Trends in
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Review

Sensory processing sensitivity: theory, evidence, and directions

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In recent years, scientific interest in sensory processing sensitivity (SPS), a personality trait reflecting increased sensitivity, reactivity, and deeper processing of stimuli, has grown exponentially. Building on this momentum, we synthesise recent SPS literature to discuss several central themes, including SPS assessment, relations to other personality traits and diverse positive and negative outcomes. We propose a novel account of SPS grounded in predictive processing, that bridges cognitive, neural, and computational domains. Specifically, we posit that brains of high-SPS individuals consistently assign high precision to incoming sensory signals. This account offers a unified explanation for the phenotypic consequences of heightened sensory sensitivity. We review behavioural and neural evidence that indirectly supports this account, and delineate important avenues for future research.

Highlights

Sensory processing sensitivity (SPS) is a trait that has caught the public eye, and is now an emerging scientific field that has drawn both interest and scepticism.

A rapidly growing body of research suggests that SPS is linked to measurable differences in sensory sensitivity as well as individual variation in brain structure and function. These differences are shaped by a complex interplay between genetic and environmental factors.

While SPS refers to a variety of characteristics rather than simply sensitivity towards sensory stimuli, it is unclear what core sensitivity is, and what secondary consequences of high SPS are. Better understanding requires improved assessment tools and further empirical and conceptual work.

SPS currently lacks a neurocognitive theory. We propose that predictive processing can provide a mechanistic account.

Origins and expansion of SPS research

Why are some people more sensitive than others to the world around them? Some individuals seem especially attuned to their surroundings: they may notice faint sounds, subtle changes in lighting, or shifts in others' affective states that go unnoticed by most. They often describe feeling easily overwhelmed in busy environments, needing more time to unwind, but also are deeply touched by art, music, or meaningful interactions. This heightened sensitivity is commonly described as being a **highly sensitive person (HSP)** and is captured by the construct of SPS.

Originally introduced by Aron and Aron [1] as a unidimensional personality trait rooted in personality and temperament theory and qualitative data, SPS is now viewed as a multidimensional construct involving several characteristics (Figure 1A): greater **sensitivity to subtle sensory inputs** (see Glossary), greater **emotional reactivity** and **empathy**, greater **depth of processing**, and greater ease of **overstimulation** [2]. Additionally, SPS has been linked to **differential susceptibility,** meaning that higher SPS brings greater vulnerability to adverse environments, but also greater susceptibility to and benefits from positive environments [3,4].

SPS is thought to be evolutionarily conserved and has been observed across species, suggesting potential adaptive value in specific ecological contexts [1] (see Figure I in Box 1). As one of several constructs within the broader **environmental sensitivity** framework (Box 1), SPS stands out in terms of public and scientific attention. The number of peer-reviewed publications on SPS has tripled since the last comprehensive review covering studies published between 1997 and 2018 [2], with the past 5 years seeing more peer-reviewed publications than the previous two decades combined[i]. Public discourse parallels this growth, with SPS increasingly featured in bestselling books, documentaries, online sensitivity tests, and self-identifying HSP communities[ii,iii,iv,v,vi,vii,viii].

Considering this increase in research and attention, key questions remain, such as to what extent and how the key characteristics of SPS are related, what constitutes core sensitivity and what are

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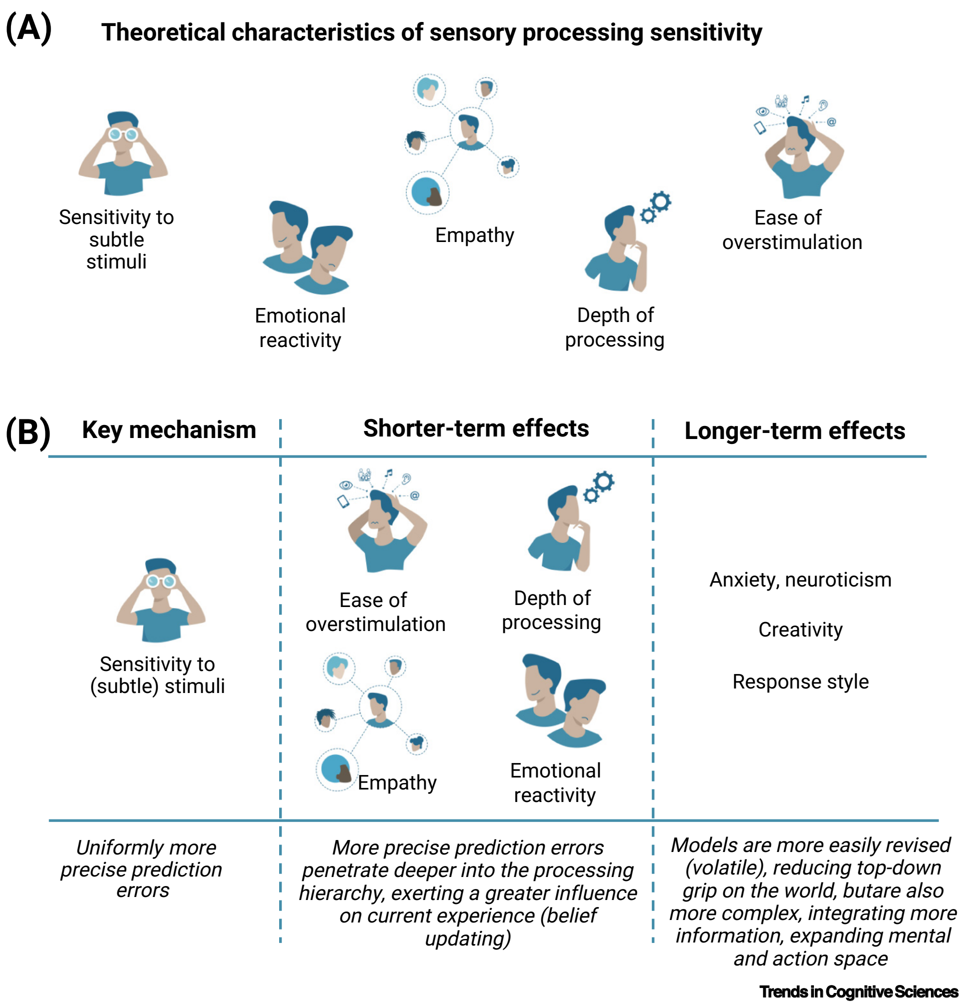

Figure 1. Key sensory processing sensitivity (SPS) characteristics. (A) Theorised SPS characteristics [2]. Note that emotional reactivity and empathy have often been listed together as one characteristic SPS characteristic, but we list them separately as these concepts differ. (B) Relations between them from a predictive processing perspective. Uniformly more precise prediction errors, as the core mechanism underlying high SPS, can explain key SPS characteristics, and SPS-associated features in a unifying manner. Prediction errors that are assigned more precision enhance sensitivity to sensory stimuli, including subtle or irrelevant inputs, permitting them to exert a greater influence over one's current attentional and emotional state (short-term or direct effects). By penetrating deeper into the processing hierarchy, (subtle) sensory events can enhance depth of processing by increasing semantic engagement. More precise prediction errors also more easily lead to model revision, which can paradoxically, contribute to overall greater uncertainty about, and reduced grip on the environment in the long run, as internal models are more volatile. This may explain the association of high SPS with anxiety and neuroticism, and inhibited behaviour [42]. At the same time, greater sensitivity to (subtle) sensory inputs, can also lead to the instantiation of richer internal models, which may account for enhanced creativity [104] in high-SPS individuals. During sensitive periods in development, the environment can in general exert a particularly strong influence on generative model formation, inducing so-called stubborn predictions that are resistant to change based on new experiences later in life [44]. Images from [81].

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the secondary consequences. These trends underscore the need for a timely, integrative review that goes beyond description and offers a mechanistic neurocognitive account of SPS. This review aims to do so and is structured in two parts. The first part synthesises key developments in SPS research, including advances in measurement, associations with other personality traits, and emerging evidence on both benefits and vulnerabilities. It also highlights conceptual

Box 1. The meta-framework of environmental sensitivity

Environmental sensitivity (ES) is a meta-framework [42,50] summarising several theories that emerged independently and in parallel across diverse study fields. This framework highlighted two commonalities: First, that sensitivity is considered an evolutionary advantage only if a minority of the population is highly sensitive (Figure I). Secondly, sensitivity can be both advantageous and harmful depending on the environment, as the same aspect responsible for sensitivity to negative environments is also responsible for flourishing in positive environments.

This latter idea is primarily known as Differential Susceptibility Theory (DS), suggesting that factors such as genetics, neurobiology, and pre-and postnatal environments can be responsible for sensitivity or resilience to the environment [4,73]. Within this idea, Vantage Sensitivity Theory (VS; [74]) and Diathesis–Stress Theory (DiaS; [75]; also known as dual-risk theory; [76]) make up two sides of the same coin. However, DiaS describes sensitivity to only adverse environments without making predictions about sensitivity to positive influences [77], whereas VS describes sensitivity to only positive environments without making predictions about sensitivity to adversity; for example, children with high IQs can excel in high-quality education without being disproportionately harmed by poor-quality education [74].

From more biological-focused fields, Biological Sensitivity to Context Theory introduced a physiological basis applied to sensitivity, suggesting that heightened biological reactivity emerges from the most supportive and adverse exposures. Here, biological systems (e.g., autonomic nervous system) that increase vulnerability to physical and mental illness in adverse environments also increase susceptibility to health and well-being in resource-rich environments [77]. This line of thought also introduced the idea of orchid children (those highly sensitive to thrive in positive and languish in unfavourable environments) and dandelion children (resilient in any environment) [78].

Finally, SPS emerged, introducing sensitivity as an evolutionarily conserved adult personality trait, documented in >100 species [1,79].

The framework of ES brings these theories together, summarising that genes and environments influence the central nervous system (both early and later in life) and that this is then expressed in (trait) psychological and physiological reactivity [42,50]. This framework also posits that the developmental environment can impact the type of sensitivity that develops if a genetic predisposition exists. For example, in neutral environments, sensitivity to positive and negative stimuli can occur (DS), while VS and DiaS can develop in positive and negative environments, respectively.

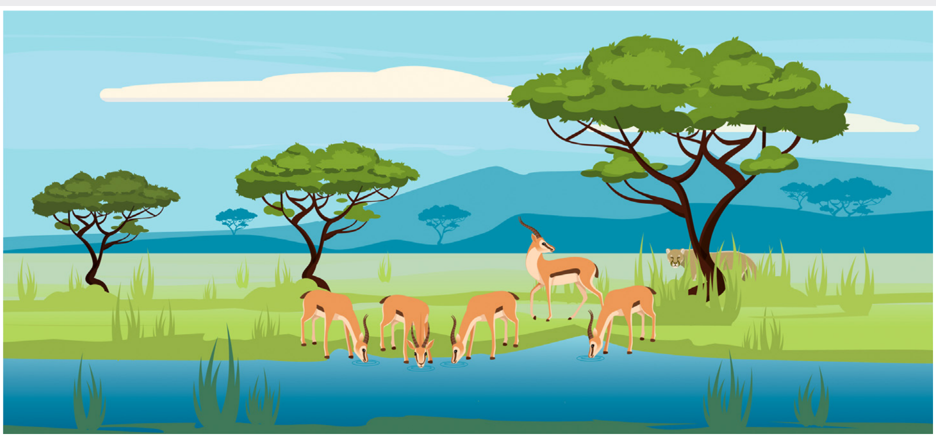

Figure I. Evolutionary perspectives on sensory processing sensitivity (SPS). High sensitivity entails costs as increased time and energy is spent on environmental monitoring, but also offers advantages. Among five gazelles, the highly sensitive individual drinks more slowly while scanning for predators (akin to pausing to check in high SPS), but is also at reduced risk of predation and quick to warn others. Evolutionarily, the success of a sensitive strategy is negative frequency-dependent, being advantageous when a minority, approximately one in five individuals, are highly sensitive [1,80]. Image from [81].

challenges that point to the need for a unifying account of SPS. The second part introduces such an account based on the framework of **predictive processing** [5,6]. This framework offers a powerful lens through which to interpret how seemingly diverse core SPS characteristics may

Glossary

Aesthetic Sensitivity (AES): a subscale of the HSP and HSC scales assessing appreciation and responsiveness to art, music or subtle environmental details.
Big 5: the Big 5 personality traits – openness to experience (short: openness), conscientiousness, extraversion, agreeableness, and neuroticism – are a widely recognised model describing key dimensions of human personality. Each Big 5 trait has subdimensions called facets.
Depth of processing: a term from classic memory research distinguishing deep semantic processing from shallow sensory processing. In the SPS literature, depth of processing relates to heightened prospective and retrospective reflection on consequences, often accompanied by inhibited behavioural tendencies (pausing to check) that enable more elaborate information processing, thorough decision-making, and a careful, thoughtful behavioural response.
Differential susceptibility: a theory proposing that some individuals (e.g., those high in SPS) are more susceptible than others to both supportive and adverse environments.
Ease of Excitation (EOE): a subscale of the HSP and HSC scales assessing sensitivity to being easily overwhelmed by external stimuli, stress, or demands.
Emotional reactivity: intensity and duration of emotional responses to both positive and negative stimuli.
Empathy: a multifaceted concept that includes emotional resonance with others' feelings and cognitive understanding of their perspectives.
Environmental Sensitivity: a meta-framework that unites theories and concepts that have in common that high sensitivity is evolutionarily beneficial for a minority and increases susceptibility to positive and negative stimuli.
General factor of sensitivity (GFS): an overarching sensitivity factor emerging from bifactor modelling labelled GFS, in analogy to the g-factor of intelligence and the Big 5 general factor of personality (GFP).
Highly Sensitive Child (HSC) scale: the childhood adaptation of the HSP scale.
Highly sensitive person (HSP): the popular term for SPS.
Highly Sensitive Person (HSP) scale: the classic SPS questionnaire,

emerge from a shared mechanism. We then evaluate the extent to which current empirical literature supports this account. Although direct computational or neuroimaging tests of this account are still lacking, we show that many recent behavioural and neural findings are consistent with its predictions.

Rather than offering a systematic review, we selectively focus on key studies published since the last comprehensive review [2] and identify key knowledge gaps. Except for Box 1, we review literature on the specific SPS construct, rather than general environmental sensitivity. In this review, we use terms such as HSPs and high SPS individuals interchangeably.

Characterising SPS: assessment, personality links, outcomes, and conceptual challenges

Fundamental questions remain about how to measure SPS, how it relates to other personality traits, and what drives its associations with diverse positive and negative outcomes. This section reviews recent findings on these topics and highlights key conceptual and methodological challenges that need to be addressed to advance a mechanistic understanding of SPS.

Assessment and links to established personality traits

SPS is considered a personality trait, capturing stable interindividual differences in patterns of perceiving, feeling, thinking, and behaving, particularly in response to environmental stimuli. Like other personality traits, SPS is most commonly assessed by self-report questionnaire. The **HSP scale** [1], used widely across SPS literature, includes three empirically derived subscales: **Ease of Excitation (EOE)**, reflecting how easily one feels overwhelmed by stimuli (e.g., 'Do you get rattled when you have a lot to do in a short amount of time?'); **Low Sensory Threshold (LST)**, reflecting discomfort in response to intense sensory input (e.g., 'Are you bothered by intense stimuli, like loud noises or chaotic scenes?'); and **Aesthetic Sensitivity (AES)**, capturing appreciation and responsiveness to subtle environmental details (e.g., 'Are you deeply moved by the arts or music?'). While these subscales offer a nuanced description of daily experiences, they capture some theorised SPS characteristics (Figure 1A), namely depth of processing and empathy, only indirectly, and tend to overemphasise negative aspects of overstimulation. This discrepancy between theorised conceptualisation and assessment may limit construct validity and complicate efforts to link SPS to underlying mechanisms. Recent work has begun to address these issues by developing more comprehensive and objective SPS assessment tools (Box 2).

Regarding links to established personality traits (Box 3), SPS shows moderate correlations with **Big 5** Neuroticism and Openness to Experiences, although it also shows incremental validity, predicting outcomes beyond Big 5 dimensions [7–12]. Research also suggests that associations of SPS with Big 5 may differ across age and culture [13,14], pointing to the need to disentangle heterogeneity. Moving forward, research should clarify the unique contribution of SPS by examining its predictive value relative to specific personality facets in real-world functioning. Clarifying this distinctiveness is essential if SPS is to be grounded in a mechanistic understanding that goes beyond existing trait taxonomies.

Positive and negative outcomes

SPS has been linked to both negative and positive outcomes. On the negative side, studies consistently report modest to moderate associations between SPS and stress-related symptoms, including higher levels of anxiety and depression [13,15,16], perceived stress [10], and burnout [17–19]. The subscales EOE and LST show the strongest associations with poorer health outcomes. Preliminary findings also suggest modest links between SPS and neurodevelopmental traits (e.g., ADHD, autism) [20–23], and with somatic complaints such as general health issues

commonly analysed as a total score and three subscales (LST, EOE, and AES).
Low Sensory Threshold (LST): a subscale of the HSP and HSC scales referring to inter-individual differences in unpleasant sensory arousal and discomfort in response to environmental stimuli such as bright lights or loud noises.
Overstimulation: state of being overwhelmed by excessive sensory input, leading to cognitive and emotional fatigue, difficulty processing information, and a need for withdrawal or rest.
Precision: a second-order estimate of the inverse variance (i.e., reliability) of a prediction error. Precision modulates the gain of prediction errors, determining their influence on belief updating. Signals assigned high precision are treated as more informative and exert stronger effects on perception and experience.
Prediction error: the mismatch between predicted and actual sensory input. Prediction errors signal a need to update internal models of the world. Their influence on experience depends not only on their magnitude but also on their precision (see above).
Predictive processing: a theoretical framework in which brains minimise sensory prediction errors to give sensations meaning and guide adaptive interactions with the environment. The brain constantly generates predictions about the causes of sensory inputs based on past experiences and updates these when prediction errors arise and the sensory evidence is deemed reliable (i.e., assigned high precision).
Sensitivity to subtle sensory inputs: the tendency to notice low-intensity stimuli, such as faint sounds or subtle emotional cues.

Box 2. SPS assessment

The seminal measure of SPS is the HSP scale, developed informed by literature and qualitative interviews with American adults [1]. Originally conceptualised as a unidimensional scale, later factor analytic approaches most commonly found a three-factor solution, namely EOE, LST, and AES [82], or a bifactor solution consisting of a **general factor of sensitivity (GFS)**, in addition to specific EOE, LST, and AES factors [49]. A bifactor model suggests that studying both the SPS total score and three subscales is important. Next to the original 27-item self-report HSP scale, short forms exist (e.g., 12-items; [50]). Latent class analyses reveal three groups along the HSP scale continuum: low, medium, and high sensitivity and referred to as dandelions, tulips, and orchids, indicating that a minority, roughly 30%, are high SPS scorers on the sensitivity continuum [49,83,84]. However, while the flower metaphor is compelling, it risks oversimplifying a normally distributed dimensional construct and may unintentionally introduce evaluative bias. First examinations [49] appear to suggest that low-medium-high classes differ in degree rather than kind. This supports the view of SPS as a continuum and the usefulness of focusing on population norm scores rather than cut-off scores to reflect a person's relative position on this dimension.

Importantly, the HSP scale, although commendably being the seminal scale, has shortcomings: it does not fully capture the theorised construct (e.g., mainly negatively phrased items, few items on sensitivity to subtle stimuli and empathy; depth of processing is only indirectly captured in the AES subscale). Furthermore, it was never designed to capture the EOE, LST, and AES subscales. Recently, new promising assessment tools have been developed that better capture the theorised SPS characteristics, such as the Adult Self-Report SPS Questionnaire [85], the DOES scale [86], and most recently the HSP-Revised scale [87]. Objective SPS assessment in adults is lacking. Performance tests on ability SPS (reflecting maximum performance) as opposed to a personality trait (reflecting typical behaviour), in analogy to trait and ability emotional intelligence [88], are a so-far unexplored avenue.

Although SPS was originally established in adults, it has since been identified and studied in children. Regarding children, the Highly Sensitive Child (HSC) scale is available in school-aged children for self-report [89] or parent-report (HSC-PR) [90]. The HSC scale shows the same factor structure (three-factor or bifactor) [89] as the HSP scale and suffers from the same conceptual limitations. To increase objectivity, a multi-informant interview for primary school children [91], a laboratory-based observational behaviour rating systems in preschoolers [92,93], a Q-set measure of broader temperamental sensitivity in preschoolers and young children [94], and a teacher-rated HSC in school scale [95] have been developed.

[7,24] and gastrointestinal symptoms [25]. However, many of these studies linking mental and somatic health are limited by cross-sectional designs, sole reliance on self-report, and nonclinical or unrepresentative samples.

Box 3. Differentiation of SPS from established personality traits

As with any novel personality construct, it is essential to examine how SPS overlaps with and differs from established traits. For instance, SPS appears moderately associated with the behavioural inhibition system, a temperament trait reflecting an individual's tendency to be cautious in response to perceived threats, and with the Big 5 personality trait Neuroticism in children and adults [14]. Additionally, SPS modestly correlates with the Big 5 trait Openness in adults, but not children, possibly due to a different operationalisation of Openness in children or due to developmental effects [14]. Big 5 Introversion mostly shows small associations or is unrelated to SPS [14]. However, cross-cultural differences may exist; for example, in Japanese samples, clearer associations of SPS with introversion are found [13].

The Big 5 traits consist of lower-order facets, and some studies suggest that SPS is a unique profile within the Big 5 personality space, but at facet level [96]. Regarding higher-order personality constructs, GFS shows a modest correlation (-0.41) with the GFP, suggesting that higher SPS people report lower GFP scores (reflecting lower emotional stability, and higher extraversion, open-mindedness, agreeableness and conscientiousness) [97].

Importantly, with exceptions [98], multiple studies demonstrate that SPS explains additional variance over and above Big 5 dimensions, for instance in theory of mind [11] and neurocognitive tasks [12], demonstrating good incremental validity. Only few studies [7–10] have explored whether SPS accounts for variance in health outcomes beyond the well-established health risk factor Neuroticism, showing associations may decrease but often remain significant. Lastly, SPS, especially EOE, correlates moderately with vulnerable and hypersensitive narcissistic traits, with Openness to Experience (positively correlated only with SPS) and Agreeableness (negatively correlated only with hypersensitive narcissism) being differentiating factors [33].

Although SPS is generally found to be associated with, yet distinct from, established traits, this conclusion warrants caution. As Brunswik's lens model [99] highlights, correlations must be interpreted in light of the abstraction level of the constructs. Comparing broad traits to specific SPS-related behaviours may create a false impression of incremental validity. Future research should examine whether relevant facets of Neuroticism and Openness account for daily-life outcomes attributed to SPS, to clarify its unique explanatory value.

In contrast, positive outcomes are most often linked to the AES subscale, including creativity [26], ethical decision-making [27,28], proenvironmental attitudes [29,30], and resilience [15,31,32]. Emerging person-centred studies suggest that such positive or negative outcomes may not apply uniformly to all highly sensitive individuals, but rather differ depending on which HSP subscale is especially high in one's SPS profile [33,34]. Importantly, while SPS is on average associated with both negative and positive outcomes, outcomes may vary considerably depending on environmental conditions, consistent with the differential susceptibility framework. Figure 2 and Supplementary Table S1 summarise evidence on SPS-related outcomes, including differential susceptibility, while Box 4 addresses their origins in early development and genetic and environmental factors.

Conceptual challenges and need for a mechanistic framework

Despite advances in the measurement of SPS and in differentiating it from established personality constructs, a key question remains unresolved: how do the seemingly distinct key SPS characteristics arise together within individuals? How can they lead to both positive and negative outcomes depending on context? As reviewed in the preceding section, current evidence points to heterogeneity in SPS expression and outcomes, raising further questions about what constitutes core sensitivity shared by everyone high in SPS versus secondary consequences. These conceptual challenges highlight the need for a mechanistic framework that not only explains how the key theorised SPS features co-occur but also accounts for the observed variability in outcomes across different environments. In the next section, we propose such a framework grounded in predictive processing.

A predictive processing account of SPS

SPS currently lacks an explanation that bridges cognitive, neural and computational perspectives. We propose that inflexibly high **precision** weighting of sensory **prediction errors** within an overall theory of brain function, predictive processing [5,6], may provide a coherent account of how the SPS phenotype logically emerges from the brain's overall imperative to predict what sensory signals are informative for goal-directed action. We first describe this account, and then evaluate the literature for empirical support of derived predictions.

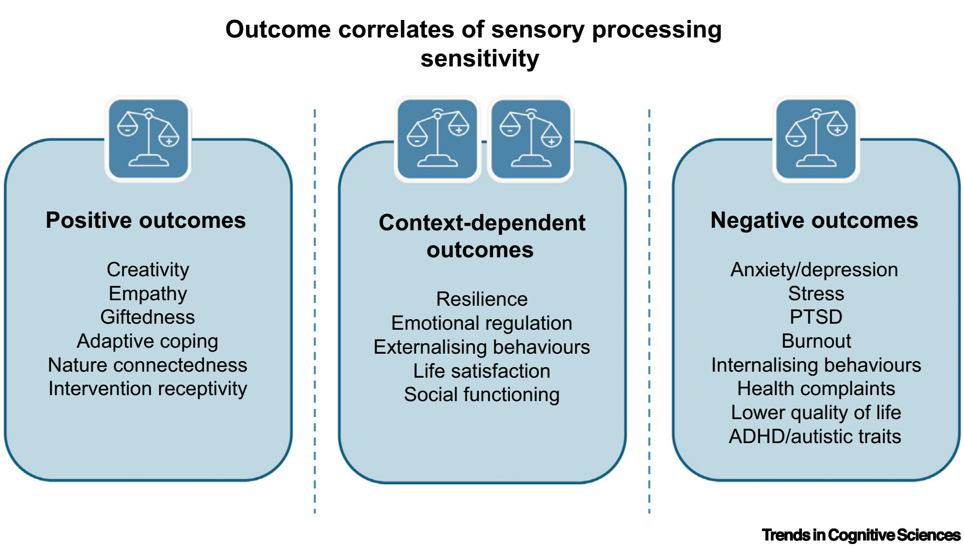

Figure 2. (Context-dependent) positive and negative correlates of sensory processing sensitivity. The studies underlying the figure are listed in Table S1 in the supplemental information online.

Box 4. Sensitive developmental periods and genetics

Tentative evidence suggests that the origin of SPS-related negative and positive outcomes may lie in development [45]. During sensitive periods in development, the environment can, in general, exert a particularly strong influence on belief formation, inducing so-called stubborn predictions that are resistant to change based on new experiences later in life [44]. This should be even more the case when sensory sensitivity is high, which may account for the observation that high-SPS individuals appear more impacted by both negative and positive environments in childhood and the development of different sensitivity profiles [42,45].

Genetics may further add to the explanation. Key evidence for a genetic basis comes from recent twin research [100,101]. In one study of 2868 adolescent twins, genetic factors accounted for 47% of individual differences in environmental sensitivity, as measured with the Highly Sensitive Child (HSC) scale [100]. The remaining variance, 53%, was attributable to non-shared environments that contribute to differences between siblings growing up in the same family. Genetic factors may affect how individuals process and respond to environmental inputs through effects on monoaminergic neurotransmitters and neurotrophins [58,102], which play essential roles in driving neuroplasticity and postnatal sensitive periods [45]. Genetics also indicates that early life experiences may shape an initially neutral genetic predisposition to increased environmental sensitivity into one that leans toward heightened susceptibility to either negative, positive, or both types of environmental influences [42]. As such, early life experiences may shape enduring patterns of environmental responsiveness, whereby subgroups of highly sensitive individuals develop different sensitivity profiles that may be challenging to modify in later development stages [81].

Future neuroimaging studies should longitudinally test the hypothesis that enhanced sensitivity to life events, whether positive or negative, permits these events to leave a greater imprint on the brain. Additionally, research should examine whether early preventive interventions can shift sensitivity profiles toward increased susceptibility to positive environments and reduced susceptibility to negative ones, particularly in light of evidence that such profiles are shaped by both early experiences and genetic predispositions.

Predictive processing, which is explained in detail in Box 5, starts from the fact that our brains can only know the world indirectly, via the electrical signals conveyed by the senses. To infer the world, brains must hence instantiate generative models of the hidden causes of their sensory inputs, based on past experiences and statistical structure in the world, while continuously assessing model accuracy. That is, the core responsibility of the brain is to minimise errors between its model predictions and the incoming input [35,36]. However, brains cannot simply revise the probability of hypotheses whenever prediction errors occur, as sensory signals are often noisy or not representative of the larger world. They hence have to predict the informativeness or precision (inverse variance) of sensory evidence (prediction errors) [37]. This precision determines the weight of the mismatch between predicted and actual sensory input, relative to the confidence in prior beliefs. It thus governs the influence of bottom-up inputs over top-down expectations in a context-sensitive manner.

To adaptively align with the environment, the brain must balance model stability and flexibility [38]. A model grounded in past experience is adaptive (it aligns the organism with its econiche) but can become maladaptive when not sensitive enough to meaningful environmental changes. Conversely, models that are easily revised based on new or irrelevant sensory inputs can become inaccurate and unstable, reducing grip on the world. The brain must also balance model accuracy versus complexity. While complex models capturing many sensory details are very accurate, they less readily generalise to new environments, reducing model accuracy in the long term (see Figure I in Box 5). However, incorporating more subtle information can also yield richer models, broader action repertoires and better contextual alignment.

How SPS might be understood within predictive processing

Given that in the predictive processing framework, sensory signals are the only currency for inferring the world, individual differences in the precision assigned to prediction errors (the expected informativeness of sensory inputs) can exert a crucial influence on mental functioning through their effects on belief updating, model stability and complexity. We thus put forward that uniformly increased precision assigned to incoming prediction errors, which correspond to generally

Box 5. Predictive processing

Over the past two decades, the notion of the brain as an organ of predicting error minimisation has rapidly gained scientific traction [35], and is receiving growing empirical support [69,70]. The core idea is this: as brains only have indirect access to the world, via electrical impulses from the senses, brains must continuously infer, based on past experiences and statistical regularities in the world, the hidden causes of its sensory input to guide interactions with the world [5,36]. In this perspective, perception is not the outcome of a largely stimulus-driven process of feature detection and evidence accumulation, as traditionally assumed, but a process of top-down inference. What ascends the processing hierarchy is not the sensory input per se, but the mismatch between the brain's a priori predictions and the input, or so-called prediction errors, which alone convey novel information, not yet accounted for by the brain's generative models (Figure I). Brains can minimise prediction errors in two ways. First, through perceptual inference, brains can update beliefs to accommodate unpredicted input. Perceptual inference can be formalised as Bayesian inference, in which prior beliefs (prior, the probability of the cause before the evidence came in) and sensory data (likelihood, the probability of the input, given the cause) are represented as probability distributions. Through Bayesian inference, prior beliefs are integrated with current sensory evidence, weighted by their precision (the inverse of their variance), forming the posterior probability, representing updated beliefs or the most likely percept. By dynamically tuning the influence (precision) of sensory inputs versus prior expectations, brains can ensure that perception is both accurate and adaptable. Second, through active inference, brains minimise prediction errors by acting to generate the expected input. For instance, expected proprioceptive feedback that fails to occur generates a prediction error, resolved through movement to match the prediction. Perceptual inference and active inference are interdependent processes: perception updates beliefs, while action tests and confirms them [6]. One can easily see how in this framework, enhanced weighting of sensory prediction errors does not only affect the influence of sensory inputs on perception (perceptual inference), but may also induce a more cautious behavioural style: when internal models are too easily revised, their volatility may render one less sure about how to act (active inference) (see Figure 1B in main text).

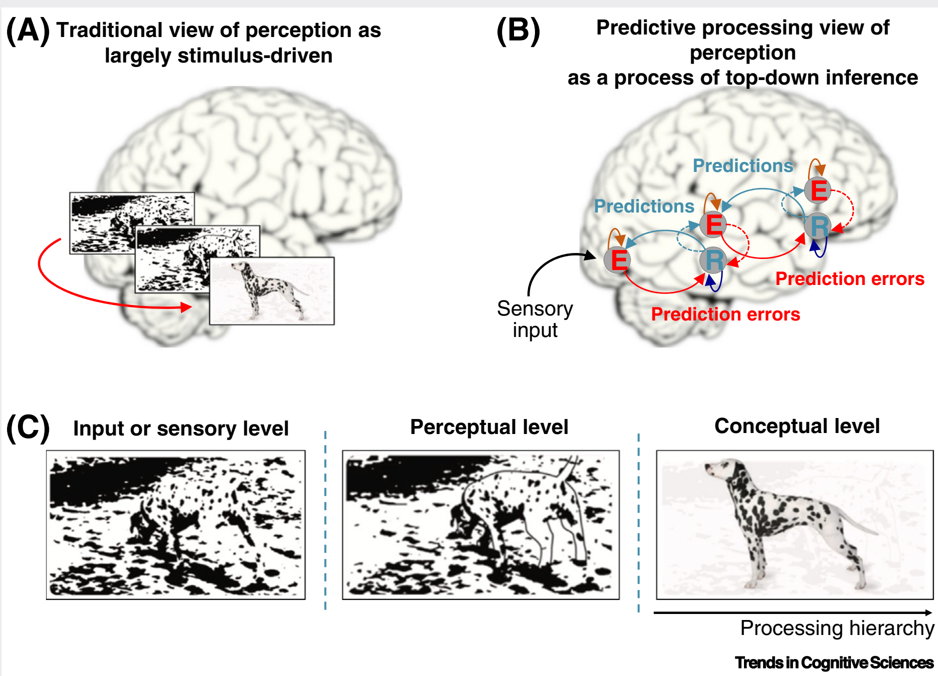

Figure I. Bottom-up perception versus predictive processing. (A) Traditional models view perception as bottom-up, stimulus-driven, where forward signals reflect stimulus properties (e.g., orientation). (B) Predictive processing reframes perception as top-down inference. At each hierarchical level, predictions from representation neurons (R) are compared to input by error neurons (E). Mismatches (prediction errors) are sent up the hierarchy until minimised via reciprocal exchanges. Thus, forward signals encode deviations from expectations, not raw input. (C) A simplified hierarchy: lower levels represent basic features (e.g., orientation), intermediate levels code shapes/objects, and top levels abstract concepts. If prediction errors are overweighted compared to top-down beliefs, too much sensory detail may reach higher levels, increasing noise and overfitting or enabling richer models. Adapted from Laukkonen *et al*. [103].

enhanced sensitivity to sensory inputs, can provide a parsimonious account of high SPS. More precise prediction errors can also penetrate deeper into the processing hierarchy, as precision weighting controls the relative influence of sensory inputs. That is, prediction errors generated by sensory inputs that are estimated to be precise (e.g., informative or reliable) are upregulated, while those of low precision are downregulated. As such, precision weighting determines what information is selected for further processing, akin to setting sensory gain. This can also explain associated downstream effects of enhanced sensory sensitivity, including a tendency to be more easily overwhelmed (by noise or irrelevant information), greater emotional reactivity, greater depth of processing, and enhanced learning from both positive and negative experiences (Figure 1B).

Consider, for instance, a person high in SPS entering their office. They are immediately affected by the brightness of the ceiling lights and detect subtle emotional tension in colleagues' expressions and tone, signals others may not notice. These sensory and affective inputs are amplified and penetrate deeper into the processing hierarchy, eliciting strong emotional responses and the environment quickly becomes overwhelming. Later, even the sound of the TV, normally tolerable, feels loud and intrusive, reflecting prolonged processing. A relatively greater sensitivity to outside signals may also explain enhanced empathy observed in high SPS individuals [39]. That is, in predictive processing, empathy arises from minimisation of discrepancies between predictions and sensory evidence and relates to altering one's own state to be in line with another's state (i.e., model revision, Box 5) [40].

Accounting for positive and negative outcomes through predictive processing

Our account of SPS as characterised by more precise prediction errors may also explain why SPS is linked to both vulnerability and strength. More precise prediction errors enhance belief updating, rendering the environment more influential. On the one hand, such greater sensitivity to environmental inputs can have negative outcomes, as internal models may become too volatile, contributing to overall greater uncertainty about the environment (e.g., what aspects are relevant?), causing anxiety and emotional instability. This may explain the association of high SPS with anxiety, emotional instability, and neuroticism [7,16,41]. Greater uncertainty about the state of the world also renders it more difficult to settle on stable policies for action, which may contribute to the inhibited, careful exploratory and reactive behavioural style of highly sensitive individuals [42].

On the other hand, greater sensitivity can have positive effects, as a greater openness and alignment to the current environment may facilitate (social) connectedness and increase adaptability. The persistent upweighting of sensory prediction errors should also lead to the instantiation of more complex internal models that accommodate and integrate more (subtle) information, which may account for enhanced creativity, and the link between SPS and vividness of mental imagery [43]. However, when this inflexible precision weighting especially affects early sensory stages, this may drive the formation of highly detailed but narrowly tuned priors, that is, internal models that are exceptionally accurate for the current context but less generalisable across environments. Such overfitted models may amplify uncertainty when faced with novel or ambiguous situations, adding to the cognitive and emotional load experienced by highly sensitive individuals.

During sensitive developmental periods, environmental input plays a particularly influential role in shaping generative models of the brain, often resulting in so-called stubborn predictions: priors that are resistant to revision later in life [44]. This effect is likely amplified in high-SPS individuals, as increased expected precision enhances the influence of early sensory experiences on model formation [45]. This may help explain why high-SPS individuals are especially impacted by both adverse and supportive environments in childhood, contributing to the emergence of distinct sensitivity profiles across development [42].

To conclude, our account of SPS offers a more comprehensive and mechanistic account of high SPS, as it explains how greater sensory sensitivity arises: through persistently strong bottom-up drive due to prediction errors being assigned high precision. It can also explain the phenotypic consequences of enhanced sensory sensitivity in a unified model, through its effects on belief updating and generative model formation.

Predictive processing hypotheses

Our account importantly makes several specific predictions. At the behavioural level, our account predicts that high-SPS individuals should be more sensitive to both (weak) signals and noise. That is, they should show enhanced perceptual sensitivity in conditions where bottom-up sensory signals are weak but truly present. This should be evident in improved detection or identification of degraded or low-contrast stimuli, reflecting an increased influence of sensory evidence in perceptual inference. Importantly, this sensitivity advantage should diminish or even reverse under high-noise conditions, where the same mechanism may lead to greater susceptibility to noisy or irrelevant input, resulting in elevated false alarm rates, and may cause the system to become overwhelmed by irrelevant sensory signals. Our account also predicts that high-SPS individuals display stronger stimulus-driven attentional capture and benefit less from top-down attentional cues, due to a general enhancement of sensory gain. That is, sensory inputs are assigned more weight, increasing the chance that bottom-up inputs, in particular when unexpected, trigger downstream processing (i.e., capture attention).

All these behavioural predictions follow from a single mechanism – increased expected precision – which enhances the strength of incoming signals at early levels of the processing hierarchy and can produce both perceptual benefits and vulnerabilities depending on the structure of the environment. At the neural level, high-SPS individuals should show amplified early sensory responses (e.g., P1/N1 ERP components) and greater activity in superficial cortical layers, which should induce greater activation of secondary areas due to stronger hierarchical propagation of prediction errors. Finally, at the computational level, high-SPS individuals should assign inflexibly high precision to sensory prediction errors, leading to persistent over-weighting of bottom-up sensory evidence relative to prior beliefs, even in contexts where sensory input is noisy or contextually unreliable.

This can be computationally differentiated from alternative mechanisms that would also enhance the relative influence of bottom-up inputs over existing beliefs, such as weakened priors or suboptimal control of precision due to an underestimation of environmental volatility. Note that weakened priors would lead to under-constrained inference that is more variable and context dependent, whereas our account predicts a consistent, trait-like amplification of prediction errors. Underestimation of environmental volatility, in turn, predicts context-dependent patterns of reactivity: relative hyper-reactivity in stable environments and hyporeactivity in volatile ones. This does not align with the consistently heightened responsiveness observed in high-SPS individuals. By contrast, our account provides a parsimonious explanation for the consistent, trait-like pattern of heightened sensitivity and overstimulation observed in high-SPS individuals.

Empirical support for the predictive processing account

In the next sections, we evaluate the extent to which existing empirical findings are consistent with the predictions of our account. Our review shows that, so far, our account lacks direct empirical testing. We therefore draw on indirect evidence from the literature and identify key avenues for future research.

Evidence from behavioural studies

In our account, inflexibly high precision weighting of sensory prediction errors or generally enhanced sensitivity to sensory inputs is core to SPS. A growing, but still small number of behavioural studies in adults, mostly using the HSP scale total score, provides first experimental support congruent with this notion and with self-reports by high-SPS individuals that they are more sensitive and reactive to sensory inputs. Consistent with enhanced sensitivity to (subtle) sensory inputs, higher HSP scale scores correlate with faster detection of meaningful visual stimuli made difficult to perceive [46–48]. For example, one recent study found across ten experiments that an individual's non-conscious visual prioritisation speed, measured using breaking continuous flash suppression, was consistent across different types of stimuli, generalised across visual masks and suppression tasks [47]. Crucially, this variation in nonconscious visual prioritisation speed was uniquely predicted by HSP scale scores and could not be explained by variation in general processing speed, perceptual decision thresholds, short-term visual memory or attention performance, suggesting that high-SPS individuals experience more of their surroundings. In another study, SPS predicted enhanced detection and identification of degraded visual stimuli beyond the Big 5 traits [46]. Individuals with higher HSP scale scores also more easily detected degraded auditory stimuli [48]. This is suggestive of enhanced perception of subtle stimuli across modalities. Notably, higher SPS scores were not related to misperception of patterns in the degraded input (pareidolia), a phenomenon typically driven by strong top-down priors, which is in line with our account that incoming evidence is favoured over top-down expectations in SPS. The aforementioned findings indicate generally heightened sensory sensitivity in SPS at the behavioural level. However, as no study on SPS so far has included computational modelling, it is challenging to differentiate between our proposed account (i.e., inflexibly high precision weighting of sensory prediction errors) and alternative mechanisms that would also enhance the relative influence of bottom-up inputs over existing beliefs, such as weakened or imprecise predictions or suboptimal control of precision due to an underestimation of environmental volatility. Future studies should test our core hypothesis by combining experimental manipulations of different sources of uncertainty (sensory, probabilistic, environmental) with computational modelling to reveal whether increased expected sensory precision is indeed the key mechanism underlying SPS.

Within predictive processing, sensory prediction errors that are treated as more informative (precise) can penetrate deeper into the processing hierarchy. This should have downstream effects and can explain other key features of SPS, such as greater emotional reactivity, ease of overstimulation, depth of processing and empathy (Figure 1). Consistent with enhanced emotional reactivity, high SPS individuals showed greater reactivity to both negative and positive emotional stimuli in the laboratory [49,50], and self-reported more intense negative, but not positive, daily life events in a diary study [51]. Moreover, individuals with higher HSP scale scores benefitted less from top-down attention-directing cues [12], indicating enhanced stimulus-driven, bottom-up attention. Another study found that higher HSP scale scores correlated with better memory when there was no distraction during a post-learning period before the memory test, but with worse memory with intermittent distractions [52], possibly indicative of deeper processing in the absence of distractibility. One study found that high-SPS participants made better ethical decisions when given more time to think, but worse decisions when asked to provide a concrete practical solution [27], consistent with greater depth of processing and an inhibited, careful exploratory behavioural style [42]. Finally, there is tentative evidence that SPS is associated with enhanced social emotion recognition [11], which may contribute to greater empathy.

Thus, behavioural studies associate SPS with individual differences in sensory sensitivity and other key SPS characteristics. Further research is needed to clarify the extent and nature of the relationships among these key characteristics of SPS, and to distinguish core features of sensitivity from secondary consequences. Future studies should determine how SPS may relate to or differ from conditions with overlapping characteristics. Core symptoms of several psychopathologies, including autism and ADHD, have also been explained as aberrant predictive processing [53]. Autism, which is, amongst others, characterised by differences in sensory processing, has been explained in terms of a uniformly high and inflexible level of precision assigned to prediction errors [54], similar to our SPS account. However, computational modelling studies have found little evidence for uniformly increased sensory precision in autism, but instead point to aberrant context-sensitive modulation of prediction errors (i.e., precision control) [55,56]. This may also explain why autism is associated with both hyper- and hyporeactivity to sensory input, whereas high SPS appears related only to hyperreactivity. Computational modelling may thus not only provide a mechanistic understanding of SPS, but also clarify how it relates to or diverges from phenotypically similar conditions.

Evidence from neurobiological studies

It is commonly believed that individual differences in SPS are related to individual characteristics of brain structure and function [2,57]. However, so far, surprisingly few studies have examined the neural mechanisms underlying SPS and the notion that SPS reflects differential sensitivity of the brain to environmental inputs [2,42,58]. Moreover, none of these directly examined the role of aberrant predictive processing in SPS. Accordingly, this body of literature can also offer only indirect insights relevant to our account. In line with the behavioural evidence discussed in the preceding text for enhanced sensory sensitivity and emotional reactivity, task-based fMRI studies have associated SPS with significantly greater activation in brain areas involved in high-order visual processing, when detecting minor changes in visual scenes [59] (n = 16), with greater reactivity to emotional stimuli in the amygdala and insula [60,61] (n = 18 and n = 14, respectively) and with affective touch in the insula [62] (n = 22). These brain regions are part of the salience network, which has been posited to play a critical role in SPS by driving bottom-up attention to external events [58]. Another fMRI study (n = 238) only found a relationship between SPS and the central executive network during threatening movie watching [63]. Other studies have associated SPS with interindividual differences in resting-state functional connectivity in the ventral attention, dorsal attention, and limbic networks [64] (n = 15), the microstructure of brain white matter [65] (n = 408), resting-state beta and gamma activity [66] (n = 115), and neural entropy as measured with EEG [67] (n = 115).

The current literature thus overall supports the notion that SPS reflects individual differences in brain and stimulus reactivity. However, it should be noted that the sample size of many of these studies was very small, so their findings should be considered preliminary and require confirmation in future research. Future studies should combine EEG and fMRI with computational modelling to reveal whether increased gain assignment is indeed the key mechanism underlying SPS and when and where in the predictive hierarchy individual differences in SPS may arise. Layer-specific fMRI could reveal whether high SPS is associated with enhanced superficial-layer activity in early sensory areas, as expected if increased weighting of sensory prediction errors underlies SPS. Finally, future research should also determine the neuromodulatory basis of SPS. Within predictive processing, activity in the cholinergic system is related to sensory precision [68], as acetylcholine receptors have been shown to modulate sensory gain. However, so far, research has focused on dopaminergic and sensory contributions to SPS, and mostly in animals or through genetic studies [45].

Concluding remarks

Scientific understanding of SPS has significantly advanced since the last comprehensive review [2]. Evidence has increased that while SPS shares variance with established personality traits, it also captures unique aspects not fully accounted for by the global Big 5 dimensions. Additionally,

Outstanding questions

What constitutes core sensitivity shared by everyone high in SPS, and what aspects of SPS give rise to positive and negative consequences of high SPS? How are secondary consequences influenced by interactions with environments and with other traits and experiences co-existing in an individual?

Could uniformly higher precision assigned to sensory prediction errors be the defining feature of core sensitivity?

What are the computational, neurobiological, pharmacological, and genetic underpinnings of SPS?

How can our account be related to predictive processing accounts of internalising (e.g., anxiety or depression) and neurodevelopmental conditions (e.g., ADHD or autism)? Is higher weighting of sensory prediction errors in SPS a transdiagnostic trait (present across diagnoses, acting as a causal risk or maintaining factor) or a stratification marker (an extension to diagnosis that clarifies the course or severity of a psychiatric condition, or likelihood of intervention response)?

Can associations between SPS and self-reported health outcomes be backed-up by objective assessments in clinical or epidemiological samples?

How can negative and positive consequences of high SPS be prevented and fostered, respectively? How can people high in SPS benefit more from positive environments?

Is SPS as constellation of Big 5 facets? Can SPS demonstrate incremental validity over established personality constructs, especially relevant facets of Neuroticism and Openness, when predicting specific behaviours and experiences in daily life?

How do genetic and environmental factors interplay to influence emotional and behavioural outcomes in highly sensitive children, adolescents and adults?

How is SPS experienced or expressed within and across different groups (e.g., culture or gender)? Are only certain SPS profiles more at risk or resilient?

SPS reflects partially heritable individual differences, which can impact cognitive functioning and mental health in both positive and negative ways. Experimental evidence has also validated key SPS characteristics, and initial studies have begun to explore its neural basis. In adults, new questionnaires better capture key characteristics of SPS, while the child and adolescent literature has introduced objective assessment tools. However, understanding of how SPS characteristics arise and relate is still limited.

In this review, we therefore introduced a novel account of SPS as uniformly higher precision assigned to sensory prediction errors, which provides not only a mechanistic explanation for enhanced sensory sensitivity as seen in SPS, but can also accommodate a broad range of positive and negative outcomes associated with high SPS through downstream effects on attention, depth of processing, learning, and the development of action policies. For example, increased depth of processing, central in the subjective experience of high SPS individuals, can be understood as a consequence of heightened sensitivity to subtle sensory inputs, which can penetrate deeper into the processing hierarchy, increasing semantic engagement. While predictive processing has gained substantial theoretical traction and growing empirical support [69,70], our application to SPS so far remains largely hypothetical. However, as delineated in the preceding text, our account offers mechanistic and neurobiological specificity sufficient to generate testable, falsifiable hypotheses. Future research combining self-report with objective tasks, computational modelling, and neuroimaging is necessary to confirm the explanatory power of our account and further understanding of the computational and neurobiological mechanisms underlying SPS.

Despite these exciting developments, the SPS field is still young and evolving (see Outstanding questions). Although quality of studies has generally increased in the past five years, many studies remain cross-sectional, still solely rely on subjective self-report, and too often use unrepresentative or convenience samples, with an over-representation of educated women. Sample size issues also persist in some research, in particular in neuroimaging. Researchers should also further study potential overlaps between SPS and Big 5, particularly using latent-level analyses, while also considering incremental validity and using newer SPS measurement instruments. While research has started exploring heterogeneity in SPS profiles using person-centred approaches [33,34], there is a lack of research exploring cultural [71] and gender [72] differences in the experience or expression of SPS. Further improved SPS assessment tools, including multi-rater objective and subjective perspectives, are needed. It is crucial to interpret the findings discussed in this review with these constraints in mind.

In summary, we have proposed a neurocognitive account of SPS that offers a unified explanation for the phenotypic consequences of heightened sensory sensitivity and provides a foundation for future research. Our review highlights both the significant progress made in understanding SPS and the wide-ranging implications of individual differences in SPS across domains, such as parenting, societal contexts and clinical settings. These insights can inform the development of tailored (preventive) interventions. As SPS gains recognition as a key trait reflecting sensitivity to environmental input with both clinical and societal relevance, future research should aim to refine our understanding of its underlying mechanisms and its expression in everyday life. We hope that our predictive processing account inspires this necessary shift from descriptive to mechanistic research on SPS, to reveal the fundamental principles that shape how individuals perceive, learn from, and adapt to the world.

Statement on AI usage

During the preparation of this work the authors used ChatGPT to improve language and readability of small sections of the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Declaration of interests

The authors declare no competing interests.

Supplemental information

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Resources

[i]https://osf.io/nqvth/?view_only=76930d5c64354f3fa93f6cb4cc3c07c9

[ii]https://hsperson.com/

[iii]https://sensitivityresearch.com

[iv]https://youtu.be/zSFBa6Xfp-s?si=j2A-L3uN6E-m24PG

[v]https://youtu.be/2tKDnsns2bg?si=LTX0zHbzLoJrGunD

[vi] https://youtu.be/HxmzcS2eQkM?si=1PFhVyixdEmvIQf9

[vii]https://sensitivethemovie.com

[viii]https://youtu.be/_lC4jY8HL4M?si=K-49UEirDyMh-D2_

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