although he found no baseline differences between the groups tested. These findings contrast with those of Palkovitz and Wiesenfeld (1980), who found no marked difference in response to auditory stimuli except for initial activation.

All these studies have identified differential patterns in sensory reactivity, showing a hyper- or hypo-response to visual and auditory stimuli, depending on the type of stimulus presented. However, research on the influence of olfactory stimuli on sensory processing using electrodermal measurements is scarce.

The absence of such studies represents a significant gap in the importance of the sense of smell in emotional regulation (Kadohisa, 2013), environmental perception, and social interaction. This has limited the comprehensive understanding of sensory perception in people with ASD, as sensory hyper- or hypo-reactivity is a key diagnostic criterion in ASD. This reality emphasizes the need to investigate and understand the reality of research in this area and justifies the present systematic review.

4 Problem statement

A review of the research on the response to olfactory stimuli in children with ASD is needed because of the growing evidence that sensory stimuli, particularly olfactory stimuli, can significantly impact these children's emotional and cognitive states. Current studies indicate that integrating olfactory stimuli into the educational environment can improve emotional regulation, reduce anxiety, and increase attention and academic performance. However, research in this area is still in its infancy, and a deeper and broader understanding is needed to develop effective and personalized educational strategies that address the specific needs of children with ASD. Combining physiological measurement techniques, such as EDA, with response to olfactory stimuli offers an opportunity to obtain more accurate and reliable data on these children's emotional and cognitive reactions, allowing the design of more effective and evidence-based interventions. Therefore, a systematic literature review can provide a solid basis for future research and practical applications in the educational setting, improving the quality of life and learning opportunities of children with ASD.

Therefore, the present study highlights the lack of scientific literature integrating implicit measures such as the electrodermal response of people with ASD to olfactory stimuli. This study is a starting point for the search for an objective marker of the condition that does not only involve visual, auditory, or tactile channels. This study, which aims to understand the reaction of children with ASD to odors, may contribute to understanding some of their reactions in the school context. Knowledge of the conditions of electrodermal reactivity in the school context will allow teachers to adapt learning conditions and spaces to the characteristics and needs of students with ASD. Knowledge of the stimuli that produce electrodermal reactivity will guarantee an educational response adapted to the characteristics of these children.

5 Objectives

This study aimed to deepen the understanding of the electrodermal response of people with ASD to olfactory stimuli exposure as a strategy to adapt the educational context to the psychoemotional characteristics of students with this profile. Based on this general objective, the following specific objectives were proposed:

1. To investigate the differences in the electrodermal response to olfactory stimuli in individuals with and without ASD and better understand their sensory and reactive particularities.
2. To deepen our understanding of the importance of the electrodermal response to olfactory stimulation in the learning process of the ASD population.

6 Methodology

6.1 Selection criteria

To achieve our objective, the search for papers focused on using olfactory stimuli monitored through EDA as a marker to differentiate people with ASD from the rest of the population. We examined articles involving children and adults in real and simulated contexts through applications or technological environments. To ensure an adequate and rigorous literature review, well-defined inclusion and exclusion criteria were established to determine the search equations (see Table 1).

A mixed and interpretative methodology was used following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement. This approach was based on the review of scientific literature to reach objective conclusions and provide robust evidence. In this way, the aim is to open new lines of research to deepen and clarify the relationships between the implicit responses of the ASD population to olfactory stimulation and to extrapolate these results to the educational context. The scarce existing scientific literature on the electrodermal response to olfactory stimulation and the few systematic reviews in this field justify the importance of the present review.

6.2 Literature review

To ensure the appropriateness of the studies considered, we first identified keywords related to the subject of this systematic review, using Boolean AND/OR to structure the search.

Keywords related to this review's focus were identified and used to ensure the appropriateness of the studies considered in this systematic review.

Initially, the combination of search terms was: (electrodermal activity OR galvanic skin response OR skin conductance) AND (autism OR autistic disorder OR ASD OR Autism Spectrum Disorder) AND (odor OR smell OR olfactory stimulus). This initial search yielded a low number of articles that did not fit the objectives of this review study. After several attempts and adjustments to the equation, the equation was formed as follows; (electrodermal activity OR galvanic skin response OR skin conductance OR sweat

TABLE 1 Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
• Studies in English and Spanish. • Published from 2000 to the present to ensure the relevance and timeliness of the data. • Clinical trials evaluating the electrodermal response to sensory stimuli (visual, auditory, and olfactory) in the ASD population. • Studies providing quantitative or qualitative data on EDA reactivity in sensory contexts.	• Studies in languages other than English and Spanish. • Non-peer-reviewed studies, such as theses, dissertations, and conferences, to maintain the data's quality and credibility. • Articles that did not focus specifically on electrodermal reactivity to sensory stimuli in the ASD population. • Meta-analyses, systematic reviews, and critical reviews. • Publications with study population with pathologies other than ASD.

response) AND (autism OR autistic disorder OR ASD OR Autism Spectrum Disorder OR developmental disorder) AND (odor OR smell OR scent OR fragrance OR olfactory perception OR olfactory stimulus OR sensory processing).

6.3 Procedure

The exhaustive search was conducted from December to March 2024 using keywords and the same Boolean operators OR/AND as in the initial search. Inclusion criteria were then applied, eliminating those documents that did not meet them. The Mendeley bibliographic manager was used to eliminate duplicate texts. Subsequently, and through reading titles and abstracts by two independent judges, the studies that met the inclusion criteria were selected. A complete reading was carried out of the selected texts, and a final decision on the selection or rejection of the texts was made after reading the abstract. After this, the content analysis of the nine selected studies was carried out. The analysis was performed on the objectives, sample, methodology, main results, and conclusions of the studies.

To ensure the quality of the selected articles, rigorous criteria were established, including blind peer review and publication in relevant journals in the field. In addition, the robustness of experimental methods and compliance with ethical standards were assessed. The selection of databases was based on their broad scientific coverage, access to high-impact publications, and their specialization and thematic specificity.

7 Results

A total of 79 articles were obtained in Scopus and 14 in WoS, for a total of 93 results, eliminating 21 duplicates. Inclusion and exclusion criteria were applied based on the title and abstract, eliminating 42 articles. The remaining 30 full texts were read, and 21 papers were discarded. The final sample of studies consisted of a total of nine papers (See Figure 1). A detailed search of the scientific literature is shown in Tables 2, 3.

Regarding the number of articles, a higher percentage of publications is observed in 2020 ($N = 2$) and 2023 ($N = 2$), each representing 22.2% of the total. The remaining publications are distributed as follows: 11.1% in 2008 ($N = 1$), 11.1% in 2009 (N

TABLE 2 Overall results of the searches performed.

Category	Scopus	WOS
Articles	79	14
Reviews	14	0
Books	17	0
Chapters	2	0
Proceeding	3	0
Found	115	14
Excluded	108	12
Included	7	2

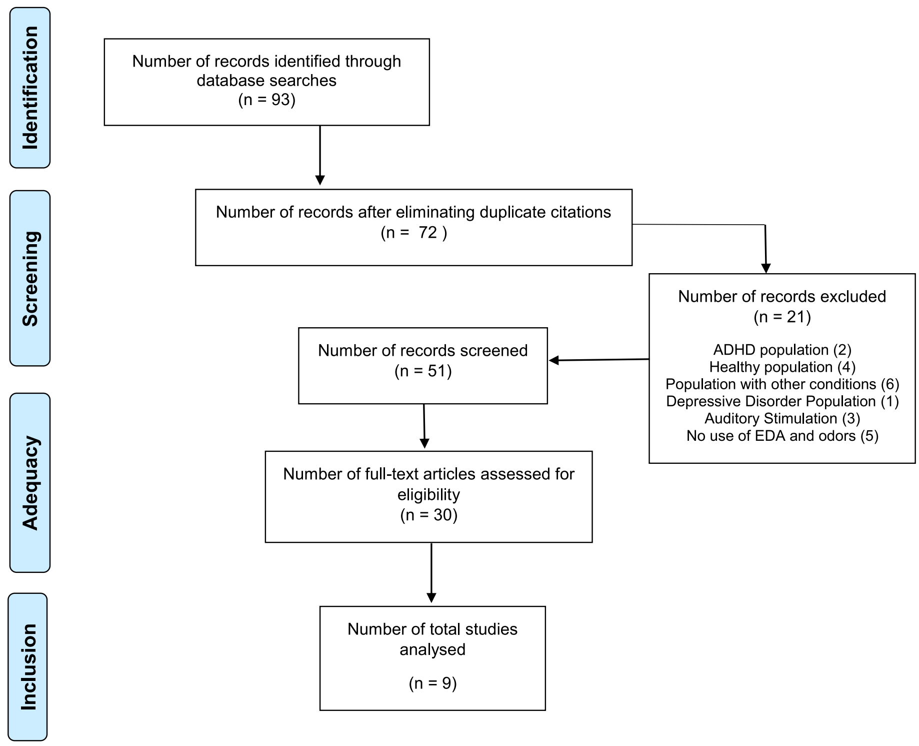

FIGURE 1
Flow diagram.

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TABLE 3 Articles included in the review.

Author	Objectives	Sample	Country	Olfactory stimulus	Experimental context	Technology used	Method/ approach	Procedure	Mean used and EDA analysis	Results
Schoen et al. (2008)	Study the EDA's reliability to characterize sensory reactivity and variability in ASD, Asperger's disease	$N = 38$ Age = 9.15 Groups: 2 (TEA: 11; Aperger: 27) Males 83% Female 17% Male Females 17% (%)	United States	Wintergreen oil in bottle	Experimental laboratory context Spaceship decoration with three-dimensional panels	Sistema PSYLAB (Contact Precision Instruments, Cambridge, MA) Sampled a 1,000 Hz	Two sessions (6 months), 1st evaluation TEA and 2nd evaluation EDA Sensory challenge protocol (Miller et al., 1999) Descriptive *T*-Test Pearson correlation Intraclass correlation coefficient	Seated participant, placement of palmar electrodes while viewing a movie, 3 min baseline, 48 sensory stimuli (12–19 s and 20 s in between), 3 min recovery time	LB (3 min) SCL and NSR (no. of responses 4–10 s/no. min observed) SCR (magnitude, latency, and recovery) (>0.02 mS*, interval 0.8–4.0 s after stimulus) (Boucsein, 1992; Dawson et al., 2000)	Feasibility: 95% of the sample Test-retest reliability: moderate SCL and NSR. SCR: magnitude and latency high There are no significant differences between SCL and SCR between groups Positive correlation between SCL LB and SCL recovery Positive correlation between SCL baseline and SCR magnitude (MAG) less in motion (higher arousal levels at baseline tend to have more intense responses to sensory stimuli) Negative correlation SCL baseline and SCR latency (LAT) less tactile and olfactory (higher arousal levels at baseline faster responses to sensory stimuli) Groups with higher LB SCL showed slower habituation throughout the experiment than groups with lower LB SCL
Schoen et al. (2009)	To assess electrodermal patterns to sensory challenges in participants with ASD and sensory modulation disorder (SMD)	$N = 104$ Age = 8.35 Groups: 3 (TEA: 40; sensory modulation disorder (SMD): 31; typical development (TD) = 33]	United States	Mint odor	Laboratory (real). Spaceship decoration with three-dimensional panels	Sistema PSYLAB (Contact Precision Instruments, Cambridge, MA) Sampled a 1,000 Hz	Two sessions: diagnosis and EDA evaluation Short sensory profile Chi2 Bonferroni adjustments Correlation	Seated participant, placement of palmar electrodes 48 sensory stimuli, 3 s duration with an interval of 10–15 s between them	LB (3 min) SCR: Orientation (initial response amplitude) Magnitude (average of the amplitude of all responses from the LB to the stimulus) Amplitude (average of the amplitude of all responses from the LB to the stimulus, including 0) non-response (% non-response 2 first trials in 2 domains)	Age does not influence a variable. No differences between groups LB significantly less OER, males higher than females Orientation, magnitude, and breadth: olfactory response ASD inferiorly significant Short sensory profile: low olfactory responsiveness No significant correlations profile/SCR (orientation, magnitude, and breadth)

(Continued)

TABLE 3 (Continued)

Author	Objectives	Sample	Country	Olfactory stimulus	Experimental context	Technology used	Method/ approach	Procedure	Mean used and EDA analysis	Results
Legiša et al. (2013)	Reaction of ASD participants to pleasant and unpleasant odors with autonomic indicators	$N = 16$ Age = 11 Groups: 2 (TEA: 8; NT = 8)	Italy	Eight scents: vanilla, cheese, pink, green grass, mint, chlorine, sweat, and feces, presented in opaque glass vials 2–3 cm from the nostrils	School hall	Comprobador visual de energía Sistema de biorretroali-mentación Elemaya	EDA Heart rate Facial expressions Self-report Kruskal-Wallis Chi-square Wilcoxon • Pearson	Palmar electrodes. Random odor exposure, recordings at baseline, video recording for facial recordings, post-olfactory ratings. 20 min	Changes in heart rate and skin conductance during each stimulus compared to baseline Phasic: peak amplitude, number of peaks, and cumulative response over time	Amplitude: no differences Peaks: no differences, but NT had higher responses in mint and color compared to LB. TEA no increase The cumulative response over time increased to odor vs. no odor in both groups. Mind odor increased in NT and not in ASD Intensity: both groups perceived odors as intense Familiarity: familiar odors for both groups, but children with ASD are more familiar with odors of feces and sweat compared to TD* Identification: low overall Agreeableness: TD children's most unpleasant odors, ASD least unpleasant chlorine, sweat, and feces
Schupak et al. (2016)	Test-retest reliability of the EDA to measure sensory processing in ASD and TD participants	$N = 32$ Age = 26.2 Groups: 2 (TEA: 14; NT = 18)	United States	Oil of wintergreen in bottles	Laboratory (real). Spaceship decoration	PsyLab system Sampling rate 1,000 Hz	Two times within a period of 2–6 weeks Sensory challenge protocol (Miller et al., 1999)	Three electrodes on the chest and the left hand Eight conditions (six conditions with stimuli and two without stimuli) Order: baseline, tone, visual, siren, olfactory, tactile, movement, and recovery	SCL Non-specific response and SCR (magnitude, amplitude, and habituation)	Test-retest reliability of SCR amplitude under olfactory stimulus is moderate, higher in ASD than in TD Variability of responses between the two tests in the SD group TEA has a greater consistency of responses to the olfactory stimulus than TD
Endevelt-Shapira et al. (2018)	To study the interpretation of chemo social cues in the ASD and TD groups	$N = 40$ Age = 7.5 Groups: 2 (TEA: 20; NT = 20)	Israel	Sweat of fear, parachuting, and control (calm person). Use of pads	Laboratory	Not specified	EDA AQ Emotional stroop ANOVA Discriminant analysis Correlation	Palm electrodes 64 tests odor emitted from their nostrils	(ER-EDA) specific EDA responses to discrete stimuli presented during the tasks	Fear odor significantly increased EDA in TD but not TEA participants The discriminant analysis correctly labeled 16 of 20 TD participants and 12 of 20 TEA participants (70%) Lower EDA responses to fear are associated with higher AQ scores

(Continued)

TABLE 3 (Continued)

Author	Objectives	Sample	Country	Olfactory stimulus	Experimental context	Technology used	Method/ approach	Procedure	Mean used and EDA analysis	Results
Haigh et al. (2020)	To study EDA variability to visual stimuli (faces) and odors between participants with ASD and those with TD	$N = 36$ Age = 27.5 Groups: 2 (TEA: 17; NT = 19)	United States	Scary odor (parachute underarm pads) and neutral (clean absorbent pad). Both in one mask	Use of analogical stimuli (real)	PowerLab 16SP Sampled at 400 Hz	EDA Autism quotient (AQ) *T*-Test • Correlations	Palmar electrodes LB (video nature) 2 min. 27 faces (250 ms). Interval 30 s. 5 min video under olfactory conditions	LB Endevelt-Shapira et al. (2018) analysis EDA data/absolute maximum value Response amplitude (response in time period of maximum peak reactivity)	TEA: Average peak EDA no difference between conditions. Higher NT condition odor fear. No differences between groups TD peak response lower variability between conditions TEA, but no differences between groups Significant group x odor interaction in mean response amplitude, TEA less variability odor fear, no difference between groups in odor neutral AQ scores decrease as mean EDA increases in fear odor and marginal neutral odor only TEA. Maximum amplitude decreases with increasing age in NT Response variability: decreases as AQ score increases in neutral odor only TEA, marginal odor fear
Alcañiz Raya et al. (2020)	To study the recognition of ASD to visual, auditory, and olfactory stimuli	$N = 92$ Experiment 1 $N = 52$ Age = 4.87 Groups: 2 (ASD: 23; SD = 29) Experiment 2 $N = 40$ Age = 4.86 Groups: 2 (ASD: 17; TD = 23)	Spain	The smell of fresh grass and butter odor. Olorama Technology	Immersive virtual environment	Empathic E4	Wireless EDA Continuous decomposition analysis (CDA)	LB, visual stimuli, auditory stimuli, olfactory stimuli	The model included basal tonic, basal phasic, and phasic continuous decomposition analysis (CDA) methods	Forest visual stimuli obtained the highest accuracy (90.3%). When auditory and olfactory stimuli were introduced, this decreased to 75% The visual stimulus city obtained the lowest accuracy with all stimuli (70.59%)
DeBoth et al. (2023)	Exploring ASD subtypes vs. sensory responsiveness	$N = 55$ Age = 9 Groups: 2 (TEA: 27; NT = 28)	United States	Peppermint oil distance 2.54 cm	Laboratory context	PsyLab Software	Pre, during, and post-sensory challenge protocol Retrospective study secondary data EDA, SNA [respiratory sinus arrhythmia respiratory neuroendocrine response (salivary cortisol)]	Palm electrodes 48 sensory stimuli, eight repetitions of six sensory inputs (tone, olfactory, visual, auditory, tactile, vestibular) 15–20 min	SCL amplitude or magnitude, responses, and non-specific (NSR) (changes not associated with stimulus from LB)	There are no significant differences between sensory profile subtypes among ASD

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TABLE 3 (Continued)

Author	Objectives	Sample	Country	Olfactory stimulus	Experimental context	Technology used	Method/ approach	Procedure	Mean used and EDA analysis	Results
							sensory challenge protocol (Miller et al., 1999) ANOVA-MANOVA Sensitivity, specificity, positive predictive value, and negative predictive value tests			
Olmos-Raya et al. (2023)	This study aims to study the use of immersive virtual environments (IVEs) in conjunction with EDA to differentiate the ASD population in visual, auditory, and olfactory contexts	$N = 86$ Age = 4.9 Groups: 2 (TEA: 46; TD = 40)	Spain	Fresh grass scent Olorama Technology	Immersive virtual environment	Empathic E4	EDA ADOS-2 Kolmogorov-Smirnov U de Mann-Whitney	Empathic E4 wireless non-dominant hand LB, visual stimulus, auditory stimulus, olfactory stimulus 9.08 min	SCL, SCR baseline, and ratio (SCR/LB)	The frenetic activation in a greater olfactory stimulus TEA in measure ratio (SCR/LB)

SCL, Tonic; SCR, Phasic; NSR, non-specific tonic response (baseline average and recovery); *mS, Micro siemens.

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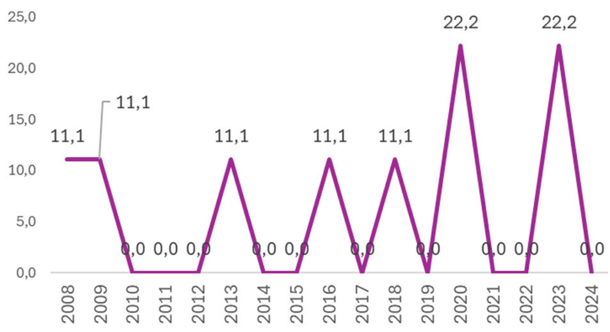

FIGURE 2
Percentage of publications by year.

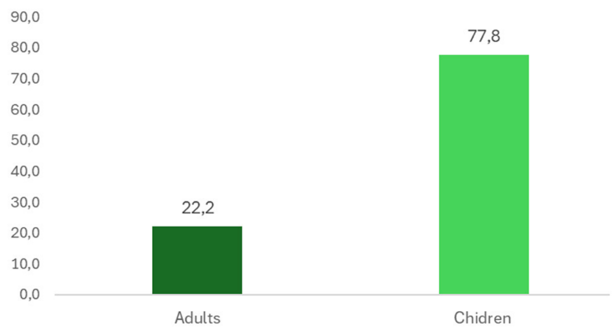

FIGURE 4
Percentage of publications by age of the sample.

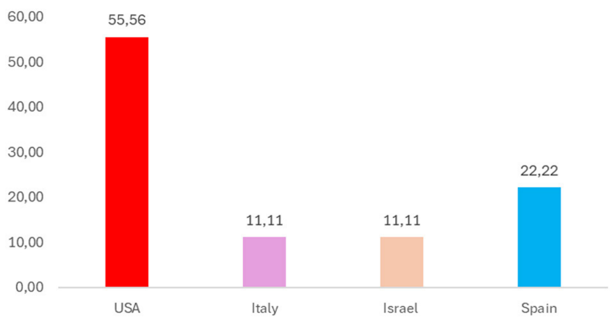

FIGURE 3
Percentage of publications by country.

= 1), 11.1% in 2013 ($N = 1$), 11.1% in 2016 ($N = 1$), and 11.1% in 2019 ($N = 1$), with a single publication in each of these years (see Figure 2).

As shown in Figure 3, the geographical distribution of the publications shows a notable prevalence in the USA, where 55.56% ($N = 5$) of the articles were produced. Spain follows with 22.22% ($N = 2$) of the publications. Italy and Israel each had 11.11% ($N = 1$) of the publications.

77.8% of the studies focused on children ($N = 7$), while 22.2% focused on adults ($N = 2$). This distribution highlights the importance of early detection of the condition, underlining the priority of research in child populations (see Figure 4).

The analyzed articles had a maximum of 104 participants in studies with children (M = 61.6; SD = 32.8) and 36 in studies with adults (M = 34.0; SD = 2.8). The minimum number of participants was 16 in studies with children and 32 in those with adults.

Regarding age, in studies with children, the maximum age of participants was 11 years, and the minimum was 4.8 years (M = 7.8; SD = 2.3). In studies with adults, the maximum age was 36 years, and the minimum was 32 years (M = 26.9; SD = 0.9) (see Table 4).

Regarding the objective of investigating the differences in the electrodermal response to olfactory stimuli in individuals with and without ASD and to understand their sensory and reactive particularities better, it is interesting to go further and note the progress in the objectives set out in each of the included studies in this paper. While Schoen et al. (2008) focused on finding differences in sensory processing between participants with ASD and Asperger's, Schoen et al. (2009) expanded their research to elucidate differences between the ASD population and patients with SMD. This progression in goals allowed them to build a solid foundation and further explore variations in sensory processing, providing a more detailed and nuanced understanding of the differences between these groups.

As studies progressed, Legiša et al. (2013) delved deeper into the differences within ASD between pleasant and unpleasant odors. Subsequently, possible differences between participants with ASD and TD were investigated in studies such as those by Endevelt-Shapira et al. (2018), Haigh et al. (2020), Olmos-Raya et al. (2023), and Schupak et al. (2016). More recent studies, taking advantage of technological advancement, have explored subtypes within the spectrum according to their sensory responsivity (DeBoth et al., 2023) and have employed machine learning techniques capable of predicting conditions (Alcañiz Raya et al., 2020).

Of the eight studies analyzed, 27% used peppermint and sweat, followed by 18% using wintergreen oil and fresh grass. The remaining olfactory stimuli, such as vanilla, cheese, rose, chlorine, feces, neutral, and butter, were used 9% each. The most widely used odors could be those with distinctive and recognizable characteristics designed to elicit specific participant responses (see Figure 5).

The olfactory stimuli presented in the studies analyzed were administered using various methods. Glass canisters were used in 40% of the cases ($N = 5$). In comparison, 16% used technological odor reproduction systems ($N = 2$), and 8% used pads or compresses ($N = 1$).

Glass jars are more straightforward and effective systems for controlling and administering olfactory stimuli, offering a greater capacity for odor concentration. On the other hand, the use of technology for odor reproduction, although more costly, allows more precise control of experimental conditions and can offer greater consistency in the presentation of stimuli (see Figure 6).

Regarding the experimental context, 54% of the studies ($N = 6$) were conducted in real laboratory or school settings, while 18% ($N = 3$) used virtual contexts.

As shown in Figure 7, natural environments allow greater control over experimental variables and provide more standardized conditions, which may increase the internal validity of the studies. However, virtual contexts offer the advantage of simulating situations that would be difficult or impossible to recreate in the real world, providing a valuable tool for exploring how olfactory stimuli affect participants under controlled conditions.

Regarding the devices used for measurement, 48% of the studies used palmar placement electrodes, which limited the participants' mobility. On the other hand, 16% of the studies used wireless devices, reflecting an advance in technological development and allowing participants greater freedom of movement. This shift toward wireless devices may improve the comfort and naturalness of responses in the studies, thus enhancing the ecological validity of the results (see Figure 8).

88.8% of the studies compared the electrodermal response to an olfactory stimulus in ASD vs. TD groups ($N = 8$). In comparison, 11.1% compared the response in participants with ASD, TD, and SMD ($N = 1$).

Of the nine articles reviewed, three correlated the Sensory Challenge Protocol (Miller et al., 1999) with electrodermal activity (Schoen et al., 2008; DeBoth et al., 2023; Schupak et al., 2016). One study correlated the Short Sensory Profile with electrodermal activity (Schoen et al., 2009), and two studies correlated electrodermal activity with the Autism Quotient (Endevelt-Shapira et al., 2018; Haigh et al., 2020). Legiša et al. (2013) studied EDA, heart rate, facial expressions, and self-reports. Finally, two studies focused solely on EDA: one using a continuous decomposition analysis (CDA) (Alcañiz Raya et al., 2020) and another against exposure to visual, auditory, and olfactory stimuli (Olmos-Raya et al., 2023). This variety of approaches reflects the diversity in sensory and neurophysiological response research.

The different EDA phases characterize the electrodermal response analyzed in the selected articles. Schoen et al. (2008) focused on SCL and NSR, Schupak et al. (2016) analyzed NSR and SCR, Alcañiz Raya et al. (2020) and Olmos-Raya et al. (2023) studied SCL and SCR; the former completed with a CDA and the latter with the Ratio (SCR/baseline) measure. DeBoth et al. (2023), Haigh et al. (2020), Legiša et al. (2013), and Schoen et al. (2009) analyzed the amplitude of the electrodermal response. Endevelt-Shapira et al. (2018) focused on specific responses to discrete stimuli. This diversity in EDA measures and phases underscores the need for further research with integrated and multidimensional approaches.

The tests applied to the type of statistical analysis employed were heterogeneous. Five articles performed correlational analyses. Schoen et al. (2008) correlated electrodermal activity in SCL, SCR,

TABLE 4 Sample characterization.

	Children		Adults	
	N	Age	*N*	Age
Mean	61.6	7.8	34.0	26.9
Maximum	104.0	11.0	36.0	27.5
Minimum	16.0	4.8	32.0	26.2
SD	32.8	2.3	2.8	0.9

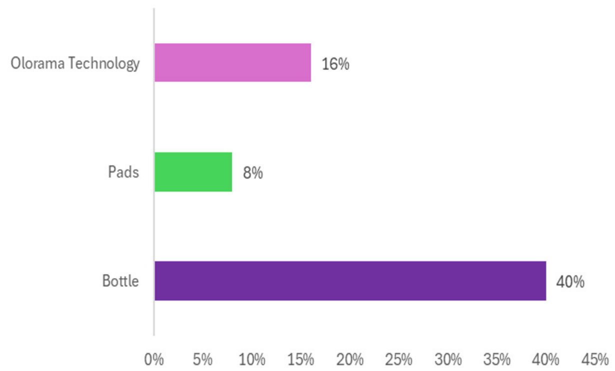

FIGURE 6
Device used for olfactory stimulation.

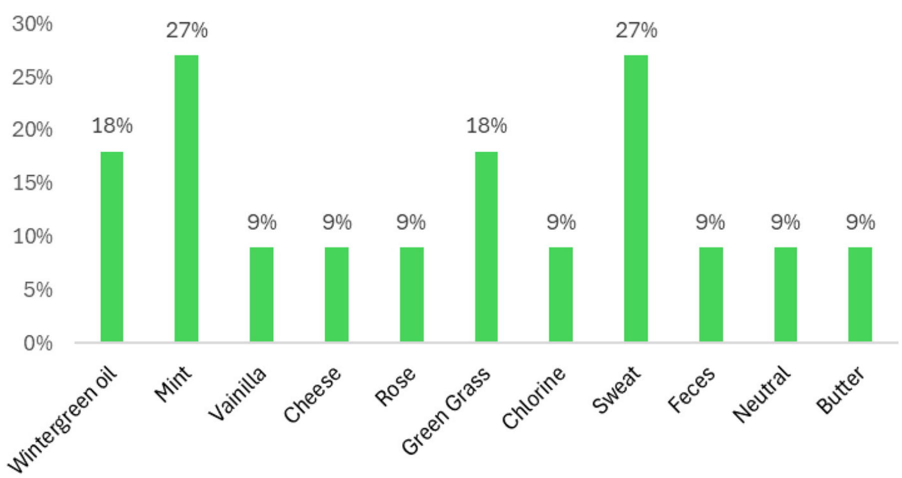

FIGURE 5
Type of olfactory stimulus used.

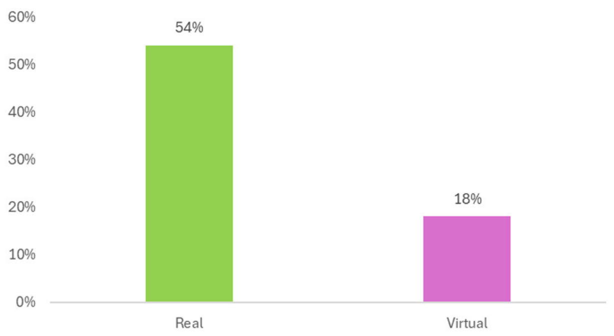

FIGURE 7
Experimental context.

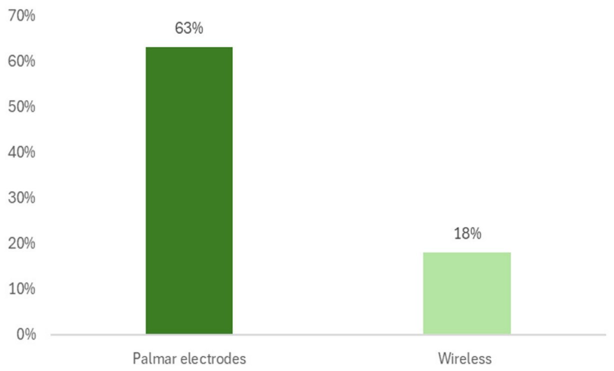

FIGURE 8
Type of EDA measuring device.

and baseline using the interclass correlation coefficient. Schoen et al. (2009) correlated SCR with the Short Sensory Profile. Endevelt-Shapira et al. (2018) and Haigh et al. (2020) correlated electrodermal activity with the Autism Quotient, exploring the relationship between EDA and autism spectrum characteristics.

In the use of parametric tests, two articles applied the two independent samples comparison T-test (T-Test) (Haigh et al., 2020; Schoen et al., 2008), and two others employed an analysis of variance (ANOVA) (DeBoth et al., 2023; Endevelt-Shapira et al., 2018). Schoen et al. (2009) found no differences in SCL and SCR electrodermal phases to peppermint odor, similar to DeBoth et al. (2023), who also found no differences between ASD and TD participants to peppermint odor exposure. Haigh et al. (2020) found no differences in average peak amplitude. However, ASD participants showed greater arousal and variability to fear-emulating odors, unlike normotypic participants, who were more aroused by neutral odors. Endevelt-Shapira et al. (2018) found significant differences in specific EDA responses to fear-emulating odors, increasing in TD participants to neutral odors, but not in the ASD group.

In studies using non-parametric tests, Legiša et al. (2013) used the Kruskal-Wallis, Chi-square, and Wilcoxon tests, while Olmos-Raya et al. (2023) used the Kolmogorov-Smirnov and Mann-Whitney U-tests. Legiša et al. (2013) found no differences between groups in amplitude and intensity but observed that the cumulative electrodermal response to mint odor was higher in TD participants. In addition, ASD participants showed greater familiarity with the stool odor, perceiving it as less unpleasant than the fear odor. Olmos-Raya et al. (2023) obtained a significantly higher response in the ASD group to the odor of fresh grass, suggesting that certain odors may be more evocative in individuals with ASD or TD.

Recognition of ASD participants by electrodermal response showed that Endevelt-Shapira et al. (2018) could differentiate between ASD and TD by 70% using a discriminant analysis with odors that simulated fear vs. neutral odors. Alcañiz Raya et al. (2020), with a continuous decomposition analysis and a more significant number of participants, achieved a detection ability of 90.3% when visual and auditory stimuli were used and 75% when the sense of smell was introduced, using vanilla and fresh grass odors.

In correlational analyses, Schoen et al. (2009) found no significant correlations between the SCR (orientation, magnitude, and amplitude) and the Short Sensory Profile of peppermint odor exposure. However, Endevelt-Shapira et al. (2018) found significant correlations between EDA responses and Autism Quotient, noting that electrodermal responding decreased as Autism Quotient scores increased with fear-simulating odors. Haigh et al. (2020) also found that Autism Quotient scores decreased with increasing average EDA in response to fear odors, suggesting that the nature of the odor influences reactivity, with peppermint odor being a possibly unevocative stimulus.

The results show that the United States has the most publications on the topic in question, focusing mainly on the pediatric population, with an average age of 7 years, rather than the adult population. In terms of administering the olfactory stimulus, this was mainly via vials, with few studies incorporating technology in the dispensing process. A similar trend was observed in the settings used, with laboratories predominating over virtual settings and electrodermal activity measurement (EDA) devices, as only 16% used wireless devices.

Overall, the results indicate differences in electrodermal response between individuals with autism spectrum disorder (ASD) and neurotypicals (NT). The former showed less reactivity to fear-associated or neutral odors, perceiving the former as less unpleasant. Furthermore, electrodermal activity was also correlated with Autism Quotient, with reactivity to fear odors decreasing as autism scores increased.

Regarding diagnosis, studies such as that of Endevelt-Shapira et al. (2018) were able to identify 70% of participants with ASD through their responses to odors that simulated fear. Alcañiz Raya et al. (2020) achieved an accuracy of 75% when combining odors with other sensory stimuli.

8 Discussion

This section will compare the results obtained with the previous literature based on the proposed objectives.

Concerning the analysis of the electrodermal responses to the presence of olfactory stimuli in the ASD population, the results suggest that the presence of differences between groups (children with and without ASD) may be conditioned by the type of olfactory stimulus presented in each experiment. In general, participants with ASD perceived mint odor as less intense (DeBoth et al., 2023; Schoen et al., 2009) compared to the perception of children without ASD (Legiša et al., 2013). However, odors such as fear-emulating odors (Endevelt-Shapira et al., 2018), as well as odors of feces (Legiša et al., 2013) or fresh grass (Olmos-Raya et al., 2023), elicit greater electrodermal reactivity in ASD children. Based on the work of Ashwin et al. (2014) and Wicker et al. (2016) on olfactory processing, these findings point to the presence of sensory dysfunction of the sense of smell in ASD children (Schupak, 2014).

Jang et al. (2019) observed that response consistency in the face of an emotion-inducing odor provides a more robust electrodermal response. This is especially relevant for adapting classroom contexts to the emotional and sensory needs of ASD children (Schupak, 2014). Furthermore, it can allow teachers, through these implicit measurements, to predict stressful situations, thus improving performance, attention, and engagement (Yu et al., 2024), thereby predicting difficulties associated with language development (Lorang, 2022) since the use of portable electrodermal measurement devices (Alcañiz Raya et al., 2020; Olmos-Raya et al., 2023), teachers have the opportunity to identify phases of acute stress that may influence learning and adapt teaching situations to the needs of these children. If teachers can modulate cognitive states in their classrooms through auditory, gustatory, and olfactory stimuli via wireless EDA devices (Olmos-Raya et al., 2023) they could have a tool that has a direct impact on improving the attention and academic performance of all students, including students with ASD (Fekri Azgomi et al., 2023).

Regarding the relationship between electrodermal response to olfactory stimulation and ASD symptomatology, evolving EDA analysis techniques can discriminate by physiological response to ASD participants vs. non-ASD children (Alcañiz Raya et al., 2020; Endevelt-Shapira et al., 2018). Li et al. (2022) suggest that a thorough understanding of the analysis methods improves robustness when implementing EDA as a reliable marker in the school context.

Recognizing emotions through multimodal analysis can be crucial for developing more effective and personalized educational strategies. For example, implementing emotional recognition systems can help teachers better understand the emotional state of students with ASD in real time. This allows interventions to be more accurate and timely, adapting the learning environment better to meet these students' emotional and cognitive needs. Wearable devices that measure activity can provide valuable information to adjust classroom activities, breaks, and interactions, reducing stress and increasing engagement. By incorporating these multimodal approaches into the educational environment, more inclusive and effective programs can be developed, improving both the learning experience and the emotional wellbeing of students with ASD, according to Ezzameli and Mahersia (2023).

Furthermore, our results indicate a relationship between fear of odor and questionnaires like the Autism Quotient (Endevelt-Shapira et al., 2018; Haigh et al., 2020). Previous studies by Fenning et al. (2017), McCormick et al. (2016), and Prince et al. (2017) already explored the relationship between sensory regulation-associated and ASD-specific symptomatology. Fenning et al. (2017) found a relationship between symptomatology severity using the ADOS questionnaire. Prince et al. (2017) related increased reactivity to repetitive and stereotyped behaviors. These findings suggest that emotions influence anxiety or reactivity states (Jang et al., 2019).

Finally, regarding the idea of deepening the importance of the electrodermal response to olfactory stimulation in the learning process of the ASD population, it should be noted that, so far, studies have been conducted in laboratory contexts. However, the use of IVE (Alcañiz Raya et al., 2020; Olmos-Raya et al., 2023) is a starting point for the development of sensory rooms with stimulus control capacity (Loomis et al., 1999) that can be extrapolated to the school context. Knowing those stimuli that can provoke stressful situations (Endevelt-Shapira et al., 2018; Legiša et al., 2013) and hinder the learning process, educators will be able to adapt teaching situations to specific moments and make personalized interventions (Jang et al., 2019).

Based on research on the relationships between EDA and ASD symptomatology (Alcañiz Raya et al., 2020; Endevelt-Shapira et al., 2018; Fenning et al., 2017), these results are especially relevant in the educational context, allowing the implementation of more targeted interventions. The implementation of EDA-based tools for stress monitoring could help educators identify critical moments when students with ASD experience high levels of stress. This information would allow for timely interventions to mitigate stress and improve students' emotional wellbeing, thus facilitating better learning and classroom participation (Greco et al., 2021).

9 Conclusions

The presence of disparate electrodermal behaviors between the ASD population and their typically developed peers suggests that the type of olfactory stimulus presented conditions sensitivity and reactivity to it. The findings indicate that more emotionally charged or less usual odors elicit greater reactivity. This suggests the existence of sensory dysfunction, specifically in the sense of smell, when these stimuli are present. This finding is relevant as it can be extrapolated beyond laboratory contexts and applied in educational settings. By predicting the response to a given stimulus, it is possible to anticipate stressful situations and adapt them to the specific needs of the ASD population, preventing them from interfering with their learning process.

EDA's ability to effectively differentiate the ASD population using machine learning or deep learning techniques is promising, allowing for more robust results. In addition, low-cost wearable devices can be a valuable tool for educators, allowing them to know the students' emotional state in real time and adapt the learning situation to their sensory, emotional, and educational needs.

Current research on the EDA to olfactory stimulation in individuals with ASD has been conducted primarily in controlled laboratory settings. However, IVEs offer a promising extension of these studies to more applicable contexts, such as sensory rooms and school settings. These environments allow precise control of stimuli and are potentially helpful for tailoring education to the needs of students with ASD.

In addition, knowing the stimuli that cause stress and hinder learning is crucial for developing personalized interventions. By tailoring learning situations to specific times, educators can improve the effectiveness of pedagogical strategies.

The relationship between EDA and ASD symptomatology is particularly relevant in inclusive education. The use of EDA-based tools to monitor stress could help identify critical moments of elevated stress in students with ASD, allowing timely interventions to mitigate such stress. This would not only improve the emotional wellbeing of students but could also facilitate better learning and increased classroom participation.

To implement the above in educational practice, the development of devices linked to mobile phones could be an effective way to monitor students' levels of reactivity, allowing teachers to access this data in real time. This would facilitate the regulation of visual, auditory, and olfactory stimuli in digitized multi-sensory classrooms. In such classrooms, teachers could control the intensity of stimulation students receive using a tablet, adapting it to the specific needs of each day. In addition, with new real-time data analysis techniques, teachers could receive daily feedback on student measurements. This could be complemented by objective measurements such as eye behavior, movement, and platforms that interconnect teachers and families to share the results obtained and the parameters used.

Despite the above, it is noted that little research combines the use of EDA with olfactory processing. However, looking to the future, in addition to extending studies with this approach, teachers should be involved in the research and design of these contexts to adapt them to their daily needs and the school reality of ASD. Forming a multidisciplinary team, including teachers, could facilitate the creation of appropriate contexts within the school setting. In addition, it would be beneficial to increase the number of participants to obtain more robust results and replicate studies using wireless technology and advanced analysis techniques in technology-mediated contexts, as their use could be crucial in the future of education for students with ASD.

10 Limitations and future prospects

Despite the findings above, it is essential to note that the number of publications combining electrodermal measures with olfactory processing is limited, which may restrict the generalizability of the results. Furthermore, the disparity in the number of participants, the variety of stimuli, and the heterogeneity of the autism spectrum disorder (ASD) population must be considered as a limitation. This variability also extends to the experimental settings and the electrodermal activity measurement methodologies.

Moreover, although studies using Virtual Reality offer greater ecological validity in terms of experimental control, according to Loomis et al. (1999), the study of odors precedes the generalization of the use of this technology. Therefore, this research is crucial and should be a starting point for implementing ecological virtual contexts. Future studies could compare participants' reactions in real and virtual environments exposed to odors to improve the generalizability of the results.

Future research should address these limitations by studying olfactory processing in previously re-evaluated ASD populations and grouping according to impairment degrees. It would also be beneficial to continue exploring the previously studied odors and include new data analysis techniques in analyzing the results that allow for identifying classifiers of participants according to electrodermal response and degree of impairment.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

DP-J: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. EO-R: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. IA-R: Data curation, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing. IP-P: Data curation, Formal analysis, Methodology, Resources, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

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