REVIEW

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The phenomenon of sensory processing: historical overview, theoretical models, and neurophysiological underpinnings

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The article provides a review of the sensory processing (SP) phenomenon, its origins, theoretical models, and neurophysiological foundations. Initiated by A. Jean Ayres' research on sensory integration in the 1960s and 70s, this field has evolved, leading to the development of concepts such as Winnie Dunn's four quadrant model and Miller's ecological model of sensory modulation. Over the years, based on theoretical considerations, the concepts of sensory processing disorder and sensory processing sensitivity were formulated. The article highlights the role of temperament and its impact on sensory processing, suggesting that individual differences can significantly affect how people respond to sensory stimuli. The neurophysiological basis including sensory gating, electrodermal responses, and neuroimaging methods is presented. There has been an interest in the relationship between SP and mental disorders in adults, despite the lack of a formal diagnosis in DSM-5 and ICD classifications. The literature analysis reveals the complexity of the subject, indicating the need for further research in this field.

Key words: sensory processing, sensory processing sensitivity, Dunn's four quadrant model

INTRODUCTION

The theory of sensory processing (SP) was developed by an American occupational therapist Anna Jean Ayres in the 1960s and 70s. Over the next 60 years, this theory evolved and was further expanded by multidisciplinary international teams, such as the Wallace Research Foundation (1994-2019). The concepts of sensory integration (SI) and sensory processing disorder (SPD) were elaborated, creating theoretical, pathophysiological, and therapeutic models. Subsequent researchers proposed developments of the sensory processing theory, presenting their models and approaches, including Winnie Dunn's four quadrant model (Dunn, 2001), Miller's ecological model of sensory modulation (Miller et al., 2001), and Mulligan's modified model of sensory integration dysfunction (Mulligan, 1998). A summary of the issue was presented in 2021, in a collection of articles in the journal Frontiers in Integrative Neuroscience (Miller et al., 2021).

Initially, interest in sensory processing appeared among psychiatrists and child psychologists, particularly in children with developmental disorders, learning disabilities, and autism spectrum disorder (ASD). In the last 20 years, there has been growing interest in the relationship between sensory processing and mental disorders in adults. However, sensory integration disorders are not recognized as a psychiatric diagnosis in either the American or international clas-

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sifications of mental disorders, DSM-5, and ICD (both 10 and 11). SPD, however, is classified in the "Diagnostic Classification of Mental Health and Developmental Disorders of Infancy and Early Childhood DC: 0-3 R" (2007), which is an important supplement to the DSM and ICD classifications. This article will present theoretical approaches to sensory processing, epidemiology, and studies of the neurophysiological basis.

This is the first systematic review of the literature to address the topic of sensory processing in its entirety, including historical context, neurophysiological background, and imaging studies, regardless of the type of mental disorder, as available to the authors.

Material and Methodology

The inclusion criteria were broad, encompassing studies of theoretical frameworks, neurophysiological basis, and animal models related to sensory processing. Articles from 1906 to 2023 were included to provide extensive historical context and the latest research findings.

The analysis utilized three databases: PubMed, MEDLINE, and Scopus. Consideration was given to review articles, literature reviews, meta-analyses, retrospective studies, and scientific textbooks. When uncertainties arose regarding individual works, researchers reached out to authors to obtain detailed information.

Articles were identified using a structured search string with keywords including "sensory processing disorder", "sensory integration", "sensory processing sensitivity", "Ayres sensory integration", "temperament history", "Dunn sensory profile". Excluding terms such as "case report", "case study", "mouse model" and "basic research" were applied to refine the search.

The process was supplemented with manual searches to identify any missing or incomplete articles. Additionally, publication reviews were scanned for relevant articles overlooked by the initial methods. The search strategy was subsequently broadened to align with the foundational works of pioneering researchers in the field, ensuring the inclusion of studies that built upon their contributions. In addition, articles exploring the neurobiological basis of sensory processing and imaging studies were included, following reviewers' recommendations.

Data Selection

The data selection process was conducted independently by two authors. Initially, duplicate studies were eliminated. Titles and abstracts were then reviewed to determine relevance. Works not aligned with the research topic or whose sources were inadequately described were excluded during the full-text analysis. This step ensured the selection of literature closely related to the research topic while adhering to the journal's standards. Ultimately 79 articles were qualified for the basis of this publication.

Historical Outline of the Concept of Sensory Processing

The first studies on sensory processing are connected with research on temperament. The father of medicine, Hippocrates, created the concept of humors, which were thought to explain health and disease. The optimal balance between the humors (blood, phlegm, black bile, yellow bile) was believed to ensure health, while imbalances were blamed for diseases. Hippocrates' concept did not mention temperament or the relationship between the proportions of the humors and behavior. Hippocrates' successor, Galen, added a psychological interpretation to the theory of humors. He distinguished four types of temperament, characterized by different ways of responding to stimuli, presenting descriptions of emotional and behavioral components depending on which humor predominated in the body: phlegmatic (*gr. phlegma – phlegm*), choleric (*gr. chole – bile*), melancholic (*gr. melas – black, chole – bile*), and sanguine (*lat. sanguis – blood*). In the 17th century emerged new concepts that resemble the modern understanding of sensory processing, as illustrated in a figure by the English doctor and philosopher Robert Fludd in his treatise *Utriusque cosmi maioris scilicet et minoris [...] historia* from 1619. In subsequent years, Jung introduced a distinction between extraversion and introversion, which still finds application in some theories of temperament, such as Eysenck's theory. The 20th century saw a trend towards replacing theoretical considerations with empirical research. The greatest contributions to the development of research on temperament are attributed to Heymans, Pavlov, and, in later years, Kretschmer. Heymans pioneered systematic studies on temperament through empirical methods, proposing a typology based on three primary dimensions: emotionality, activity, and secondary function (Heymans, 1909). He observed that temperament traits, such as stability and emotional responsiveness, were heritable, a groundbreaking assertion that laid the foundation for future genetic studies of personality. Heymans aimed to redefine the classic humor-based temperaments by categorizing them according to key psychological variables. He constructed types by combining classes of these variables, identifying three traditional temperaments— sanguine, phlegmatic, and choleric, while aligning the melancholic type with newer syndromes in contemporary literature, which eventually became the "sentimental" type. His classification system, later known as "Heymans' cube," took on a geometric form that visually represented these types. By categorizing individuals along these dimensions, he created one of the earliest typological systems linking personality to psychological and biological factors (Heymans & Wiersma, 1906-1909).

Pavlov's contributions expanded this work by exploring the physiological basis of temperament. His experiments on dogs led to the classification of temperament according to the strength, balance, and mobility of nervous processes, corresponding to types such as "choleric," "sanguine," "phlegmatic," and "melancholic" (Pavlov, 1927). Pavlov's work suggested that these types were linked to specific patterns of nervous system functioning, demonstrating an empirical connection between the nervous system and behavioral responses. This insight provided a biological framework for understanding individual differences in temperament, illustrating how nervous system dynamics could predict and explain varying temperamental traits (Pavlov, 1955).

Kretschmer, meanwhile, approached temperament from a physiological-anatomical perspective, proposing that temperament was closely linked to body types. He identified three main types—schizothymic, cyclothymic, and ixothymic—each associated with a distinct body build: asthenic, pyknic, and athletic, respectively (Kretschmer, 1921). Kretschmer posited that these temperamental types had corresponding psychological predispositions, such as a tendency towards mood instability in the cyclothymic type or a propensity for introversion in the schizothymic type. His theory provided an early interdisciplinary approach, connecting physical constitution with psychological traits and inspiring subsequent research on the relationship between physique and personality.

An earlier but equally pivotal figure was Sir Charles Sherrington, whose pioneering work laid foundational principles in understanding the nervous system's role in behavior and temperament. Sherrington introduced the concept of "sensory integration," proposing that the nervous system functions as a coordinated network where sensory inputs are integrated to produce adaptive motor and behavioral responses (Sherrington, 1906). Sherrington's focus on the reflex arc and the central integration of sensory inputs influenced subsequent researchers in studying the physiological basis of behavior, a focus later built upon by Pavlov in exploring the connection between nervous system types and temperament. Sherrington's work on the synaptic processes in the spinal cord and brain contributed significantly to understanding how behavioral responses could arise from complex sensory processing and neural integration (Sherrington, 1963). Sherrington's insights into the integration and coordination of sensory information as a basis for behavior not only set the stage for empirical studies of temperament but also inspired later theories linking physiological processes to personality traits, highlighting the biological underpinnings of individual differences in temperament.

Currently, temperament is defined as an individual, genetically determined, stable type of emotional responses with a biological basis, which refers to the formal characteristics of behavior, such as intensity, energy, and variability of behavior (Mehrabian, 1991). With the development of neuroscience, more precise studies began on the relationships between temperament and sensory processing. For example, individuals with an extroverted temperament show lower sensitivity to external stimuli and seek new experiences, while introverted individuals are more sensitive to their environment and prefer calmer, less stimulating surroundings. Zuckerman, based on Eysenck's biological interpretation of extraversion, studied the amplitude and orienting reflexes in terms of electrodermal and cardiovascular activity and the phenomenon of enhancing-suppressing evoked potentials (Zuckerman, 1985). The researcher demonstrated that in sensation-seekers, an increase in the level of stimulation was accompanied by an increase in the amplitude of evoked potentials, i.e., an enhancement of stimulation, in contrast to sensation-avoiders, where an increase in stimulation was accompanied by a decrease in the amplitude of evoked potentials, i.e., a suppression of stimulation. Based on a study conducted on over 2000 individuals, Strelau described the structure of temperament using six traits: briskness, perseverance, sensory sensitivity, emotional reactivity, endurance, and activity (Strelau & Zawadzki, 1995). Strelau and his team in studies of electrodermal responses showed that individuals with different temperaments exhibit different patterns of electrodermal reaction. For example, extraverts show a higher level of electrodermal activity in response to positive stimuli, which increases proportionally to the strength of the stimulus, while introverts show greater reactivity to negative stimuli, and strong stimuli cause protective inhibition and a decrease in electrodermal activity (Strelau, 1996). These studies suggest that temperament traits may be related to differences in emotional regulation and nervous system reactivity (Strelau, 1998). Currently, it is believed that significantly intensified temperament traits may lay at the basis of affective disorders (Akiskal, 1994).

Under the influence of sensory experiences, a spatial image of the body in relation to the environment is created (Dunn & Westman, 1997). As a result, the brain integrates sensations from different senses, creating complex behavioral response patterns that are modified throughout life depending on the environment, activities, and learning processes. Both genetic and environmental factors determine the threshold of stimulation, affecting individual differences in perceiving and responding to stimuli, which translates into differences in temperament and the organization of daily life (Buchsbaum & Pfefferbaum, 1971; Dunn & Brown 1997; Dunn & Westman 1997; Baranek, 1999). Individual sensory sensitivity to stimuli may be related to several factors, such as overall perceptual reactivity, gating, defined as the ability to filter stimuli, and habituation, which is the rate of decrease in response to repetitive stimulus. Recently, it has been shown that about 47% of the variability in sensory sensitivity is related to genetic variants (Assary et al., 2021).

The Concept of Sensory Processing and Its Development

A. Jean Ayres – A Pioneer in Sensory Processing Research

The term sensory integration was first used by neurophysiologist Charles Sherrington in 1902. However, it was the research of A. Jean Ayres (Ayres, 1965; 1972; 1979) combined neurophysiology and neurobiology with psychology, leading to the development of the theory of sensory integration. Ayres' concept of sensory integration is a multidimensional issue, encompassing the interactions and coordination of two or more functions of the central nervous system (CNS), where received sensory information is organized and interpreted in a way that allows for the creation of an effective behavioral response. Theoretically, this concept is based on three pillars: plasticity, integrity of the nervous system, and sequential development of sensory integration processes. Neuronal plasticity refers to the process that allows for changes and modifications within the nervous system. This phenomenon is possible due to the ability of axons to branch out and eliminate unnecessary neural connections. One of the most significant discoveries in this field, made by Eric Kandel, was the identification of mechanisms of long-term potentiation (LTP) and long-term depression (LTD), which form the basis of synaptic plasticity and the learning process. These forms of plasticity play a crucial role in creating and modifying connections between neurons, enabling the encoding of new information and the formation of long-term memories (Kandel, 2001). LTP is a process that increases synaptic transmission efficiency after repeated activation of synapses. Kandel demonstrated that LTP involves molecular changes in synaptic receptors, including NMDA and AMPA receptors, leading to an increase in the number of receptors on the postsynaptic membrane. This process requires a calcium-activated signaling cascade, which activates protein kinases and ultimately leads to the synthesis of new proteins essential for stabilizing synaptic changes (Kandel, 2001). LTD, on the other hand, works in the opposite way to LTP, reducing synaptic transmission efficiency in response to specific patterns of activity. Kandel and his collaborators showed that LTD engages different signaling pathways, including the activation of phosphatases, which counteract the effects of kinases and decrease the number of postsynaptic receptors (Kandel et al., 2000).

Another area of Kandel's research explored the role of emotions and serotonin in plasticity processes. Kandel identified mechanisms by which serotonin release leads to the activation of adenylate cyclase and an increase in cAMP levels, supporting the consolidation of long-term synaptic changes (Kandel, 2001). The role of the hippocampus is particularly important in integrating sensory stimuli and emotions in the process of forming long-term memory. Kandel's research demonstrated that the hippocampus functions as a key region responsible for memory consolidation, where sensory and emotional stimuli are integrated, allowing for the formation of complex, multimodal memories (Kandel & Spencer, 1961). The hippocampus plays a central role in spatial mapping and the sequential organization of events, which is essential for creating complex memories and effective navigation in the environment.

For his groundbreaking research on synaptic plasticity mechanisms, including discoveries related to LTP and LTD as well as the role of emotions and serotonin in learning and memory, Eric Kandel was awarded the Nobel Prize in Physiology or Medicine in 2000.

Ayres emphasized in her work that it allows for the development of processes that enable proper interaction with the environment. The second pillar is the integrity of the nervous system, which describes the hierarchical division into lower and higher CNS structures that interact with each other. These two pillars led to the theory that proper stimulation of lower structures enables the refinement of brain responses, including learning processes. The last pillar of the sensory integration concept is sequentiality, which describes the successive stages reflecting developmental milestones. According to the theory, based on the acquired skills, subsequent, more complex perceptual-motor functions emerge. Ayres demonstrated the relationship between the model of receiving sensory stimuli and the learning process. Initially, her method was applied among students with learning difficulties, but it quickly expanded to include children with developmental disorders. Ayres' work laid the foundations for further scientific research that built upon her basis to create new concepts related to sensory integration.

Despite the groundbreaking nature of Ayres' theory, critics highlight its shortcomings, especially regarding scientific validity and therapeutic effectiveness. Hoehn and Baumeister point out that the theory of sensory integration is based on incomplete empirical evidence that does not conclusively confirm the impact of sensory processing disorders on learning difficulties. The authors emphasize that many studies Ayres cites do not meet contemporary methodological standards, such as the presence of control groups and objective, standardized measures of therapeutic outcomes. Hoehn and Baumeister also observe that inconsistent findings in SI research may stem from the diversity of individual patient profiles, indicating that Ayres' assumptions about universal sensory patterns are overly generalized and fail to consider individual differences. They concluded that the current research may be sufficient to recognize sensory integration therapy not only as unproven but demonstrably ineffective as a primary or supportive treatment for learning disabilities and other disorders (Hoehn & Baumeister, 1994).

Further significant criticisms come from Arendt's work (Arendt et al., 1988), which emphasizes that in children with intellectual disabilities SI does not address deeper aspects of cognitive development that may have a greater impact on the functioning than sensory processing disorders alone. Sensory interventions may have negligible or short-term effects in individuals with intellectual disabilities, indicating the need for a more differentiated therapeutic approach. Cummins, on the other hand, points out that Ayres' analysis may contain methodological flaws that distort the interpretation of the relationship between sensory processing and academic outcomes. Cummins suggests that Ayres' findings may be overestimated and require reanalysis based on more contemporary statistical standards (Cummins, 1991).

One of the most recent studies critically examines the application of sensory integration (SI) and sensory processing treatments, emphasizing the need for robust empirical support (Camarata et al., 2020). Researchers point out that while these therapies are widely used, particularly in treating children with autism and learning disabilities, their scientific validation remains limited. It is highlighted that many studies supporting SI therapies lack methodological rigor, making it difficult to draw reliable conclusions about their effectiveness. Moreover, researchers caution against overgeneralizing the use of sensory-based treatments without individualized assessments, as sensory challenges vary significantly between individuals.

Researchers conclude that many elements of Ayres' hypotheses regarding the nature of the disorder align closely with current literature on sensory processing in children with ASD, though some inconsistencies remain (Lane at al., 2019; Kilroy et al., 2019).

Development of the Sensory Processing Concept

L. J. Miller in her research justified the use of the term "sensory processing" in contrast to "sensory integration" proposed by Ayres, arguing that "sensory processing", although similar to "sensory integration", is not synonymous with it, as the integration of sensory processes is one of the dimensions of sensory processing (Miller & Lane, 2000). Based on the theory of sensory processing, a classification of sensory processing disorder (SPD) was developed (Miller et al., 2007), as presented in Fig. 1. SPD is recognized in individuals with significant difficulties or atypicalities in receiving, modulating, processing, and responding to an average sensory stimulus (Miller et al., 2007). The researcher described three dimensions of sensory processing disorders: sensory modulation disorder, sensory-based motor disorder, and sensory discrimination disorder. Each type of disorder can affect any sense and co-occur in any configuration, which highlights the multidimensionality of sensory processing. Modulation disorders are divided into three subtypes: hypersensitivity, also known as sensory defensiveness, involving a disproportionate, excessive reaction to a stimulus; hyposensitivity, where a slow reaction to a stimulus is observed; and sensation seeking, which involves an active need to satisfy sensory needs. The subtypes differ in the threshold of stimulus reception, which is lowered in the case of hypersensitivity and raised in hyposensitivity. Sensory-based motor disorders manifest as dyspraxia, described as disorders in gross (dressing) and fine motor skills (drawing, using utensils), and postural disorders related to body stabilization and muscle tension. The last type is sensory discrimination disorders, which involve the assessment and differentiation of stimuli from the environment, e.g., selecting the appropriate muscle force for riding a bike.

One of the most frequently used concepts is the four quadrant model proposed by Winnie Dunn in

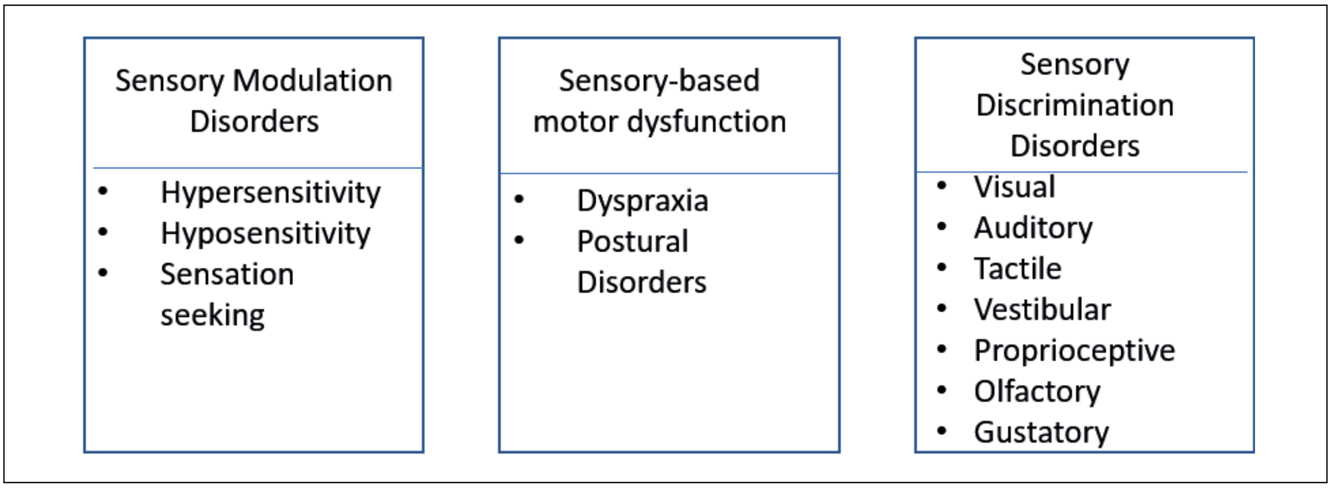

Fig. 1. Sensory processing disorder division based on Lucy J. Miller concept (2007).

1997, which stems from occupational therapy (Fig. 2). This model proposes the existence of differences in sensory processing based on a high or low threshold for receiving stimuli and an active or passive way of responding. By recognizing these two characteristics as axes, a model was created that shows four types of sensory processing. In Dunn's model, the threshold and response are measured as a continuum, reflecting the individual's response to stimuli. The four quadrants are described as: Sensory Sensitivity, characterized by a low threshold for receiving stimuli, passive response, and slow habituation; Sensation Avoiding with a low threshold and active response of opposing sensory experiences; Low Registration, characterized by a high neurological threshold and passive response; and Sensation Seeking, described as a high threshold for receiving environmental sensations and an active response. On one end of the spectrum are individuals with a high arousal threshold, who need strong stimuli to break through it and often do not notice various sensory stimuli. In the case of Low Registration, such individuals are often perceived as withdrawn, inattentive, and lacking motivation, while individuals with Sensation Seeking profile may exhibit risky behaviors or have difficulties with planning. On the other end are individuals with a low neurological threshold. Those with a Sensory Sensitivity profile easily notice sensory stimuli, may feel discomfort with their excess, and are easily distracted by them. At the same time, their response is passive; unlike in Sensation Avoiding, where individuals actively seek ways to limit the stimuli they receive, trying to avoid places with many sensory experiences, they willingly create rituals of daily activities, and often negatively perceive the disruption of their habits. According to Dunn, the sensory processing profile is relatively stable over time (Dunn, 1999; 2001). When sensory processing does not affect daily functioning, it is considered a variant of the norm (Dunn, 2001). However, if the sensory processing profile shows abnormalities that negatively affect functioning and participation in daily life, it may be treated as SPD (Miller et al., 2007). Despite some similarities between the four quadrant model and the four quadrant model of personality (Eysenck & Eysenck, 1965), where introversion/extraversion served as the horizontal axis, and neuroticism was placed on the vertical axis, studies on the healthy population did not show a correlation between these two concepts, indicating their distinctiveness (Metz et al., 2019).

Another theoretical model is the ecological model of sensory modulation proposed by L. J. Miller in 2001, which focuses on often overlooked aspects of sensory integration, such as the impact of external factors: environment, interpersonal relationships, culture, requirements, and tasks (Miller et al., 2001). The internal dimensions are sensations, emotions, and attention. In this model, each external dimension interacts with each internal dimension, supporting or inhibiting reactions in specific situations. Proper cooperation between these dimensions ensures proper functioning. It has been proven that excessive sensory stimulation beyond an individual's perceptual capabilities can lead to underreactivity, and such reactions have been observed in patients diagnosed with schizophrenia (Chapman, 1966). In a study of electrodermal reactivity among a group of children with ASD, in terms of sensations, physiological underreactivity and excessive sensitivity to olfactory, gustatory, visual, and motor stimuli were demonstrated (Miller et al., 2001). Emotional overreactivity and attention disorder were also found, although they were less

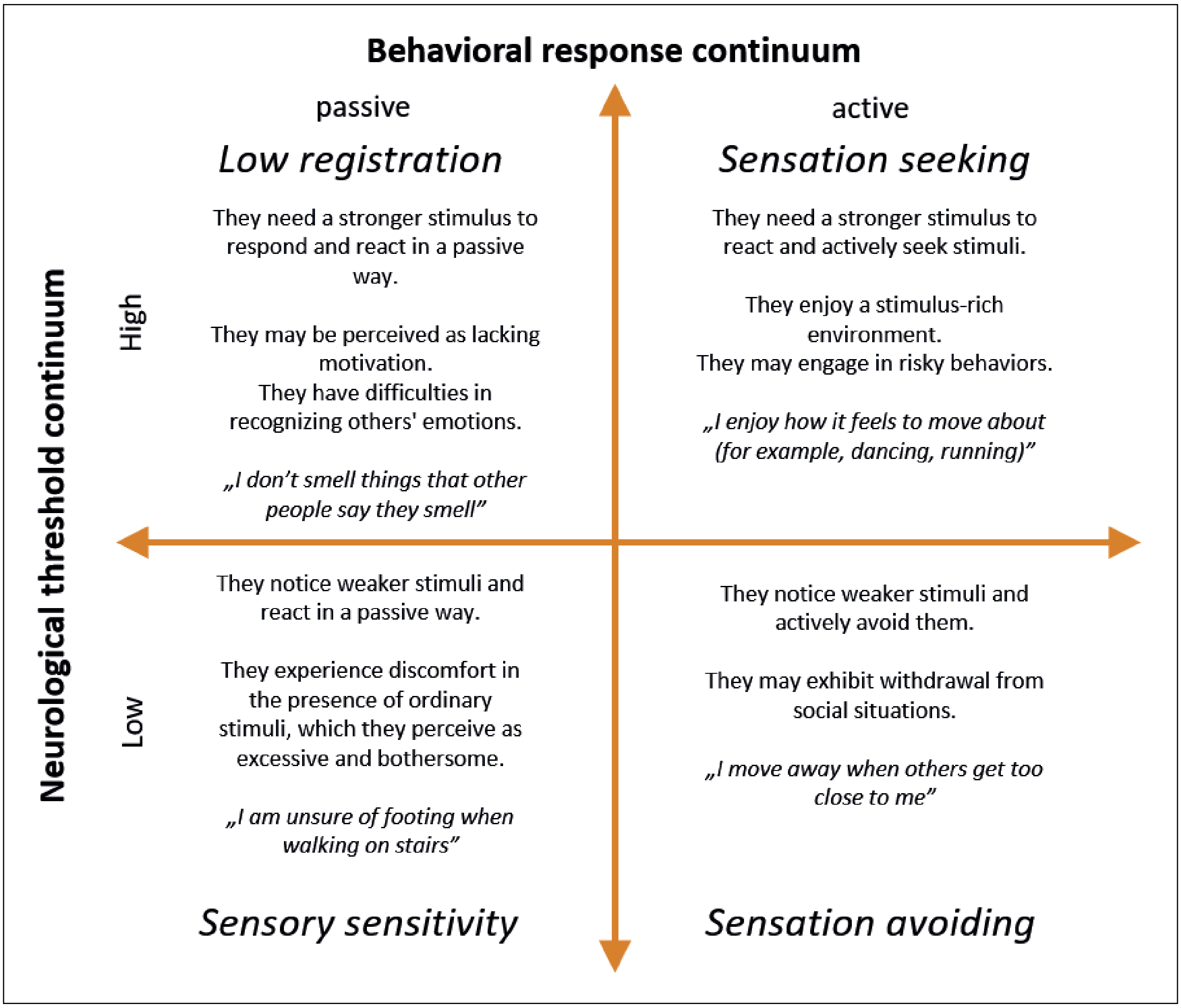

Fig. 2. The Four Quandrant Model based on Winnie Dunn, own translation.

pronounced compared to sensational and emotional disturbances.

Mulligan's modified model of sensory integration dysfunction expands on the classic concept of sensory integration dysfunction, introducing more complex interactions between sensory processes and behavioral responses. This model emphasizes the importance of adaptive responses to sensory challenges, suggesting that inadequate sensory integration can lead to difficulties in daily functioning as well as impact emotional and social development (Mulligan, 2003). Within the context of occupational therapy, Mulligan's model serves as a foundation for assessment and intervention, aiding therapists in identifying specific areas of dysfunction and designing effective therapeutic strategies (Chandoo, 2008).

New Look at Sensory Processing – Sensory Processing Sensitivity

In 1997, Elaine Aron and Arthur Aron introduced the concept of sensory processing sensitivity (SPS), which is a construct that overlaps in part with the concepts of neuroticism and introversion but is not identical to them (Aron & Aron, 1997). The authors indicated that about 20% of the population is highly sensitive, and this trait has a genetic basis (Aron et al., 2012) and can be treated as an independent risk factor for anxiety and depression (Liss et al., 2005). Initially treated categorically, the SPS trait is currently understood as a continuum of sensitivity in the population, from low (29%), through medium (40%), to high (31%) (Lionetti et al., 2018). Its main features are described by the acronym DOES, i.e., depth of processing (D), overstimulation (O), emotional reactivity and empathy (E), and sensing the subtle (S). Based on seven studies, Elaine Aron and Arthur Aron (Aron et al., 2012) created a 27-item Highly Sensitive Person Scale (HSPS), and further studies (Smolewska et al., 2006) identified three dimensions of SPS: ease of excitation (EOE), aesthetic sensitivity (AES), and low sensory threshold (LST). The EOE and LST factors relate to the neurophysiological assumptions of sensory processing and Gray's behavioral inhibition system (Gray, 1981), however, the authors emphasize that the key feature of SPS is the depth of processing of stimuli in higher cortical centers, which has been confirmed in neuroimaging studies (David et al., 2022).

Comparing the SPS construct to sensory processing theories has led to conclusions that the HSPS scale primarily examines emotional responses, and the Adolescent/Adult Sensory Profile (hereafter referred to as AASP), based on the four quadrant model, mainly measures behavioral responses to sensory stimuli (Turjeman-Levi & Kluger, 2022). Initially, researchers treated both concepts interchangeably (Meredith et al., 2016) or equated SPS with sensory sensitivity (Benham, 2006) or Sensation Avoiding (Ben-Avi et al., 2012). However, SPS researchers emphasize processes related to empathy, self-assessment in relation to others, awareness, and reflective thinking, which was confirmed in functional magnetic resonance imaging (fMRI) studies, observing increased activity in relevant cortical areas in highly sensitive individuals (Acevedo et al., 2018). Therefore, it is important to emphasize that using different concepts and terminology regarding sensory processing interchangeably can complicate the interpretation of research results and lead to wrong conclusions (Schauder & Bennetto, 2016).

Neurophysiological basis of Sensory Processing

Knowledge about the neurophysiological basis of sensory processing has significantly advanced over the last 20 years. Research has pointed, among other findings, to increased electrodermal responses and decreased habituation among children with autism spectrum disorders (McIntosh et al., 1999) and in patients with Fragile X syndrome (Miller et al., 2001).

Other researchers, using brain bioelectrical activity studies, have pointed to reduced sensory gating in children with SPD compared to those without SPD (Davies & Gavin, 2007), and the use of animal models has shown that the basis of this phenomenon is related to cholinergic, glutaminergic, and adrenergic activity (Skefos et al., 2014; Schneider et al., 2017). Sensory gating, particularly the P50 wave, is an essential neurophysiological mechanism for filtering out redundant or irrelevant stimuli, allowing for more efficient processing of sensory information. In relation to sensory processing, studies have indicated that individuals with SPD may exhibit impaired sensory gating, as evidenced by altered P50 wave patterns. This impairment in sensory gating can lead to an overload of sensory information, contributing to sensory hypersensitivity and difficulties in sensory regulation (Bramon et al., 2004; McPartland et al., 2004). Furthermore, the investigation of P50 wave patterns offers insights into the underlying neurobiological mechanisms of SPD, highlighting the role of cortical and subcortical circuits in sensory processing and modulation.

The neurophysiological basis of sensory processing is a complex process involving various brain structures that work together to integrate and select sensory information. Studies using fMRI have enabled detailed mapping of these processes, revealing both specific areas involved in sensory input reception and their integration at a multimodal level. In studies on visual processing, it has been found that different image features (e.g., color, motion) are processed in specialized regions of the visual cortex, such as the primary cortex (V1) and associative areas like MT+, which is responsible for motion (Tootell et al., 1995). fMRI has also identified the role of the temporal and parietal cortices in spatial processing and in integrating visual stimuli with information from other senses (Sereno et al., 1995).

Auditory processing involves both the primary auditory cortex (A1) in the temporal lobe and higher areas, such as the superior temporal cortex, which participate in analyzing more complex sounds, such as speech and music (Binder et al., 2000). Imaging studies show that spatial auditory stimuli are integrated with visual information in the parieto-temporal area, facilitating complex environmental analysis and adaptive behavioral responses (Calvert et al., 2001).

In the context of sensory integration, fMRI reveals that the parietal cortex and insula play a key role in merging stimuli from different modalities, enabling the simultaneous reception and analysis of information from multiple senses, such as touch, vision, and hearing (Immordino-Yang et al., 2014). The insula, due to its extensive connections with the limbic system, is involved in emotional processes related to sensory input, as evidenced by studies on the role of emotions in sensory processing (Craig, 2009). Recent fMRI research also suggests that sensory processing is dynamically modulated by the prefrontal areas, responsible for attention control and information selection, confirmed by studies on the relationship between attentional and cognitive processes with activity in the frontal lobes (Corbetta & Shulman, 2002). The prefrontal cortex influences sensory stimulus selectivity, regulating which information is considered important and forwarded for further analysis. Studies using positron emission tomography have indicated the possible involvement of dopaminergic pathways, their impact on decreased sensory and affective regulation and hypersensitivity to stimuli (Miller et al., 2017). Among neuroimaging methods in humans, currently used are EEG, fMRI, and diffusion tensor imaging (DTI). Associations have been shown between sensory profiles and the cortical volume in the corresponding sensory area (Yoshimura et al., 2017) (in particular, correlations were shown between visual sensations and the thickness of the orbitofrontal cortex and the language area) and taste and smell experiences with the volume of the hippocampus in patients with ASD (Habata et al., 2021). DTI studies have shown a correlation between the white matter microstructure of the caudate nucleus and the results of tactile sensation on the AASP scale (Nakagawa et al., 2023). Another study using DTI among patients diagnosed with ASD and attention deficit hyperactivity disorder (ADHD) showed some similarities as well as some differences in white matter organization in relation to sensory processing (Ohta et al., 2020). Differences were also indicated in the integrity of white matter microstructure among children with SPD and typically developing children (Chang et al., 2016).

A study using magnetoencephalographic imaging (MEG) indicated that children with SPD are characterized by an intermediate phenotype of somatosensory processing, compared to children with ASD and typically developing children (Demopoulos et al., 2017).

The Role of Emotions and Memory in Sensory Integration Processes

Emotions and memory play a crucial role in sensory integration processes, enabling the organism to respond effectively to sensory stimuli and adapt to its environment. In the context of emotions, structures of the limbic system, such as the amygdala, are responsible for the rapid emotional processing of sensory stimuli, especially in situations that may pose a threat. The amygdala influences the intensity of emotional reactions and determines which information is prioritized and stored as long-term memories (LeDoux, 2000). For example, visual or auditory stimuli that evoke strong emotions are integrated more quickly and effectively due to the heightened impact of emotions on sensory processing.

Memory, especially long-term memory, is essential in sensory integration, allowing for the retention and recall of past sensory experiences, which in turn affects the interpretation of new stimuli. The hippocampus, critical for memory consolidation, integrates sensory and emotional stimuli, enabling the formation of complex, multimodal memories (Kandel, 2001). Functional magnetic resonance imaging (fMRI) studies show that the hippocampus and amygdala work together in creating emotional memories, supporting adaptive behavioral responses based on sensory experiences (Phelps, 2004).

Mechanisms of synaptic plasticity, such as long-term potentiation (LTP), which were extensively studied by Eric Kandel, play a crucial role in integrating sensory information with memory (Kandel et al., 2000). LTP enables the strengthening of neuronal connections in the hippocampus, which store information related to both emotions and sensory stimuli, allowing for the creation of stable and lasting memories (McGaugh, 2004). As a result, emotionally charged experiences, such as sudden sounds or intense colors, are better remembered and more easily integrated into further perception processes.

Thus, sensory integration is deeply connected with emotions and memory, and their interaction enhances the organism's adaptive responses, enabling the quick processing of important stimuli and the formation of lasting associations that influence behavior and environmental interactions.

CONCLUSIONS

The theory of sensory processing was initiated by A. Jean Ayres in the 1960s and 1970s. Over the following decades, this theory evolved and was supplemented by various researchers, leading to the creation of comprehensive theoretical and therapeutic models concerning sensory processing and sensory processing disorder. Research on sensory processing is multidisciplinary, combining elements of psychology, neurophysiology, and occupational therapy. Concepts such as Winnie Dunn's four quadrant model, L. J. Miller's ecological model of sensory modulation, and the concept of sensory processing sensitivity by Elaine N. Aron and Arthur Aron emphasize the complexity and multidimensionality of sensory processing. Research on SPD in children and adults shows that these disorders can significantly impact daily functioning and the quality of life of those affected by this problem. Despite advances in research and theory development, SPD is still not recognized as a psychiatric diagnosis in major systems of mental disorder classification, such as the DSM-5 and ICD, which may affect the availability of appropriate support and therapy for individuals with SPD. The results of existing publications suggest the need for further research to better understand the relationships between sensory processing and other developmental and mental disorders, as well as the need to develop more effective methods for diagnosing and treating sensory processing disorders.

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