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The relationship between sensory phenomena and interoception across the obsessive–compulsive spectrum: a systematic review

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Abstract

Background Uncomfortable sensations preceding repetitive behaviours, known as sensory phenomena, have been documented across the obsessive–compulsive spectrum. Indirect evidence suggests altered interoception may play a role in these shared experiences of sensory phenomena; however, research explicitly measuring this relationship is limited. The current systematic review aimed to establish the nature of sensory phenomena and interoception in obsessive–compulsive and related disorders (OCRDs) and tic disorders as potential maintaining factors of these disorders.

Methods PsycINFO, PubMed, and Scopus databases were searched from 2007 to April 2024, yielding 65 studies.

Results While the majority of studies presented low risk of bias, significant overlap and ambiguity characterised the measurement and conceptualisation of sensory phenomena and interoception. Overall, higher sensory phenomena was associated with greater symptom severity in several obsessive–compulsive spectrum disorders. Obsessive–compulsive disorder and tic disorder samples were characterised by lower interoceptive accuracy, with mixed findings on interoceptive sensibility. Some limited research emerged suggesting altered interoceptive abilities may be associated with greater sensory phenomena in obsessive–compulsive disorder and tic disorders.

Conclusions Sensory phenomena are experienced across the obsessive–compulsive spectrum. Future research should explore interoceptive abilities across the OCRDs, and build upon evidence supporting a relationship between sensory phenomena and interoception in OCD and tic disorders.

Trial registration CRD42023422817.

Keywords Obsessive–compulsive disorder, Obsessive–compulsive spectrum, Interoception, Sensory phenomena, Systematic review

Background

Prevailing theoretical models of obsessive–compulsive disorder (OCD) emphasise the role of dysfunctional appraisal of intrusive thoughts and the performance of compulsions to prevent perceived harm [59, 112, 135]. The predominant cognitive understandings of OCD were a key organising feature that contributed to the creation of the obsessive–compulsive and related disorders

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(OCRDs) category in the *Diagnostic and Statistical Manual of Mental Disorders* (DSM-5; e.g., [97]), which additionally includes skin picking disorder (SPD), trichotillomania (TTM), body dysmorphic disorder (BDD), and hoarding disorder (HD), American Psychiatric Association (APA) [3, 4]. Some viewed the creation of the OCRDs category as topographical, minimising the role of anxiety and dysfunctional cognitions typical of OCD [2, 97]. Despite criticisms, evidence supports a number of factors connecting OCRDs, including: shared patterns of comorbidity,performance of cognitive and body-focused ritualised or repetitive behaviours; neural circuitry (e.g., fronto-striatal circuitry and involvement of the insula); and poor treatment response to non-serotonergic medications [107, 121, 122, 143, 146]. Chronic tic disorders (CTD), including Tourette syndrome (TS), are another group of disorders considered to be part of a broader obsessive–compulsive spectrum, which share many similarities with OCD, including: high rates of comorbidity [38], comorbidity with other OCRDs [83]; high familiality [101], clinical characteristics (e.g., greater blinking or touching compulsions, spontaneous and self-damaging repetitive behaviours; [65, 72], and shared neurological correlates (e.g., cortico-striato-thalamo-cortical circuit dysfunction and altered insula connectivity, leading to excessive motor execution and difficulty with urge suppression [13, 125, 132, 138].

Recent research suggests that the phenomenology of OCD may extend beyond accepted cognitive models. It is well documented that not all compulsions are driven by harm avoidance motivations, and some individuals do not report identifiable feared consequences of their obsessions [31, 45, 56, 127]. Approximately 65% of individuals with OCD report experiencing uncomfortable sensations preceding their compulsions [54]. Globally referred to as "sensory phenomena" (SP, [101, 110]), compulsions preceded by these mental and/or bodily sensations are typically motivated by a sense of incompleteness and performed to alleviate feelings of imperfection and discomfort with one's body or environment [128], suggesting a potential role for an altered mind–body connection. The exploration of SP and its associated mechanisms in OCD warrants particular attention, given current gold standard treatments for OCD often leave individuals experiencing compulsions preceded by SP without meaningful symptom reduction [20, 118, 127]. Conducted more than 15 years ago, Prado et al.'s [101] review in OCD and tic disorder samples concluded that SP was an appropriate and comprehensive term for capturing the range of "subjective experiences" found to be particularly prevalent among individuals with early-onset and tic-related OCD. In the time following Prado et al.'s review, a significant amount of research has been conducted on the various forms of SP across the obsessive–compulsive spectrum, including the development of additional measures of this construct (e.g., [16, 128]. SP in OCD can manifest in multiple forms, including "not just-right" experiences [31, 32], feelings of incompleteness [128], and sensory over-responsivity to external stimuli [113]. SP has also been reported across the broader obsessive–compulsive spectrum, including: premonitory urges (PMUs) in TS/CTD [34, 82], incompleteness in BDD [27], NJREs in HD [139],and sensory over-responsivity and NJREs in TTM and SPD [18, 51, 75]. These forms of SP, shared among disorders of the broader obsessive–compulsive spectrum, may further suggest common aetiological or maintenance factors.

An emerging perspective highlights the role of interoception in experiences of SP across the obsessive–compulsive spectrum [25, 50, 73, 104, 123]. Interoception refers to one's ability to detect, interpret, and integrate internal bodily sensations [61, 91]. The leading model of interoception consists of three domains: (1) interoceptive accuracy comprises objective precision of one's detection of bodily states, while (2) interoceptive sensibility encompasses one's subjective sensitivity to internal processes, including how bodily sensations are interpreted and used to guide behaviour [61]. Finally, (3) interoceptive awareness is conceptualised as the congruence between one's objective accuracy and their reported confidence in their performance, that is, an individual's meta-cognitive representation of their interoceptive abilities [61]. In addition to these three core domains, the discrepancy between an individual's performance on objective interoceptive accuracy tasks and scores on self-report measures of interoceptive sensibility has been referred to as interoceptive trait prediction error, and is calculated by subtracting standardised scores on interoceptive accuracy tasks from interoceptive sensibility scores [62]. Exploration of the relationship between each interoceptive domain (i.e., objective, subjective, metacognitive, prediction error) and forms of sensory phenomena may reveal disorder-specific processes through which the mind–body connection contributes to symptom expression and maintenance.

Few studies have explicitly measured interoception in OCD, with even less direct exploration of the relationship between interoception and SP. Findings are mixed regarding the nature of interoceptive accuracy, with some studies reporting diminished interoceptive precision in OCD [39, 116], while others found enhanced interoceptive accuracy [149]. Regarding interoceptive sensibility, some researchers have proposed "adaptive" and "maladaptive" profiles of interoceptive sensibility based on attentional styles and correlates of psychopathology

[53, 89, 145]. Mehling [89] identified that the self-regulation, attention regulation, body listening and trusting subscales of the Multidimensional Assessment of Interoceptive Awareness (MAIA [90, 91]) are typically considered to reflect "adaptive" skills, while the noticing and emotional awareness subscales are ambiguous in their "adaptiveness". Conversely, lower scores on both the not-distracting and not-worrying MAIA subscales (i.e., reflecting greater distraction from sensations and greater worrying about sensations, respectively) may reflect "maladaptive" manifestations of interoceptive sensibility.

In OCD participants, while a principal components analysis of the MAIA [90] identified "adaptive" and "maladaptive" interoceptive sensibility components, a third component also emerged, comprising only the MAIA not-distracting subscale, which was associated with greater severity of SP and symmetry symptoms [50]. This could suggest that the relationship between SP and profiles of interoceptive sensibility is more nuanced in the context of OCD, not so easily delineated into a simple "adaptive" versus "maladaptive" dichotomy. Analogous findings linking interoception and SP have emerged in participants with TS [60, 104]. Both higher interoceptive accuracy on a heartbeat tracking task [60] and higher interoceptive sensibility on the Body Awareness subscale of Porges' [100] Body Perception Questionnaire (BPQ-BA [104],) were significantly associated with greater PMU severity in TS samples. Higher scores on this proposed measure of "maladaptive" interoceptive sensibility also predicted greater tic severity and functional impairment [104]. It is essential to clarify the nature and conceptualisation of both interoception and SP across the obsessive–compulsive spectrum, in order to reliably compare the role of specific domains or profiles of interoception in SP across these conditions.

The culmination of these findings suggests altered interoception may exacerbate SP in both OCD and TS, with potential for the generalisation of this relationship to OCRDs. However, it is first essential to clarify current understandings of both SP and interoception across the obsessive–compulsive spectrum. The current systematic review was guided by the following research question: What is the nature of sensory phenomena and interoceptive abilities across the obsessive–compulsive spectrum (i.e., OCD, TS/CTD, TTM, SPD, BDD, and HD), and what evidence currently exists in support of the relationship between these constructs as a maintaining factor of these disorders? In addressing this question, this review aimed to: (1) describe SP preceding compulsions, tics, and body-focused repetitive behaviours (BFRBs) across the obsessive–compulsive spectrum; (2) describe interoceptive abilities across the obsessive–compulsive spectrum; and (3) document existing relationships between SP and interoception in the context of obsessive–compulsive spectrum disorders.

Methods

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines [95] and registered on PROSPERO (ID: CRD42023422817).

Search strategy

The current study provides an update to Prado et al.'s [101] review of SP in OCD and tic disorders. As Prado et al.'s [101] review encompassed literature from 1980 to 2007, the current review canvassed literature from PubMed, PsycINFO, and Scopus databases from 2007 until 22nd of April, 2024. Two groups of search terms were created and combined for the current review; (1) disorder-specific terms (e.g., "obsessive–compulsive disorder", "Tourette syndrome"), and (2) terms relevant to SP and interoception (e.g., "sensory phenomena", "incompleteness", "interoceptive accuracy"). Each group was paired with equivalent index and MeSH terms in PsycINFO and PubMed, respectively. For the full search strategy, see Appendix 1.

Study eligibility

Eligible studies were required to investigate SP and/or interoception in adults with a self-reported or clinician-diagnosed OCRD and/or TS/CTD. For studies with mixed age groups, at least 80% of the sample had to be aged ≥ 18 for inclusion (per [5]). Only studies using a dedicated measure of SP and/or interoception were included, such that the measure needed to make an explicit attempt to assess a construct of interest. Exploration of any interoceptive domain was accepted, and we were primarily guided by Garfinkel et al.'s [61] three-factor model comprising interoceptive accuracy, interoceptive sensibility, and interoceptive awareness. Rosário et al.'s [110] University of Sào Paulo Sensory Phenomena Scale (USP-SPS) was utilised as our primary framework for conceptualising SP, including a hypersensitivity subscale (per Sampaio et al.'s [113] English validation of the USP-SPS). Peer-reviewed cross-sectional, longitudinal, observational, or experimental studies were eligible. Studies solely evaluating the efficacy of interventions were excluded. Eligible papers were required to be written in English.

Study selection and data extraction

Search results were exported to Covidence, where duplicates were removed before screening titles, abstracts, keywords, and full-texts to determine eligibility. Data were screened by two independent reviewers (LW and

MJ), in consultation with two other reviewers (IR and JS) to resolve disagreements. The inter-rater reliability was 0.75 for title and abstract screening, and 0.87 for full-text screening. Data were extracted from eligible studies using a Data Extraction Tool in Excel. Extracted data included demographic characteristics, host country of the study, participants' diagnostic status, physical and psychological comorbidities, conceptualisation of SP and interoception, research design, psychometric measures, and study results.

Risk of bias assessment

Risk of bias and article quality was assessed by two independent reviewers (LW and MJ) using the Joanna Briggs Institute (JBI) Critical Appraisal Checklists for Analytical Cross-Sectional Studies [92] and Quasi-Experimental Studies [142]. Risk of bias for each primary study was expressed in terms of low, moderate, or high risk. Total scores were calculated, with 'Yes' responses equating to one point, while 'No' or 'Unclear' responses received zero points. In the case that certain criteria were not applicable to the studies assessed, a weighted score was calculated by subtracting one point from the maximum score for each irrelevant criterion (per [43]). Total ratings were classified as low (≥70% criteria met), moderate (≥50% and <70% criteria met), and high risk of bias (<50% criteria met). No disagreements emerged between authors LW and MJ on risk of bias assessment.

Synthesis of results

Given the volume of results retrieved, the findings of included studies that explicitly purported to investigate SP and/or interoception as a central research goal were of primary focus in the narrative review. Results were divided into SP and interoception, then further stratified by disorder. SP findings were partitioned into global SP, NJREs, incompleteness, sensory over-responsivity, and PMUs. Interoception results were divided into interoceptive accuracy, interoceptive sensibility, interoceptive awareness, and interoceptive trait prediction error. Given a number of reports utilised the same dataset, 20 reports were consequently subsumed under a primary identifying study (see Appendix 2 for the identification of all primary studies and secondary reports).

Results

Initially, a total of 1,377 results were retrieved. After removing 319 duplicates, the titles and abstracts of 1,058 reports were screened. The full-texts of 248 reports were assessed for eligibility, with a final 65 studies (85 reports) eligible for inclusion. The PRISMA flowchart is displayed in Fig. 1. Of the 65 included studies: three studies employed a longitudinal design [80, 109, 116],47 studies were cross-sectional; and 16 utilised an experimental design. Schultchen et al. [116] was classified as both longitudinal and experimental, assessing interoceptive accuracy over the time course of cognitive behavioural therapy (CBT) in OCD. Appendix 2 contains study characteristics and results by disorder of interest. Conceptualisations of each domain of SP and interoception, as described within the included studies, are displayed in Table 1. Regarding risk of bias, the majority of studies were of high quality and demonstrated low risk of bias (see Appendices 3 and 4). An extended reference list containing eligible studies included in the results table but not cited in the narrative review can be found in Appendix 5.

Regarding gender distribution, the majority of OCD studies (k=21/32, 65%), and all studies on TTM, SPD, and BDD (k=12/12, 100%) were predominated by women, while all TS/CTD studies (k=24/24, 100%) were predominated by men. The mean age of samples ranged from 18.83 (SD=1.80) to 47.42 (SD=15.27) across studies investigating SP, and from 28.60 (SD=7.20) to 40.72 (SD=15.78) across studies investigating interoception. Three studies (5%) sampled participants with TTM [18] and TS/CTD [22, 104] with self-reported diagnostic status, and 60 studies (92%) specified the diagnostic tools and procedures (e.g., interview administered by trained clinician) through which participants' clinical diagnoses were established. Two studies (3%) only stated that participants had TS/CTD, but did not specify the procedures through which this diagnosis was established. Study characteristics per construct of interest are presented in Fig. 2.

Sensory phenomena

Global sensory phenomena

Fourteen studies assessed global SP, all of which utilised the USP-SPS [110]. In the context of OCD, a number of studies investigated the neuroanatomical correlates of global SP. Subirà et al. [125] found that, compared with healthy controls, OCD participants with SP showed significantly increased grey matter volume in the medial sensorimotor cortices, basal ganglia structures, and locomotor regions. Collins et al. [33] found severity of SP was not correlated with global connectivity within the orbitofrontal cortex. Two studies [25, 124] found SP severity correlated with increased activity in the bilateral postcentral gyri and mid-posterior insula during an eyeblink suppression task [124] and the presentation of "body-focused" videos [25]. Four studies explored the clinical and behavioural correlates of global SP [54, 86, 110, 120]. See Appendix 2 for results regarding the remaining ten secondary reports subsumed under Ferrão et al. [54]. SP was found to be associated with higher

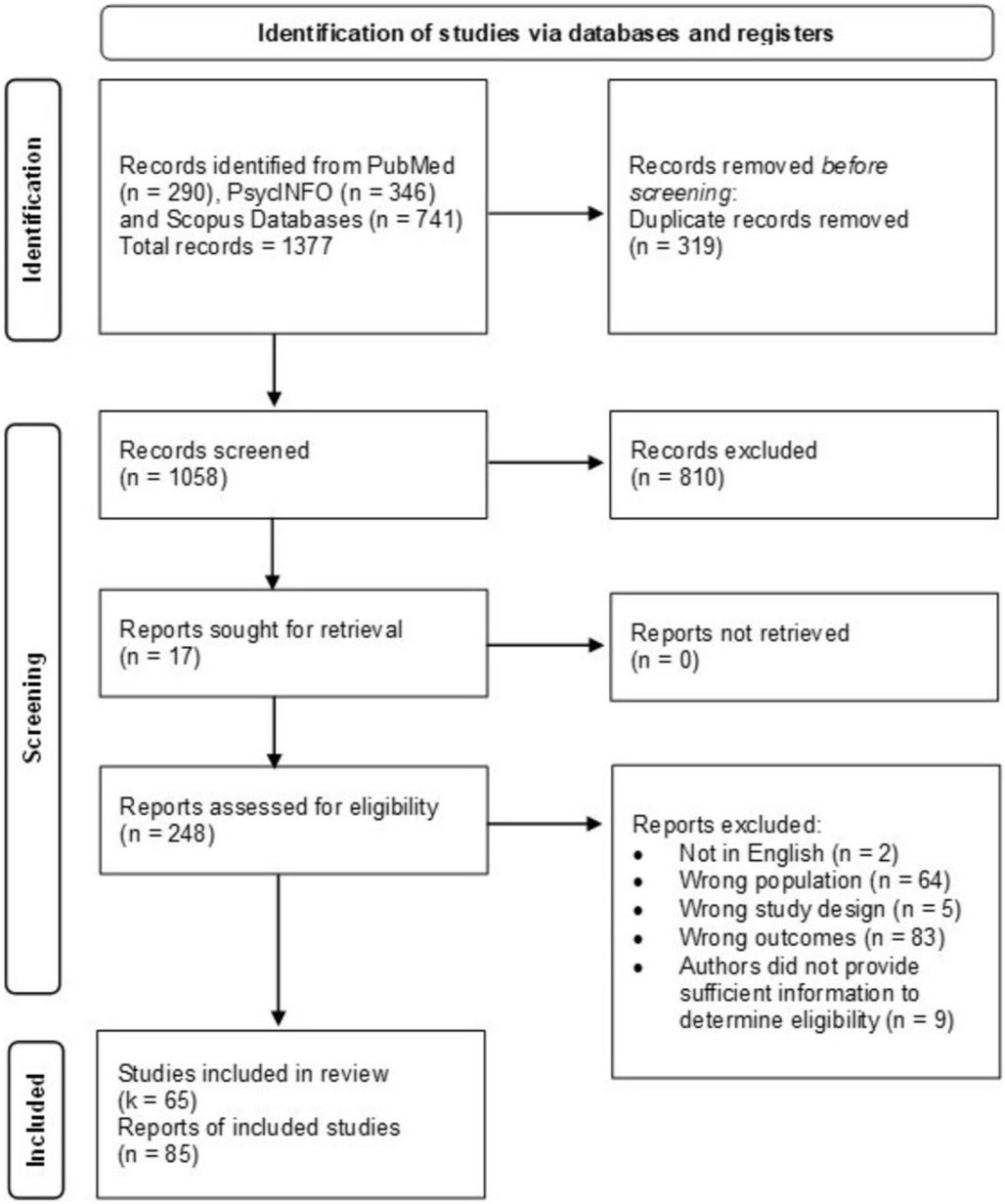

Fig. 1 PRISMA flowchart

severity of symmetry/ordering and contamination symptoms, history of tics, and diminished insight [54],early OCD symptom onset [110],the *doubts over actions* facet of perfectionism [86],the tendency to focus on interoceptive sensations [50] and control-equivalent levels of risk sensitivity, when compared to OCD participants without SP, who demonstrated higher risk sensitivity [120].

In the context of TS, Bhikram et al. [14] found significant associations between higher global SP and reduced activity in the insula, superior temporal, precentral, and middle frontal gyri during a disgust provocation experiment. In a follow-up assessment four years after a previous study, Kano et al. [80] found previous SP scores were significantly positively correlated with current OCD and tic severity. Brandt et al. [23] also found SP to be significantly correlated with obsessive–compulsive symptom severity, along with feelings of incompleteness, PMUs, and NJREs in a TS sample. In SPD, Dieringer et al. [44] found the most- to least-frequently reported SP forms were "just-right" feelings, physical sensations and "urge-only" phenomena

Table 1 Conceptualisation of sensory phenomena and interoception as per included studies

Construct		*Conceptualisation*
Sensory phenomena		
	Global sensory phenomena	An umbrella term encompassing aversive or uncomfortable sensations immediately preceding, triggering or accompanying compulsions, tics, or repetitive behaviours. May manifest as localised or diffuse, general feelings and can occur even in the absence of a feared outcome. SP has also been considered to include PMUs and "just right" perceptions in the context of TS and SPD, and even used to describe the quality of PMUs in SPD
	"Not just-right" experiences	A perceptually-tinged phenomena; subjective, unsettled feeling that something just is not as it should be in one's body or environment. May drive performance of compulsions, tics, or repetitive behaviours in an effort to alleviate associated discomfort and restore feelings of perfection, satisfaction or things being "just right". Often used interchangeably with incompleteness despite recent research suggesting the two do not fully overlap and may represent distinct aspects of the same construct
	Incompleteness	A motivational factor driving the performance of compulsions and repetitive behaviours, which may be triggered, accompanied, or maintained by the need to ameliorate an inner sense of imperfection, discomfort or dissatisfaction (i.e., NJREs) with one's actions and/or perceptions. Sensory-affective dysregulation expressed through all sensory modalities, as well as through complex phenomena including thoughts or language. Occasionally used interchangeably with NJREs
	Sensory over-responsivity	Temporally pervasive trait characterised by excessive, prolonged and/or intense responses, awareness, avoidance, or reactivity to external stimuli that would not ordinarily be perceived as aversive. Not temporally linked to the performance of tics, unlike PMUs
	Premonitory urges	An uncomfortable bodily, or internal sensation that accumulates prior to a tic, typically relieved by tic execution. Descriptions include localised somatic sensations occurring at the site of the impending tic (i.e., itch, pressure, tingling) or generalised, diffuse feelings of dissatisfaction, incompleteness, feeling as though something is not "just-right", feelings of pressure, energy build-up, internal urges, or restlessness
Interoception		
	Interoceptive accuracy	Performance on objective behavioural interoceptive tasks (i.e., heartbeat tracking tasks), or precision at detecting internal, visceral sensations. Occasionally mistakenly referred to as interoceptive awareness
	Interoceptive sensibility	A multifaceted construct comprising an individual's perceived or subjective sensitivity to internal bodily sensations, including how these sensations are interpreted, regulated and used to inform behaviour. Occasionally confined to one's confidence in their objective interoceptive ability
	Interoceptive awareness	Metacognitive insight into one's interoceptive ability, calculated as the congruence, or discrepancy, between objective interoceptive accuracy (i.e., heartbeat tracking tasks) and reported confidence in one's performance. Occasionally positioned as analogous to interoceptive sensibility
	Interoceptive trait prediction error	The discrepancy between objective interoceptive accuracy and subjective interoceptive sensibility, calculated by subtracting the standardised z-scores on interoceptive accuracy tasks from scores on self-report measures of interoceptive sensibility (i.e., BPQ)

(equally), energy build-up, and incompleteness. No studies investigated global SP in TTM, BDD, or HD.

"Not Just-Right" experiences

Eighteen studies measured NJREs utilising Coles et al.'s [31, 32] Not Just-Right Experiences Questionnaire—Revised (NJRE-Q-R), while several studies conducted NJRE provocation tasks [57, 130, 131]. In OCD, two studies [6, 11] concluded NJREs were a *state* vulnerability marker of OCD, as opposed to a *trait* characteristic or genetic marker. Also assessing *state* NJREs, Fornés-Romero and Belloch [57] found NJREs and symmetry/ordering symptoms were significantly correlated with physical discomfort at the mandatory stopping point of a symptom provocation task. NJREs were most commonly correlated with higher symmetry/ordering symptoms [11, 30, 57]. Higher NJRE severity distinguished OCD from anxiety and depressive disorders [67, 148], and accounted for longer reaction times on a Go/No-Go task in OCD compared to controls [66]. Pascual-Vera et al. [96] found intolerance of uncertainty beliefs mediated the path between NJREs and OCD severity.

In TS, Neal and Cavanna [94] found the total number of NJREs reported was significantly higher in participants with comorbid OCD than those without, and was strongly significantly correlated with symmetry/ordering and neutralising symptoms. Also in TS, Brandt et al. [23] found NJREs demonstrated stronger associations

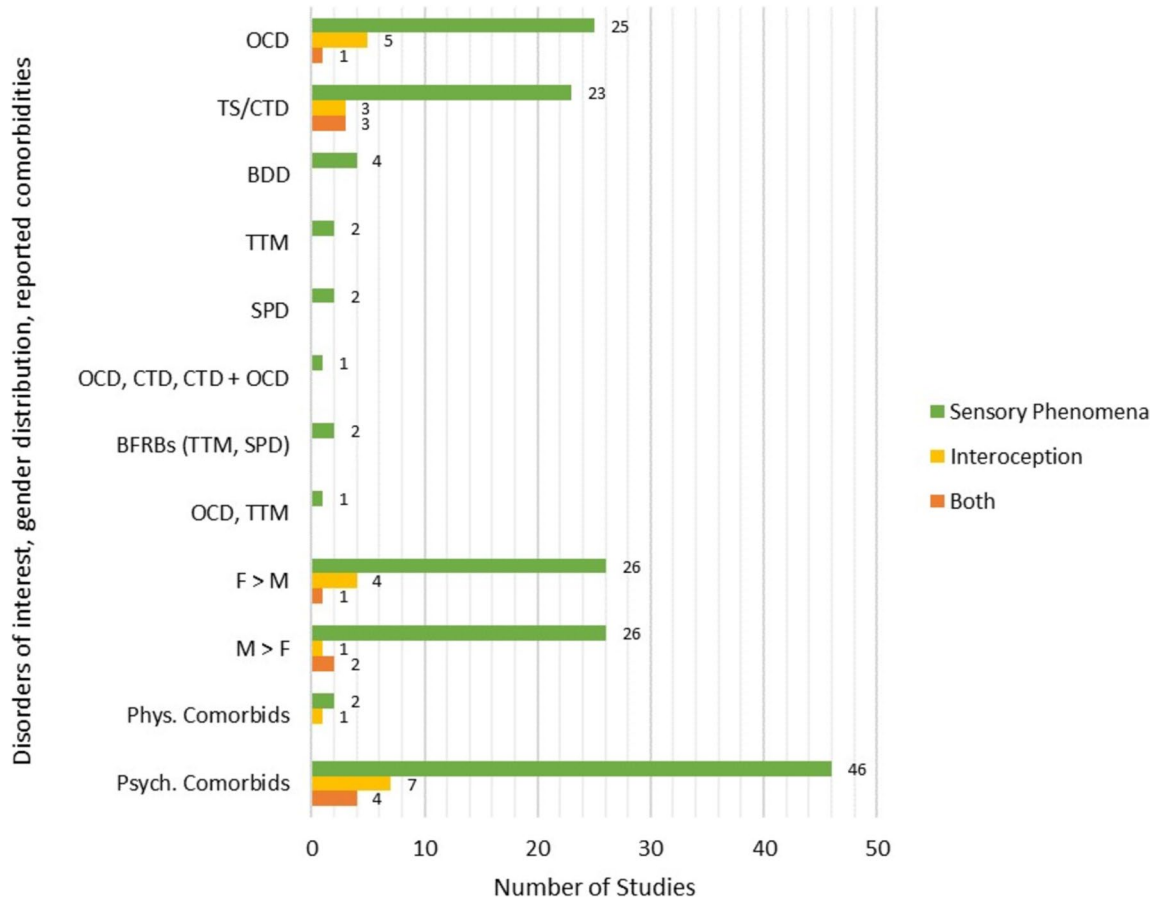

Fig. 2 Study characteristics per constructs of interest

Note. Studies in "Sensory Phenomena" and " Interoception " categories are also inclusive of studies investigating both SP and interoception. F > M = Studies predominated by female-identifying participants. M > F = Studies predominated by male-identifying participants. Phys. Comorbids = Physical comorbidities reported. Psych. Comorbids = Psychiatric comorbidities reported. Sica et al. [119] was not included in the gender distribution ratio as this study investigated separate OCD and TTM samples, but found greater male predominance in the OCD group and greater female predominance in the TTM group. Two studies did not report gender distribution

with obsessive–compulsive symptoms than tic severity. The same study also concluded NJREs were a related yet distinct construct from PMUs. In the context of TTM and SPD, Ricketts et al. [108] found higher NJRE severity significantly predicted SPD diagnosis, while Sica et al. [119] found NJRE severity did not differ between OCD and TTM groups. In BDD, Cerea et al. [27] found BDD symptoms were significantly predicted by higher NJRE severity. Summers et al. [130] found participants with clinically significant BDD symptoms experienced more discomfort in response to an in vivo visual NJRE task than those with low BDD symptoms, with no differences on tactile or auditory tasks. Further, Summers et al. [131] found this heightened discomfort extended to clutter, body asymmetry, and facial asymmetry NJREs, compared to controls. Summers and Cougle [129] also found BDD participants with lower baseline NJRE severity, who underwent interpretation bias training, had lower BDD symptoms post-treatment compared to a placebo training group. No studies investigated NJREs in HD.

Incompleteness

Eleven studies measured incompleteness utilising the Obsessive–Compulsive Core Dimensions Questionnaire (OC-CDQ) [128], with Boisseau et al. [16] also using the recently developed Brown Incompleteness Scale (BINCS). One study [23] utilised the Feelings of Incompleteness Questionnaire (FSU-12, [46]). In a clinical OCD group, Summerfeldt et al. [128] validated a two-factor measure of the motivational domains underpinning

OCD, comprising (1) incompleteness and (2) harm avoidance, where incompleteness displayed a greater range of item loadings than harm avoidance. Further, Boisseau et al. [16] found two facets of incompleteness in OCD: (1) task completion and (2) sensory incompleteness. Both Boisseau et al. [16] and Belloch et al. [11] found greater sense of incompleteness was associated with greater OCD severity. Incompleteness was also found to be consistently positively associated with greater symmetry/ordering symptoms [11, 19, 30, 45, 47, 48, 57]. Similarly, Bragdon and Coles [19] found higher incompleteness was associated with higher *perfectionism/intolerance of uncertainty* beliefs. Further, Ecker et al. [48] found controlling for incompleteness eliminated all previously significant associations between a perfectionistic "careful" personality style and OCD severity. Ecker et al. [47] also found incompleteness was significantly higher in OCD than anxiety or depressive disorder groups. Hellriegel et al. [70] found incompleteness was associated with greater sensory processing difficulties, even when controlling for OCD severity and trait anxiety. In participants with TS, one study [23] found incompleteness, as measured by the FSU-12 [46], was substantially correlated with NJREs, global SP, and obsessive–compulsive symptoms. Regarding BDD, Summers et al. [130] found participants with clinically significant BDD symptoms reported significantly higher incompleteness feelings than those with subclinical BDD symptoms. Further, Summers et al. [131] found the clinical BDD group had higher levels of incompleteness and harm avoidance than controls. No studies investigated incompleteness in TTM, SPD, or HD.

Sensory over-responsivity

Eight studies measured self-reported sensory over-responsivity: three studies [75, 77, 78] used the Sensory Gating Inventory (SGI; [71], four studies [33, 70, 74, 99]) used the Adolescent/Adult Sensory Profile (AASP; [24]), one study [51] utilised their recently developed measure of sensory over-responsivity and Schoen et al.'s [115] Sensory Over-Responsivity Scales, and one study [99] utilised the Sensory Habituation Questionnaire [98] and the short version of the Sensory Processing Quotient (SPQ; [133]). Two studies found participants with OCD presented a sensory profile of heightened sensory sensitivity and sensory avoidance, in addition to low registration [70] and slower sensory habituation [99]. Similarly, Isaacs et al. [78] found participants with OCD scored higher on the *perceptual modulation* subscale of the SGI (i.e., subjective experience of stimulus intensity) than participants with CTD. Finally, Collins et al. [33] found sensory avoidance and sensory sensitivity were positively correlated with higher severity of OCD symptoms and global SP, as well as higher global connectivity within the orbitofrontal cortex. In CTD, Isaacs et al. [78] found participants with OCD, and those with CTD with and without comorbid OCD, did not differ on overall sensory over-responsivity severity. However, both Isaacs et al. [77] and Isaacs et al. [78] found tic severity was not significantly correlated with sensory over-responsivity, while OCD symptoms were.

In TTM, Falkenstein et al. [51] found clinical participants endorsed significantly higher severity of tactile and auditory sensory over-responsivity than controls, modalities that were also strongly correlated with *doubts over actions* and *concern over mistakes* perfectionism domains. In participants with clinical and subclinical BFRBs (i.e., hair pulling, skin picking, nail biting, cheek biting, teeth grinding, skin biting), Houghton et al. [74] found higher scores on low registration, sensory sensitivity, and sensation avoiding subscales of the AASP [24] were significantly associated with greater BFRB severity. Houghton et al. [75] also found individuals with TTM and SPD reported greater frequency and intensity of sensory over-responsivity, lower tactile detection thresholds, and abnormal feed-forward inhibition compared to controls. However, performance on these vibrotactile tasks only marginally predicted the *fatigue/stress vulnerability* subscale of the SGI and SPD severity. No studies investigated sensory over-responsivity in BDD or HD.

Premonitory urges

Twenty-two studies measured PMUs, all of which utilised the PUTS [147]. In TS/CTD, Tinaz et al. [138] found PMU severity was significantly correlated with higher functional connectivity between the bilateral supplementary motor area and right dorsal anterior insula, linking interoceptive processing with execution of motor urges. Bhikram et al. [13] also found that lower functional connectivity between the insula and inferior frontal gyrus was associated with greater PMUs. PMUs in TS/CTD were also positively associated with various domains of interoception, including greater embodiment prediction error [103], higher interoceptive accuracy [60], higher interoceptive sensibility on the BPQ-BA [104], higher emotional awareness, higher self-regulation, and lower not-worrying about interoceptive sensations [93]. Four studies found no significant correlations between PMUs and objective measures of sensory or perceptual processing [7, 12, 58, 117], while Isaacs et al. [77] reported higher subjective reports of sensory over-responsivity were significantly correlated with PMUs, but not with tic severity. Assessing obsessive–compulsive symptoms in participants with TS/CTD, [22] and Rajagopal and Cavanna [105] found obsessive–compulsive symptoms

were significantly correlated with greater inner tension, "just-right" feelings, and energy PMU qualities, while Crossley et al. [36] found higher pressure, incompleteness, and energy PMUs were significantly correlated with compulsion severity. Further, Crossley and Cavanna [35] found significant correlations between greater PMUs and checking and obsessing symptoms in TS/CTD participants, as well as neutralising, washing and ordering symptoms. Kano et al. [80] found previous PMUs were significantly correlated with current obsessive–compulsive symptom severity in participants with TS, while [23] found PMUs were comparably correlated with obsessive–compulsive symptoms and tic severity in TS participants. No studies investigated PMUs in OCD, TTM, SPD, BDD, or HD.

Interoception

Interoceptive accuracy

Five studies measured interoceptive accuracy. Four studies utilised Schandry's [114] heartbeat counting task [39, 60, 104, 116], requiring participants to count their heartbeats silently in their mind. One study [149] used Canales-Johnson et al.'s [26] tapping accuracy task, requiring participants to tap with their hand in time with their heartbeat. In OCD, two studies reported reduced interoceptive accuracy compared to healthy controls [39, 116], while Yoris et al. [149] found OCD participants displayed higher interoceptive accuracy than participants with panic disorder and healthy controls. In TS, Ganos et al. [60] found lower interoceptive accuracy on a heartbeat counting task compared with healthy controls, while Rae et al. [104] found that higher interoceptive accuracy on a heartbeat discrimination task was significantly positively correlated with tic severity. No studies investigated interoceptive accuracy in TTM, SPD, BDD, or HD.

Interoceptive sensibility

Five studies assessed interoceptive sensibility; three of which utilised the MAIA or MAIA-2 [90, 91], one study used the BPQ-BA [100], and one study operationalised interoceptive sensibility as a single item assessing subjective confidence in one's interoceptive accuracy [149]. In OCD, one study [49, 50], found significantly greater MAIA scores on noticing and emotional awareness, as well as diminished bodily trust, lower not-worrying, and lower not-distracting compared to healthy controls. Eng et al. [49] also found significant associations between: higher noticing and symmetry and responsibility for harm symptom dimensions,lower not-worrying with responsibility for harm and contamination; and lower not-distracting and unacceptable/taboo thoughts. Further, Eng et al. [50] found higher scores on a proposed "adaptive" interoceptive sensibility component (i.e., higher noticing, attentional control, emotional awareness, self-regulation, listening, and trusting) were correlated with greater functional connectivity between the insula and multiple brain regions. Lower scores on a proposed "maladaptive" interoceptive sensibility component (i.e., lower scores meaning more worrying and noticing, less emotional awareness) were correlated with reduced functional connectivity between the insula and dorsal anterior cingulate cortex. Higher not-distracting from sensations (i.e., more focusing) was associated with higher symmetry symptoms and greater global SP, as well as reduced functional connectivity between the insula and inferior frontal gyrus [50]. Yoris et al. [149] reported individuals with OCD had significantly lower interoceptive sensibility, conceptualised as confidence in interoceptive accuracy, compared with control and panic disorder groups. Finally, Belanger et al. [10] found OCD participants with current suicidal ideation reported lower bodily trust, while a lifetime history of at least one suicide attempt was associated with greater noticing of bodily sensations. Two studies measured interoceptive sensibility in TS [104] and CTD [93]. Rae et al. [104] found no significant difference in interoceptive sensibility levels between TS participants and controls on the BPA-BA. However, higher interoceptive sensibility on the BPQ-BA significantly predicted tic severity, PMUs, and functional impairment in TS participants. Similarly, Narapareddy et al. [93] found participants with CTD demonstrated higher MAIA-2 scores on noticing, less not-worrying, and lower bodily trust than healthy controls. Further, in participants with CTD, Narapareddy et al. [93] found no significant predictors of noticing, while female sex and more severe obsessive–compulsive symptoms predicted lower not-worrying. No studies investigated interoceptive sensibility in TTM, SPD, BDD, or HD.

Interoceptive awareness

Two studies measured interoceptive awareness, both conceptualising this domain as the congruence between one's objective interoceptive accuracy on heartbeat tracking tasks and their subjective confidence in their accuracy. However, while one study [149] utilised Canales-Johnson et al.'s [26] tapping accuracy task, the other [104] utilised Schandry's [114] heartbeat counting task. In OCD, Yoris et al. [149] found significantly lower interoceptive awareness compared to healthy controls and individuals with panic disorder, where both control and panic disorder participants displayed

high interoceptive awareness. In TS, Rae et al. [104] found that while interoceptive awareness was comparable between TS and control groups on both heartbeat counting and discrimination tasks, higher interoceptive awareness on the counting task was associated with lower functional impairment. No studies investigated interoceptive awareness in TTM, SPD, BDD, or HD.

Interoceptive trait prediction error

One study [104] measured interoceptive trait prediction error in TS. TS participants reported significantly greater interoceptive trait prediction error than controls on the heartbeat counting task [104]. No studies investigated interoceptive trait prediction error in OCD, TTM, SPD, BDD, or HD.

Discussion

Summary of findings

The current systematic review aimed to examine the nature of SP and interoception across the obsessive–compulsive spectrum, and document evidence supporting the relationship between SP and interoception as potential maintaining factors in these disorders. Studies investigating the various forms of SP (i.e., global, NJREs, incompleteness, sensory over-responsivity, PMUs) and domains of interoception (i.e., interoceptive accuracy, interoceptive sensibility, interoceptive awareness, interoceptive trait prediction error) in the context of OCD, TS/CTD, TTM, SPD, BDD, and HD were examined. Overall, the most frequently investigated forms of SP differed between disorders, with global SP, NJREs, and incompleteness examined most commonly in OCD and BDD, and to a lesser extent, NJREs and global SP in TTM and SPD. PMUs were examined in TS/CTD only. No findings emerged on any form of SP in HD. Interoception was only examined in OCD and TS/CTD, with the findings indicating that participants with these disorders demonstrated diminished interoceptive accuracy. Interoceptive awareness was lower in OCD samples, and higher interoceptive awareness in TS was associated with less functional impairment. TS samples also demonstrated high interoceptive trait prediction error compared to controls. Findings on interoceptive sensibility were less conclusive; samples with TS/CTD [93] and OCD [49, 50] reported greater noticing, lower not-worrying, and lower bodily trust than controls. Regarding the relationship between SP and interoception, only one study in OCD [50] and three studies in TS/CTD [60, 93, 104] examined this. While lower MAIA-2 scores on not-worrying [93] and higher scores on the BPQ-BA [104] were associated with PMUs in TS/CTD, only higher MAIA scores on not-distracting were associated with greater global SP in OCD [50]. While this could be interpreted as indicative of differences between disorders, it may instead demonstrate the need for an alternative method of clarifying the nuanced ways in which interoceptive sensibility interacts with forms of SP across the obsessive–compulsive spectrum. As such, issues regarding the conceptualisation of SP and interoception will first be addressed, followed by discussion of the nature of SP and interoception across disorders of interest. Finally, important limitations of the current review, clinical implications, and future directions are proposed.

Conceptual and measurement issues

Regarding the conceptualisation of SP across the obsessive–compulsive spectrum, substantial overlap emerged between forms of SP, primarily regarding the interchangeable use of the terms "NJREs" and "incompleteness" in the OCD literature (e.g., [29, 70]). It is likely that NJREs and incompleteness are related, with similar phenomenological descriptions and clinical correlates, as demonstrated in this review [6, 11, 19, 30, 48]. However, NJREs and incompleteness may reflect two distinct facets of the same underlying construct, with *trait* incompleteness predisposing individuals to experience NJREs as a transient *state* manifestation [6, 11]. It is recommended that, in future, NJREs and incompleteness are referred to and measured as separate, but related constructs, in order to clarify conceptualisations of different forms of SP. Similarly, several frameworks utilised to assess SP were identified, including the USP-SPS [110], NJRE-Q-R [31, 32], OC-CDQ [128], SGI [71] and PUTS [147], with overlap between a number of items and concepts across scales (e.g., [110, 147]). However, even items putatively measuring similar forms of SP across questionnaires were shown to reflect distinct constructs, with [23] reporting only medium correlations between the NJRE-Q-R and the "just right" item of the PUTS. Factor analysis could be performed on existing measures of SP, much like Desmedt et al.'s [41] work on measures of interoceptive sensibility, to confirm the structure of the various forms of SP. This may allow for future examination of SP across the obsessive–compulsive spectrum with less psychometric overlap. Further, researchers may consider expanding on Cervin et al.'s [28] factor and network analyses of the Dimensional Yale Brown Obsessive–Compulsive Scale (DY-BOCS [111]), which revealed an overarching and highly central incompleteness factor, by including additional measures of SP in analyses, such as the USP-SPS, NJRE-Q-R, or OC-CDQ.

Inconsistencies were also observed in the conceptualisation of interoception, although to a lesser extent. This may be a testament to Garfinkel et al.'s [61] three-factor

model of interoception, which appeared to have informed the majority of studies conducted in OCD and TS/CTD [49, 50, 39, 93, 104, 149]. However, ambiguity regarding the multidimensionality of interoceptive sensibility, in particular, was evident. This domain presented the most inconsistency in terms of its measurement in the current review. Indeed, recent literature has questioned the structure and domains of the interoceptive sensibility core construct (i.e., [41, 53, 89, 141, 145]). This was reflected in the current review, as associations between MAIA domains and OCD symptom dimensions appeared to differ when comparing correlates of interoceptive sensibility principal components [50] to individual domains [49]. Associations between MAIA domains and forms of SP (e.g., PMUs, global SP) also differed across disorders [50, 93]. Based on the findings of this review, further research is recommended to explore the possibility of novel interoceptive profiles beyond the proposed "adaptive" and "maladaptive" dichotomy, and the ways in which any such profiles relate to SP across disorders and specific OCD symptom dimensions.

Phenomenology of sensory phenomena and interoception

Obsessive–compulsive disorder

In the context of OCD, all forms of SP, excluding PMUs, were investigated. Global SP, NJREs, and incompleteness were all most frequently associated with symmetry/ordering symptoms in OCD [11, 30, 45, 57, 54, 110], in accordance with previous research that did not meet inclusion criteria for the current review [20, 126, 134, 136]. Moreover, the current review found that global SP, NJREs, and incompleteness were all associated with higher perfectionism [6, 11, 19, 86]. In light of the robust associations between NJREs and symmetry/ordering symptoms in this review, the association between NJREs and perfectionism is not unexpected given previous research demonstrating a relationship between perfectionism and symmetry/ordering symptoms [21, 55, 134]. Incompleteness itself has also been previously described as "sensation-based perfectionism" [31], p. 683). The current review also found that both NJRE and incompleteness severity were able to distinguish OCD from anxiety and depressive disorder groups [47, 67, 148], while NJREs could not distinguish between OCD and TTM groups [119]. This could suggest NJREs may be a vulnerability marker specific to OCD, TTM, and other OCRDs, as suggested in the current review (e.g., [44, 130]). However, further research is needed to confirm this.

Higher global SP severity in OCD was found to be associated with both heightened interoceptive neural activation (i.e., insula hyperactivity) [25, 124], and greater focusing on bodily sensations (i.e., higher MAIA not-distracting) [50]. It is possible that this insula hyperactivity may result in excessive interoceptive error signals, which are experienced as the uncomfortable sensations characteristic of SP. The discomfort generated through these interoceptive urges may be exacerbated by the tendency to focus on bodily sensations [50]. However, while OCD participants were, overall, more likely to distract themselves from uncomfortable sensations, less distracting – typically considered an "adaptive" trait [89] – was associated with greater SP and symmetry severity [50]. This may suggest that multiple, potentially conflicting profiles of interoceptive sensibility underpin different OCD symptoms, for example, distinguishing between individuals with and without SP. While these findings provide promising evidence for the role of altered interoceptive processing in experiences of SP, further direct investigation of this relationship is required to draw firmer conclusions.

Moreover, Eng et al. [50] found higher noticing and higher emotional awareness were cross-loaded across their proposed "adaptive" and "maladaptive" interoceptive sensibility components, reflecting previous research suggesting these subscales are often ambiguous in their adaptiveness [89]. In light of this, as well as the emergence of a third component beyond the proposed "adaptive" and "maladaptive" components [50], future research should consider a latent profiling approach to interoceptive sensibility in OCD. Such an approach may reveal diverse combinations of high and low scores on various MAIA subscales, which may uniquely relate to the facilitation of different forms of SP. The existence of such profiles may be further supported by Belanger et al.'s [10] findings, which indicated a nuanced relationship between domains of interoceptive sensibility and specific facets of suicidality in OCD. The associations between higher noticing and lower trusting with greater suicidality in this study also reiterate the importance of further investigating the role of altered interoception as an influential factor in OCD symptom maintenance and exacerbation. A profiling approach may also be useful for confirming patterns of association between interoceptive sensibility domains and OCD symptom dimensions, given the inconsistencies in this area (e.g., [49, 50]). It may also be that the use of the Dimensional Obsessive–Compulsive Scale (DOCS; [1]) in Eng et al.'s studies is problematic for assessing relationships between symmetry symptoms and SP, given the symmetry subscale of the DOCS also includes items measuring completeness and the need for things to be "just right". This situation may confound the association between SP and symmetry symptoms and creates uncertainty when attempting to interpret the symptom dimensions related to both

SP and interoceptive sensibility domains [50]. Future research should endeavour to utilise measures that disentangle symmetry from SP-related obsessive–compulsive symptoms when assessing relationships between OCD symptom dimensions and SP. Finally, regarding the current review's findings on interoceptive accuracy, Demartini et al. [39] and Schultchen et al. [116] found lower interoceptive accuracy in OCD. While Yoris et al. [149] reported enhanced interoceptive accuracy, compared to control and panic disorder groups, this may be explained by Yoris et al.'s use of a heartbeat tapping accuracy task, as opposed to the silent counting task used by Demartini et al. [39] and Schultchen et al. [116]. This may align with the "Seeking Proxies for Internal States" model, which proposes that access to biofeedback may mitigate the attenuated access to internal states observed in OCD [84]. When considered in light of similar findings in TS/CTD, the findings of the current review may suggest a profile of reduced interoceptive accuracy characterising both OCD and tic disorders. However, as Bragdon et al. [20] emphasised, additional research is required to confirm this interoceptive profile across multiple organ systems. It is also worth acknowledging that the conclusions of the current study on interoceptive sensibility differ slightly from those of Bragdon et al.'s review, in that we could not conclude that this domain was the most consistently altered in OCD. This divergence may be due to Bragdon and colleagues' inclusion of findings on physical anxiety sensitivity to illustrate abnormal interoceptive sensibility, emphasising the overlap between certain facets of these constructs [90]. While we acknowledge that anxiety sensitivity and interoceptive sensibility are conceptually related, we did not find it appropriate to conflate the two constructs. Nor was the direct exploration of the differences and similarities between these constructs considered to fall within the scope of this review. Our conservative eligibility criteria for the explicit and dedicated measure of interoception may have also contributed to these differing findings. Future exploration is recommended, like that of Mehling et al. [90], that seeks to compare and contrast interoceptive sensibility with anxiety sensitivity.

Tourette syndrome and chronic tic disorders

Global SP [80], NJREs [23, 94], sensory over-responsivity [77, 78], and PMUs [35, 36, 80, 105] were all associated with greater obsessive–compulsive symptom severity in participants with TS/CTD. NJREs were also correlated with symmetry/ordering symptoms in a TS sample [94], demonstrating the cross-disorder pervasion of the association between SP and this symptom dimension. These findings may have important implications for TS/CTD assessment, treatment planning, and formulation, given most forms of SP were associated with greater comorbid obsessive–compulsive symptoms in this review.

PMUs were the most frequently investigated form of SP in TS/CTD. The current review suggests PMUs are not related to objective abnormalities in exteroceptive sensory or perceptual processing in TS/CTD [7, 12, 58, 117]. However, PMUs were related to both higher objective interoceptive accuracy [60] and higher self-report interoceptive sensibility on the BPQ-BA [104]. This may provide further support for the relationship between PMUs and interoceptive processing, in line with suggestions that PMUs may be underpinned by aberrant sensorimotor and interoceptive processing rather than exteroceptive sensory thresholds [117]. Regarding interoceptive sensibility, the associations found between PMUs and lower MAIA-2 not-worrying [93] and higher scores on a proposed measure of anxiety-related interoceptive attention (i.e., the BPQ-BA [104],) may suggest a role for anxious psychopathology in the exacerbation of SP in TS/CTD. Given OCD samples also frequently endorsed lower MAIA not-worrying in the current review [49, 50], it is possible that TS/CTD and OCD share a similar profile of interoceptive sensibility, characterised by a tendency for anxious bodily monitoring. This may also align with previous observations of anxiety-induced somatisation in autistic persons [141]. Bonaz et al. [17] reported that autistic people may experience reduced interoceptive accuracy and exaggerated interoceptive sensibility, reminiscent of the current study's findings in OCD and TS/CTD. SP is also a shared experience across autism spectrum disorder (ASD), OCD and TS/CTD. Kloosterman et al. [81] reported that parents with multiple autistic children, compared to a single autistic child, endorsed higher levels of incompleteness, corresponding to higher repetitive sensory motor actions in their children. Additional research is required to investigate shared interoceptive and sensory experiences across OCD, TS/CTD and ASD, such as the work conducted by Hellriegel et al. [70] on the relationship between incompleteness and ASD symptoms in an OCD sample.

Trichotillomania and skin picking disorder

Regarding the paucity of findings on SP and NJREs in TTM and SPD, only limited and tentative conclusions can be drawn. NJREs were found to be prevalent in TTM [18, 119], with indistinguishable severity from OCD [119]. While further research is needed to explore SP in TTM, this latter finding may provide evidence towards the role of NJREs beyond OCD, and may further support

the classification of TTM as an OCRD. Endorsement of NJREs in TTM is consistent with reports from the current review that TTM individuals often pull hair that does not "feel right" [18]. Global SP was also investigated in SPD, with Dieringer et al. [44] reporting visual and tactile "just-right" perceptions were the most frequently reported form of SP. This may reflect the need for skin to look or feel a certain way (i.e., "just-right") in SPD [44], as well as the current review's findings on overall heightened objective and subjective tactile sensory over-responsivity in BFRBs [51, 75]. The current review also revealed an identical profile of heightened sensory over-responsivity in participants with BFRBs (including TTM and SPD [74]) and OCD [70, 99], further suggesting the role of sensory experiences in linking OCD to TTM and SPD, as putatively related disorders.

Body dysmorphic disorder

Only NJREs and incompleteness were investigated in BDD [27, 129–131]. Visual NJREs, both symptom-related and unrelated, were associated with higher BDD severity, reflecting the primarily visual nature of the disorder [130, 131]. This may align with existing findings of abnormal visual perceptual processing in BDD [150]. However, this may also contradict previous findings that aesthetic perceptual sensitivity does not differ between BDD, OCD, and social anxiety groups [76]. Future research could explore if visual NJREs in BDD extends to visual sensory over-responsivity. Incompleteness was also more strongly associated with clinically significant BDD symptoms compared with subclinical symptoms, while groups did not differ on harm avoidance, suggesting incompleteness may be specific to BDD [130]. As incompleteness was only investigated in OCD and BDD in this review, it is not possible to draw firm conclusions on this construct across the obsessive–compulsive spectrum. Finally, Summers and Cougle's [129] finding that lower baseline NJREs were associated with better treatment outcomes in BDD may mirror Mathes et al.'s [88] findings on obsessive–compulsive symptoms, whereby higher pre-treatment NJRE-related discomfort significantly predicted higher contamination symptoms in undergraduate students following treatment with exposure and response prevention (ERP). This may suggest higher NJRE severity predicts worse treatment outcomes across OCRDs and may serve as a viable treatment target to integrate into traditional ERP approaches.

Gaps identified from the current review

The current review found no studies investigating the role of SP in HD, meaning no conclusions can be provided on SP in this disorder. The lack of investigation in this area may relate to different behavioural symptoms in HD compared with other disorders across the obsessive–compulsive spectrum. OCD, TS/CTD, BDD, TTM, and SPD all involve the reactive behavioural performance of compulsions, tics, or BFRBs. While it could be argued that compulsive acquiring in HD may constitute impulsive or compulsive behaviours, past research has suggested that difficulty discarding and accumulation of clutter are more central to HD phenomenology than acquiring [137]. While one study in the current review found associations between global SP and higher hoarding symptoms, this was conducted in an OCD sample [140]. Further, past literature, excluded from the current review, found associations between hoarding severity and a single item assessing not "just-right" feelings in a clinical HD sample [139]. However, further research is required to determine the role of SP in HD. It is also essential to acknowledge that no findings were retrieved on interoception in BDD, TTM, SPD or HD, and as such, we are unable to provide any conclusions on the role of interoception across these OCRDs. This may be because interoception has relatively recently been conceptualised under an operationalised framework (i.e., [61]. Further, while the phenomenological links between OCD and TS/CTD have been long established [38, 101], the DSM-5 classification of OCRDs has been debated [2], potentially leading to a reluctance among researchers to consider BDD, HD, and especially TTM and SPD, as part of a wider obsessive–compulsive spectrum. Nonetheless, some literature has provided commentary or tentative evidence towards the role of interoception in OCRDs, including: theoretical interoceptive models of BDD [79],research on interoceptive accuracy and muscle dysmorphia symptoms in undergraduates [69],and unpublished studies from doctoral theses on interoceptive accuracy in BDD [102] and interceptive sensibility in BFRBs [73]. Such literature provides a promising foundation for research to further explore the role of interoception in OCRDs.

Limitations

It is important to consider the findings of this review in light of several limitations. Firstly, as we did not perform hand searches or citation tracking, some studies may not have been captured in our searches. Additionally, while dissertations from the PsycINFO database were considered, we did not include ProQuest as a database, meaning a degree of unintentional publication bias may have skewed results. However, given our comprehensive range of search terms, inclusive of all domains of SP and

interoception, it is likely an adequate picture was captured regarding the nature of these constructs across the obsessive–compulsive spectrum. Second, our decision not to include studies of SP and interoception in children and adolescents prevented us from comparing these processes across the lifespan. This may be particularly problematic in the case of PMUs, which have been found to develop with increasing age [9, 82, 85]. However, previous research has identified important differences between children and adults in forms of OCD, such as paediatric autoimmune neuropsychiatric disorders associated with Streptococcal infections (PANDAS [64],), as well as interoceptive development (i.e., insula connectivity, [40]). We believe this evidence justifies the investigated age range. Similarly, the overwhelming lack of eligible longitudinal studies included in the current review limits the extent to which SP and interoception can be evaluated as maintaining factors across the obsessive–compulsive spectrum. Future longitudinal research is required to adequately explore the role of SP and interoception in the potential onset or maintenance of these disorders. It may also be beneficial to examine any possible sequential relationship between obsessional cognitions, like those observed in OCD and BDD, and the maladaptive appraisal of the interoceptive sensations associated with SP. Such research may elucidate whether dysfunctional cognitions distort or inflate the significance or intensity of SP, in turn, influencing one's interoceptive abilities. Conversely, it may also be that obsessional doubt, as proposed by Dar et al. [37], is generated through attenuated access to internal states, which has been likened to reduced interoceptive accuracy [20].

While the majority of studies were of high quality and demonstrated low risk of bias, the samples were skewed towards women in all disorders except TS/CTD. However, higher prevalence of TTM and SPD in women is common [3, 18, 68], as is a higher prevalence of TS/CTD in men [8]. Findings on OCD were also weighted towards women, reflecting existing research suggesting women are at greater risk of experiencing lifetime OCD [52]. However, as paediatric OCD samples tend to be male predominant [63], the current review's female predominance in OCD may be explained by our decision to only include adult participants. Further, despite female predominance in BDD in the current review, equivalent BDD prevalence has been found across men and women [151]. Further research is needed to adequately address the manifestations of BDD in men, given Grunewald et al.'s [69] findings that muscle dysmorphia symptoms were associated with every MAIA-2 subscale, except noticing. Further, very few studies included in the current review reported on participants' physical comorbidities. Future research is needed to determine the bidirectional relationship between physical comorbidities and interoceptive processing, given existing research has implicated interoception in chronic pain [42] and a range of neurodevelopmental, neurodegenerative, and somatic disorders [17]. Finally, one-third of studies were conducted in the United States, followed by Germany and the UK. As such, further research should endeavour to investigate SP and interoception in more diverse samples, particularly when considering the documented cultural and spiritual differences in interoceptive experience [87, 144].

Implications and future directions

Overall, the current review predominantly offered a collection of disparate findings on diverse associations between SP and interoceptive domains across the obsessive–compulsive spectrum, and with a range of clinical correlates. Some emerging patterns and theories were nonetheless identified. SP appeared to be associated with greater overall disorder severity, for example, the association between NJREs, incompleteness, and higher OCD severity [11, 16], and the association between higher sensory over-responsivity and BFRB severity [74]. Further, SP was also associated with greater severity of a number of clinical correlates, including higher perfectionism and severity of symmetry/ordering symptoms [11, 19, 48, 86], a history of tics, diminished insight [54], and early symptom onset [110] in OCD, as well as higher obsessive–compulsive symptom severity [23, 94], lower distress tolerance [106], and smaller reductions in tic severity over time [109] in TS/CTD samples. It is thus unsurprising that individuals who experience SP, particularly in the context of OCD, often report worse treatment outcomes without a dedicated approach for addressing these experiences [56, 88, 127]. Despite this, the volume and diversity of conceptual frameworks utilised made it challenging to synthesise overarching findings. It is recommended that future researchers endeavour to standardise their use of measures and terminology, and focus on replicating findings established in the current review.

Without further research, we cannot yet make firm recommendations on the precise combinations of interoceptive domains that clinicians should target as a means of addressing compulsions, tics, or BFRBs elicited by SP. Considering the ambiguity between existing measures of the interoceptive sensibility construct [41, 53, 145], and existing evidence proposing a different MAIA factor structure in OCD compared to controls [50], future research to establish reliable profiles of interoceptive sensibility is imperative. In addition, novel interventions

could be developed and trialled, which integrate the discomfort generated through SP into traditional exposure regimes for OCD. For example, while Coles and Ravid [30] reported significantly lower NJRE severity following CBT, the authors acknowledge that their clinicians were trained to position NJREs as exposure stimuli within a traditional fear hierarchy. If interoception is indeed found to contribute to the maintenance of SP and associated OCD symptoms, future research could assess the feasibility of implementing an existing interoceptive exposure framework, comparable to interventions utilised in panic disorder treatment (i.e., [15]), where the interoceptive discomfort generated by SP is addressed during ERP. Finally, more exploratory research is also required to determine the nature of interoception across OCRDs as further justification of their place in the broader obsessive–compulsive spectrum.

Appendix 1

Full search strategy for each database

Search terms across all three databases:

Group 1)"Obsessive-Compulsive Disorder" OR "OCD" OR "Body dysmorphic disorder" OR "body dysmorphia" OR "hoarding disorder" OR "hair pulling disorder" OR "trichotillomania" OR"excoriation disorder" OR "skin picking disorder" OR Tourett* OR "Tourette syndrome" OR "Tourette's disorder" OR"tics" OR "tic disorder"

Group 2) "sensory phenomena" OR "sensory intolerance" OR "sensory over-responsivity" OR "NJRE" OR "incompleteness" OR"premonitory urge" OR "interoceptive sensibility" OR"interoception" OR "interoceptive" OR "body awareness" OR "bodily awareness" OR "interoceptive accuracy" OR "interoceptive awareness" OR "interoceptive sensitivity" OR "tactile sensitivity" OR "sensory gating" OR "somatisation" OR "somatization" OR"perceptual sensitivity" OR "not just-right experience" OR"not just-right experiences" OR "not just-right" OR "just-right perceptions" OR "somatosensory"

Filters for each database:

PsycINFO:

- Date range: 2007 to present (22nd April 2024)
- English language
- Types of documents: Academic journals, electronic collections and dissertations (excluding reviews)
- Age boxes to tick: Young Adulthood (18-29 yrs), Adulthood (18 yrs & older), Thirties (30-39 yrs), Middle Age (40-64 yrs), Aged (65 yrs & older), Very Old (85 yrs & older)
- Index terms:
  - Group 1 = DE "Obsessive Compulsive Disorder" OR DE "Tics" OR DE "Tic Disorders" OR DE"Hoarding Behavior" OR DE "Excoriation Disorder" OR DE"Trichotillomania" OR DE "Obsessions" OR DE"Compulsions" OR DE "Body Dysmorphic Disorder" OR DE"Hoarding Disorder"
  - AND Group 2 = DE "Sensory Feedback" OR DE "Interoception" OR DE "Sensory Gating" OR DE"Somatization" OR DE "Somatosensory Cortex" OR DE"Body Awareness"

PubMed:

- Date range: 2007 to present (22nd April 2024)
- English language
- Age boxes to tick: Adolescent, Young Adult, Adult 19+, Adult 19-44, Middle Aged + Aged: 45+ years, Middle Aged: 45-64, Aged, 80 and over.
- MeSH terms:
  - Group 1 = "Tourette Syndrome"[Mesh] OR"Tic Disorders"[Mesh] OR "Obsessive-Compulsive Disorder"[Mesh] OR "Obsessive Behavior"[Mesh] OR "Hoarding Disorder"[Mesh] OR "Body Dysmorphic Disorders"[Mesh] OR"Trichotillomania"[Mesh] OR "Compulsive Behavior"[Mesh] OR"Hoarding"[Mesh] OR "Tics"[Mesh]
  - AND Group 2 = "Interoception"[MeSH Terms] OR "Sensory Gating"[MeSH Terms] OR "Somatosensory Cortex"[MeSH Terms] OR "feedback, sensory"[MeSH Terms]

Scopus:

- Searching in "Article, Title, Abstract, Keywords"
- Date range: 2007 to present (22nd April 2024)
- English language
- Types of documents: Limit to 'Article' and'Short survey' (no reviews)
- NOT ("child" OR "children" OR "adolescent")

Appendix 2

Table 2 Primary study characteristics and results by disorder of interest

Disorder of interest	Author (Year)	Country	Sample size, age *M(SD)*, gender	Control group	Sensory phenomena	Interoception	Measures	Main findings
OCD								
	Apa et al. (2022)	Turkey	$N = 51$ $M_{age} = 32.45$ (11.20) 33 F, 18 M	Non-related healthy controls	NJREs		NJRE-Q-R	Higher NJRE severity in OCD group compared to first-degree relatives and controls. NJRE severity was related to age, OCD symptom severity and the *Doubts over actions* facet of perfectionism.
	Belanger et al. (2023)	United States	$N = 145$ $M_{age} = 31.5$ (11.60) 59.3% F	OCD groups with no current suicidal, no history of suicide attempts		IS	MAIA	Current suicidal ideation associated with lower body trusting. Lifetime history of at least one suicide attempt associated with greater noticing of bodily sensations. Indicates a nuanced relationship between specific facets of interoception and specific facets of suicidality.
	Belloch et al. (2016)	Spain	$N = 47$ $M_{age} = 34.82$ (8.43) 61.7% F	Undergrads	NJREs, INC		NJRE-Q-R, OC-CDQ	INC and NJREs both increase with OCD risk, but are not fully overlapping. May represent distinct aspects of same construct. NJRE severity associated with checking, ordering, washing and hoarding symptoms. INC related to ordering only. INC related to importance/control of thoughts belief, NJREs related to *perfectionism/intolerance to uncertainty, responsibility/threat overestimation and importance/control of thoughts* beliefs.
	Boisseau et al. (2018)	United States	$N = 100$ $M_{age} = 47.42$ (15.27) 51.5% F	No	INC		OC-CDQ, BINCS	Two factors of INC: (1) *Task completion*, and (2) *Sensory*. Both subscales demonstrated positive correlations with OCD severity.
	Bragdon & Coles (2017)	United States	$N = 85$ $M_{age} = 29.01$ (12.96) 51.8% M	No	INC		OC-CDQ	High INC associated with lower *Inflated responsibility/overestimation of threat and higher Perfectionism/intolerance of uncertainty beliefs.*
	Bragdon et al. (2023)	United States	$N = 86$ $M_{age} = 30.53$ (10.92) 65.1% F	Healthy controls	SP		USP-SPS	Neither SP or OCD symptom severity was significantly associated with blink count, urge intensity ratings, or urge suppression difficulty in a blink suppression task.
	Brown et al. (2019)	United States	$N = 19$ Age and gender not reported	No	SP		USP-SPS	During presentation of "body-focused" videos, SP correlated with increased activity in bilateral postcentral gyri, mid-posterior and mid-anterior insula. SP severity predicted insula activation, while OCD severity did not.
	Chik et al. (2010)	United States, Canada	$N = 88$ $M_{age} = 36.41$ (13.60) Gender not reported	Anxiety disorder group and undergrads	NJREs		NJRE-Q-R	NJRE-Q-R subscales that differentiated high- vs. low-belief groups consistently related to OCD symptoms in low-beliefs group, but not in high-beliefs group. The *Delayed Distress* scale of the NJRE-Q-R alone could differentiate low- from high-belief OCD subgroups.
	Coles & Ravid (2016)	United States	$N = 45$ $M_{age} = 28.36$ (13.49) 62.2% M	Anxiety disorder group and university students	NJREs, INC		NJRE-Q-R, OC-CDQ	Both INC and NJRE severity more strongly correlated with symmetry/ordering than obsessing symptoms.
	Collins et al. (2024)	United States	$N = 119$ $M_{age} = 30.1$ (10.9) 66.4% F	No	SP, SOR		AASP, USP-SPS	Higher SOR associated with higher OCD and SP severity, plus higher global OFC connectivity. SP not associated with OFC connectivity.
	Demartini et al. (2021)	Italy	$N = 18$ $M_{age} = 40.72$ (15.78) 10 F, 8 M	Healthy controls		IAcc	Heartbeat counting task	Reduced IAcc in OCD compared with controls.
	Ecker & Gönner (2008; **2014a; 2014b**)	Germany	$N = 202$ $M_{age} = 37$ (11) 60% F	Anxiety disorder, depressive disorder groups, university students	INC		OC-CDQ	Controlling for INC eliminated all associations between perfectionistic "careful" personality style and OCD severity. INC higher in OCD compared to healthy controls, anxiety or depressive disorder groups. OCD and anxiety groups did not differ on HA.
	Eng et al. (**2020**; 2022)	United States	$N = 71$ $M_{age} = 31.6$ (10.9) 50 F, 27 M	Healthy controls	SP, SOR	IS	USP-SPS, MAIA	Compared to controls, OCD reported higher MAIA worrying, noticing, distracting, and emotional awareness, and lower bodily trust. Higher noticing associated with greater symmetry and responsibility for harm symptoms. Lower not-worrying associated with greater responsibility for harm and contamination symptoms. Lower not-distracting associated with greater taboo/unacceptable thoughts.

Disorder of interest	Author (Year)	Country	Sample size, age *M(SD)*, gender	Control group	Sensory phenomena	Interoception	Measures	Main findings
								Higher "adaptive" IS associated with greater FC between insula and multiple brain regions, plus lower OCD severity. "Maladaptive" IS (higher worrying and noticing, less emotional awareness) associated with reduced FC between insula and dACC, plus higher responsibility for harm symptoms. Less distracting from sensations associated with higher SP, higher symmetry symptoms, less FC between insula and IFG.
	Ferrão et al. (2012; **Blanco-Vieira et al., 2019; de Alvarenga et al., 2012; de Avila et al., 2019; Ferrão et al., 2023; Franz et al., 2015; Imthon et al., 2020; McLauchlan et al., 2022; Shavitt et al., 2014; Torres et al., 2012; 2013)**	Brazil	$N = 1,001$ $M_{age} = 34.85$ (12.99) 56.8% F	No	SP		USP-SPS	Symmetry/ordering and contamination symptoms, family history of tics, diminished insight were predictors of SP. SP also associated with comorbid CTD, ADHD, separation anxiety disorder, hoarding symptoms, poor insight, love-precipitated OCD, and stressful life events. One report also found "pure" vs. OCD with comorbidities did not differ on SP. One report found the absence of SP was associated with the presence of mental rituals.
	Fornés-Romero & Belloch (2017)	Spain	$N = 20$ $M_{age} = 36.39$ (10.69) 55% M	Undergrads	NJREs, INC		NJRE-Q-R, OC-CDQ, symptom provocation task	NJREs and INC correlated with physical discomfort at the mandatory stopping point of a symptom provocation task.
	Gentsch et al. (2012)	Germany	$N = 18$ $M_{age} = 35.4$ (9.5) 33.3% F	Healthy controls	INC		OC-CDQ	Higher INC and symmetry/ordering symptoms associated with higher agency judgements on a visual agency perception task.
	Ghisi et al. (2013)	Italy	$N = 22$ $M_{age} = 33.23$ (9.80) 54.5% M	Healthy controls	NJREs		NJRE-Q-R	NJRE severity, but not OCD severity, accounted for longer reaction times on a 'Go/No-Go' task when compared to controls.
	Ghisi et al. (2010)	Italy	$N = 30$ $M_{age} = 33.6$ (12.6) 40% M	Anxiety disorder, depressive disorder groups, university students	NJREs		NJRE-Q-R	NJRE severity could discriminate OCD from those with depressive and anxiety disorders, while dysfunctional obsessive beliefs could not. May suggest specificity of the NJREs to OCD.
	Hellriegel et al. (2017)	United Kingdom	$N = 25$ $M_{age} = 46.84$ (11.19) 64% F	No	INC		AASP, OC-CDQ	OCD had a sensory profile of *low registration, sensory sensitivity, and sensory avoiding, but not sensation seeking. INC was associated with these sensory processing difficulties, even when controlling for OCD severity and trait anxiety.*
	Lee et al. (2009)	Brazil	$N = 37$ $M_{age} = 37$ (12) 51% F	OCD-free community controls	SP		USP-SPS	*Doubts over actions* (a facet of perfectionism) associated with general SP, auditory "just-right", and INC subscales. INC associated with almost all perfectionism domains.
	Pascual-Vera et al. (2021)	Spain, Italy	$N = 62$ $M_{age} = 31.86$ (11.04) 24 F, 38 M	No	NJREs		NJRE-Q-R	Intolerance of uncertainty mediated 16.17% of the path between NJRE severity and OCD severity. Effect increased at the same rate of NJRE severity.
	Podoly et al. (2022)	Israel	$N = 30$ $M_{age} = 32.82$ (10.21) 53% F	Healthy controls with low and high obsessive-compulsive symptoms	SOR		AASP, SPQ, S-Hab-Q	OCD group and controls with high obsessive-compulsive symptoms both recorded higher SOR (i.e., sensory avoidance, sensory sensitivity) and slower sensory habituation than controls with low obsessive-compulsive symptoms.
	Rosário et al. (2009)	Brazil	$N = 76$ $M_{age} = 35.4$ (12.4) 40 F, 36 M	No	SP		USP-SPS	SP associated with early onset of OCD symptoms, higher severity of symmetry/ordering symptoms, and higher likelihood of tics.
	Schultchen et al. (2019)	Germany	$N = 26$ $M_{age} = 28.6$ (7.2) 12 F, 14 M	Healthy controls		IAcc	Heartbeat counting task	Reduced IAcc in OCD compared to controls. OCD severity displayed a descriptive increase in IAcc over 4-6 weeks of CBT, but this did not reach significance.
	Stamatis et al. (2021)	United States	$N = 90$ $M_{age} = 38.14$ (11.95) 31.11% M	OCD without SP, healthy controls	SP		USP-SPS	OCD participants without SP displayed higher risk sensitivity on a gambling task (i.e., placing lower bets) compared to controls. Those with SP did not differ from controls or participants without SP.
	Stern et al. (2020)	United States	$N = 46$ $M_{age} = 32.5$ (11.1) 32 F, 14 M	Healthy controls	SP		USP-SPS	During an eyeblink suppression task, SP correlated with increased activity in pre- and postcentral gyri, paracentral lobule, and mid-posterior insula.
	Subirà et al. (2015)	Brazil, Spain	$N = 106$ $M_{age} = 33.11$ (9.37) 52.8% F	OCD without SP, healthy controls	SP		USP-SPS	OCD participants with SP showed greater grey matter volume in medial sensorimotor cortices, basal ganglia structures, and mesencephalic locomotor region compared to controls. Participants without SP and controls did not differ.

Disorder of interest	Author (Year)	Country	Sample size, age *M(SD)*, gender	Control group	Sensory phenomena	Interoception	Measures	Main findings
	Summerfeldt et al. (2014)	Canada	$N = 289$ $M_{age} = 34.41$ (11.26) 185 F, 104 M	Undergrads	INC		OC-CDQ	Validated a two-factor model of OCD motivational domains: (1) INC and (2) HA. In OCD group, INC displayed a greater range of item loadings than HA than in undergraduates.
	Yang et al. (2023)	China	$N = 91$ $M_{age} = 29.99$ (8.91) 48 M, 52 F	Anxiety disorder group, major depressive disorder groups, healthy controls	NJREs		NJRE-Q-R	All clinical groups reported greater number and severity of NJREs than healthy controls. OCD group had higher NJRE severity than anxiety and depressive groups when controlling for anxiety and depression. Higher NJRE severity correlated with greater OCD severity when controlling for anxiety, depression and obsessive beliefs.
	Yoris et al. (2017)	Argentina	$N = 15$ $M_{age} = 30.40$ (9.98) 8 F, 7 M	Panic disorder group, healthy controls		IAcc, IS, IAw	Heartbeat tapping accuracy task	Higher IAcc, lower IS, and lower IAw in OCD compared to controls and panic disorder group.
TS/CTD								
	Arbuzova et al. (2022)	Germany	$N = 22$ $M_{age} = 27.84$ (9.84) 5 F, 17 M	Healthy controls	PMUs		PUTS	No correlation between PMUs and visual or tactile discrimination in TS.
	Beste et al. (2016)	Germany	$N = 15$ $M_{age} = 29.13$ (15.14 3 F, 12 M	Healthy controls	PMUs		PUTS	Weaker visual perceptual binding (i.e., impaired sensory gating) in TS not associated with PMUs.
	Bhikram et al. (**2020a**; 2020b; **2021**)	Canada	$N = 39$ $M_{age} = 37.1$ (13.1) 8 F, 31 M	Healthy controls	PMUs, SP		PUTS, USP-SPS	In TS, SP associated with reduced activity in insula, temporal, precentral, and frontal gyri, plus increased activity in SMA, cerebellum, and hippocampus. PMUs associated with lower FC between insula and IFG, and lower activity in thalamus, hippocampus, caudate, middle temporal gyrus, precuneus, and mid-cingulate when presented with angry faces in TS.
	Brandt et al. (2023a)	Germany	$N = 291$ Age groups: 18–25 ($N = 115$), 26–35 ($N = 79$), 36–45 ($N = 49$), 46–55 ($N = 35$), 56–65 ($N = 13$). 24.1% F, 75.9% M	No	PMUs		PUTS	OCD symptoms in CTD participants correlated with inner tension, "just-right", and energy descriptions of PMUs.
	Brandt et al. (2023b)	Germany	$N = 111$ $M_{age} = 34.8$ (12.9) 33% F	No	SP, PMUs, NJREs, INC		USP-SPS, NJRE-Q-R, PUTS, FSU-12	In TS, NJREs were more strongly associated with obsessive-compulsive symptoms than tic severity. PMUs were similarly correlated with both obsessive-compulsive symptoms and tic severity. NJREs and PMUs found to be related but are not the same construct. NJREs substantially correlated with INC. Global SP significantly correlated with NJREs, INC and PMUs.
	Crossley & Cavanna (2013)	United Kingdom	$N = 72$ $Mdn_{age} = 26$ (IQR = 17) 65.3% M	No	PMUs		PUTS	PMUs correlated with overall OCD severity, checking and obsessing symptoms in particular, as well as neutralising, washing and ordering symptoms in participants with TS.
	Crossley et al. (2014)	United Kingdom	$N = 102$ $M_{age} = 30.0$ (12.7) 66.7% M	No	PMUs		PUTS	PMUs descriptions (pressure, INC, energy) highly correlated with compulsion severity in participants with TS.
	Draganski et al. (2010)	United Kingdom	$N = 40$ $M_{age} = 32.4$ (11) 10 F, 30 M	Healthy controls	PMUs		PUTS	PMU severity positively correlated with grey matter volume and cortical thickness in left somatosensory and prefrontal cortices.
	Friedrich et al. (2021)	Germany	$N = 24$ $M_{age} = 27.62$ (1.82) 9 F, 15 M	Healthy controls	PMUs		PUTS	PMUs not correlated with rebinding cost between binding-compatible and incompatible conditions for reaction time or accuracy on somatosensory perception-action binding task.
	Ganos et al. (2015)	United Kingdom	$N = 19$ $M_{age} = 39.1$ (16.9) 6 F, 13 M	Healthy controls	PMUs	IAcc	PUTS, heartbeat counting task	Lower IAcc in TS compared to controls, but higher IAcc predicted severity of PMUs.
	Ganos et al. (2012; **2014**)	Germany	$N = 15$ $M_{age} = 31.9$ (7.28) 1 F, 14 M	No	PMUs		PUTS	No relationship between PMUs and tic suppression, operationalised as either inhibition ability or local connectivity of the IFG.
	Isaacs et al. (2020)	United States	$N = 34$ $M_{age} = 33.5$ (*SD* not reported) 10 F, 24 M	Healthy controls	PMUs, SOR		PUTS, SGI, SPQ	Higher self-reports of impaired sensory gating (SOR) correlated with PMUs, but not with tic severity.
	Kano et al. (2020)	Japan	$N = 20$ $M_{age} = 30.2$ (11.2) 4 F, 16 M	No	SP		USP-SPS	Previous SP scores correlated with current OCD and tic severity. Previous PMUs also correlated with current OCD symptoms.

Disorder of interest	Author (Year)	Country	Sample size, age *M(SD)*, gender	Control group	Sensory phenomena	Interoception	Measures	Main findings
	Narapareddy et al. (2022)	United States	$N = 48$ $Mdn_{age} = 31$ (*SD* not reported) 20 F, 28 M	Healthy controls	PMUs	IS	PUTS, MAIA-2	Greater PMUs associated with worrying about sensations, higher emotional awareness, and self-regulation. CTD participants also reported higher noticing and lower bodily trust compared to controls, and higher worrying compared to controls.
	Neal & Cavanna (2013)	United Kingdom	$N = 71$ $Mdn_{age} = 27$ (IQR = 18) 25 F, 46 M	No	NJREs		NJRE-Q-R	Number of NJREs higher in TS participants with comorbid OCD than TS without comorbid OCD. NJREs also strongly correlated with symmetry/ordering and neutralising symptoms across all TS participants.
	Rae et al. (2019; **2018a; 2018b; 2020**)	United Kingdom	$N = 21$ $M_{age} = 34$ (*SD* not reported) 9 F, 12 M	Healthy controls	PMUs	IAcc, IS, IAw, and Interoceptive Trait Prediction Error	PUTS, heartbeat counting task, BPQ	PMUs only predicted by higher IS on the BPQ. Lower IAcc and higher IS on BPQ in TS compared to controls. No group differences in IAw. Higher prediction error in TS compared to controls. PMUs not associated with FC of the IFG, but with greater FC of the pre-SMA with basal ganglia structures in TS participants. PMUs did not predict proprioceptive drift change in rubber hand illusion, but predicted subjective embodiment prediction error. Greater PMUs correlated with insula FC with SMA, posterior cingulate, precuneus, fusiform gyrus, cerebellum. No differences in PMUs when presented with neutral or angry faces in TS participants.
	Rajagopal & Cavanna (2014)	United Kingdom	$N = 108$ $M_{age} = 31.4$ (12.9) 66.7% M	No	PMUs		PUTS	Inner tension, "just-right", INC, and energy descriptions of PMUs correlated with obsession and compulsion severity in TS participants.
	Ramsey et al. (2022)	United States	$N = 80$ $M_{age} = 22.87$ (2.70) 75% M	No	PMUs		PUTS	Participants with greater PMUs reported lower levels of distress tolerance.
	Ricketts et al. (2022)	United States	$N = 80$ $M_{age} = 22.87$ (2.70) 75% M	No	PMUs		PUTS	Higher baseline PMU severity predicted smaller reductions in change in tic severity after 11 years, controlling for prior tic treatment effects.
	Schunke et al. (2016)	Germany	$N = 14$ $M_{age} = 31.7$ (7.8) 2 F, 12 M	Healthy controls	PMUs		PUTS	Beyond enhanced cold detection, no differences emerged between TS and control groups on a quantitative sensory testing battery. PMUs were not associated with any sensory testing parameters.
	Szejko et al. (2023)	Canada	$N = 123$ $M_{age} = 29.3$ (13.96) 54 M, 61 F, 8 gender minority	Participants with functional tic-like behaviours	PMUs		PUTS	No significant differences on PUTS total or items between participants with tics only, functional tic-like behaviours, or both. Patients with both functional tic-like behaviours and a prior history of tics had higher total PUTS score and individual item scores than the remaining two groups, but this difference was non-significant.
	Tinaz et al. (2015; **2014**)	United States	$N = 13$ Age not reported 3 F, 10 M	Healthy controls	PMUs		PUTS	Positive correlations between PMUs and FC of the bilateral SMA and right dorsal anterior insula. No significant correlations between PMUs and the volume or FC of the bilateral sensorimotor cortex.
	Wehmeyer et al. (2023)	Germany	$N = 24$ $M_{age} = 30.21$ (9.07) 6 F, 18 M	Healthy controls	PMUs		PUTS	Greater PMUs correlated with smaller task transition effects in a visual perceptual binding task.
TTM								
	Bottesi et al. (2016)	Italy	$N = 122$ M_{age} = Online group: 26.22 (7.88), face-to-face group: 31.08 (10.92) Online group: 93.9% F, face-to-face group: 91.7% F	Healthy controls	NJREs		NJRE-Q-R	TTM reported higher NJREs compared to controls. 26.2% of TTM participants pulled hair that did not "feel right."
	Falkenstein et al. (2018)	United States	$N = 609$ 18 to 24 = 29%, 25 to 34 = 34%, 35 to 44 = 20%, > 45 = 18% 96% F	TTM-free controls	SOR		SOR Scales, SensOR	TTM endorsed higher tactile and auditory SOR compared to controls. Strong correlations between perfectionism domains (*Doubts over actions, Concern over mistakes*) and auditory and tactile SOR in TTM participants.
SPD								
	Dieringer et al. (2019)	Germany	$N = 15$ $M_{age} = 25.8$ (3.4) 11 F, 4 M	No	SP		USP-SPS	Most to least frequently reported SP were: "just-right" feelings (visual, tactile, auditory), equal physical sensations and "urge-only" phenomena, energy build-up, and INC.

Disorder of interest	Author (Year)	Country	Sample size, age *M(SD)*, gender	Control group	Sensory phenomena	Interoception	Measures	Main findings
	Ricketts et al. (2021)	United States	$N = 61$ $M_{age} = 22.1$ (4.1) 86% F	Undergrads	NJREs		NJRE-Q-R	NJRE severity predicted SPD diagnostic status in a logistic regression, but was not correlated with tendency to experience NJREs during picking episodes, skin picking severity, or skin picking frequency.
BDD								
	Cerea at al. (2022)	Italy	$N = 24$ $M_{age} = 32.17$ (12.91) 19 F, 5 M	BDD-free controls seeking cosmetic intervention, community controls not seeking cosmetic intervention	NJREs		NJRE-Q-R	BDD group reported greater NJREs compared to both control groups. BDD symptoms were predicted by age, drive for thinness, and NJRE severity.
	Summers & Cougle (2017)	United States	*N =30* M_{age} = experimental condition: 19.63 (2.57), placebo condition: 19.95 (3.26) 80% F	No	NJREs		NJRE-Q-R	BDD participants who underwent interpretation bias training with lower baseline NJRE severity had lower BDD symptoms post-treatment compared to placebo training group.
	Summers et al. (2017)	United States	$N = 28$ $M_{age} = 19.21$ (1.85) 71.4% F	Undergrads, undergrad participants scoring 2 or below on the BDD-YBOCS-SR	NJREs, INC		NJRE-Q-R, *in vivo* NJRE task, OC-CDQ	BDD group reported higher NJRE severity compared to controls. High BDD group experienced more discomfort and INC in response to a visual NJRE task compared to low BDD group. High and low BDD did not differ in discomfort on tactile or auditory tasks, controlling for non-symmetry related OCD symptoms.
	Summers et al. (2020)	United States	$N = 50$ $M_{age} = 28.52$ (9.32) 80% F	Healthy undergrads	INC, NJREs		OC-CDQ, visual NJRE task	Controlling for age and comorbid OCD and depression, BDD group had greater INC and HA than controls, as well as greater NJRE discomfort on clutter, body asymmetry and facial asymmetry provocation tasks.
BFRBs								
	Houghton et al. (2018)	United States	$N = 26$ (clinical), 48 (sub-clinical) $M_{age} = 18.84$ (1.21) (clinical), 18.83 (1.80) (sub-clinical) 73.1% F (clinical), 72.9% F (sub-clinical)	BFRB-free undergrads	SOR		AASP	Higher scores on *low registration*, *sensory sensitivity*, and *sensation avoiding* subscales of the AASP were associated with greater BFRB severity, while *sensation seeking* subscale was not.
	Houghton et al. (2019)	United States	$N = 46$ $M_{age} = 24.85$ (8.05) 84.8% F	Healthy controls	SOR		SGI	TTM/SPD participants reported greater frequency and intensity of impaired sensory gating symptoms (SOR), lower tactile detection thresholds, and abnormal feed-forward inhibition compared to controls. Performance on vibrotactile tasks marginally predicted *Fatigue/Stress Vulnerability* subscale and skin picking severity, with no predictors of hair pulling severity.
CTD+OCD, CTD, OCD								
	Isaacs et al. (2022)	United States	N = CTD: 37, CTD+OCD: 32, OCD: 69 M_{age} = CTD: 31, CTD+OCD: 28, OCD: 29 (SD not reported) CTD: 22 M, 15 F, CTD+OCD: 17 M, 15 F, OCD: 39 M, 30 F	Healthy controls	SOR		SGI	OCD group had higher scores on the *Perceptual Modulation* domain of the SGI than CTD without comorbid OCD. Total SOR did not differ between OCD or CTD groups with and without comorbid OCD. Regression results showed OCD symptoms and diagnosis significantly contributed to SOR total, but CTD diagnosis and tic severity did not.
OCD, TTM								
	Sica et al. (2015)	Italy	$N = 41$ (OCD), 38 (TTM) M_{age} = OCD: 34.4 (11.8), TTM: 30 (10.5) OCD: 30% F, TTM: 92% F	Gambling and eating disorder groups	NJREs		NJRE-Q-R	Higher NJRE severity in OCD compared to gambling disorder and eating disorder groups, while TTM group scored comparably to OCD.

Note: **Emboldened** studies are secondary reports of primary identifying studies

Note. AASP Adult/Adolescent Sensory Profile, *ADHD* Attention-Deficit/Hyperactivity Disorder, *BDD* Body dysmorphic disorder, *BDD-YBOCS-SR* Yale Brown Obsessive-Compulsive Scale Modified for BDD – Self Report Version, *BFRBs* Body-focused repetitive behaviours, *BPQ* Body Perception Questionnaire, *CBT* Cognitive behavioural therapy, *CTD* Chronic tic disorder, *dACC* Dorsal anterior cingulate cortex, *FC* Functional connectivity, *FSU-12* Feelings of Incompleteness Questionnaire, *HA* Harm avoidance, *IFG* Inferior frontal gyrus, *IAcc* Interoceptive accuracy, *IAw* Interoceptive awareness, *INC* Incompleteness, *IS* Interoceptive sensibility, *MAIA* Multidimensional Assessment of Interoceptive Awareness, *MAIA-2* Multidimensional Assessment of Interoceptive Awareness – Version 2, *NJREs* "Not just-right" experiences, *NJRE-Q-R* Not Just-Right Experiences Questionnaire – Revised, *OC-CDQ* Obsessive-Compulsive Core Dimensions Questionnaire, *OCD* Obsessive-compulsive disorder, *PMUs* Premonitory urges, *PUTS* Premonitory Urges for Tics Scale, *SensOR* Sensory Over-Responsivity Inventory, *SGI* Sensory Gating Inventory, *S-Hab-Q* Sensory Habituation Questionniare, *SMA* Supplementary motor area, *SOR* Sensory over-responsivity, *SP* Sensory phenomena, *SPD* Skin picking disorder, *SPQ* Sensory Perception Quotient, *TS* Tourette syndrome, *TTM* Trichotillomania, *Undergrads* Undergraduate students, *USP-SPS* University of São Paulo Sensory Phenomena Scale

Appendix 3

Table 3 Risk of bias: JBI cross-sectional analytical checklist for primary studies

Authors (Year)	1. Were the criteria for inclusion in the sample clearly defined?	2. Were the study subjects and the setting described in detail?	3. Was the exposure measured in a valid and reliable way?	4. Were objective, standard criteria used for measurement of the condition?	5. Were confounding factors identified?	6. Were strategies to deal with confounding factors stated?	7. Were the outcomes measured in a valid and reliable way?	8. Was appropriate statistical analysis used?	Overall risk of bias: Low, moderate, high
Apa et al. (2022)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Belanger et al. (2023)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Belloch et al. (2016)	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Boisseau et al. (2018)	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Low
Bottesi et al. (2016)	Yes	Yes	N/A	Unclear	Yes	Yes	Yes	Yes	Low
Bragdon & Coles (2017)	Unclear	Yes	Yes	Yes	No	No	Yes	Yes	Moderate
Brandt et al. (2023a)	No	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Low
Brandt et al. (2023b)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Cerea at al. (2022)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Chik et al. (2010)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Coles & Ravid (2016)	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Collins et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Crossley & Cavanna (2013)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Crossley et al. (2014)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Demartini et al. (2021)	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Draganski et al. (2010)	Yes	Yes	N/A	Yes	Yes	Yes	Yes	Yes	Low
Ecker & Gönner (2008)	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Eng et al. (2022)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Falkenstein et al. (2018)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Ferrão et al. (2012)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low

Authors (Year)	1. Were the criteria for inclusion in the sample clearly defined?	2. Were the study subjects and the setting described in detail?	3. Was the exposure measured in a valid and reliable way?	4. Were objective, standard criteria used for measurement of the condition?	5. Were confounding factors identified?	6. Were strategies to deal with confounding factors stated?	7. Were the outcomes measured in a valid and reliable way?	8. Was appropriate statistical analysis used?	Overall risk of bias: Low, moderate, high
Ganos et al. (2015)	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Ganos et al. (2012)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Ghisi et al. (2013)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Ghisi et al. (2010)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Hellriegel et al. (2017)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Houghton et al. (2018)	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Low
Isaacs et al. (2020)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Isaacs et al. (2022)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Kano et al. (2020)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Lee et al. (2009)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Naraparedddy et al. (2022)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Neal & Cavanna (2013)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Pascual-Vera et al. (2021)	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Podoly et al. (2022)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Rae et al. (2019)	Yes	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Low
Rajagopal & Cavanna (2014)	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Low
Ramsey et al. (2022)	Unclear	Yes	Yes	Yes	Yes	No	Yes	Yes	Low
Ricketts et al. (2021)	Unclear	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Low
Ricketts et al. (2022)	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Rosario et al. (2009)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Sica et al. (2015)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Stamatis et al. (2021)	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Low
Subirà et al. (2015)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low

Authors (Year)	1. Were the criteria for inclusion in the sample clearly defined?	2. Were the study subjects and the setting described in detail?	3. Was the exposure measured in a valid and reliable way?	4. Were objective, standard criteria used for measurement of the condition?	5. Were confounding factors identified?	6. Were strategies to deal with confounding factors stated?	7. Were the outcomes measured in a valid and reliable way?	8. Was appropriate statistical analysis used?	Overall risk of bias: Low, moderate, high
Summerfeldt et al. (2014)	Yes	Yes	Yes	Yes	Unclear	Unclear	Yes	Yes	Low
Summers et al. (2017)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Szejko et al. (2023)	No	Yes	Yes	Unclear	Yes	No	Yes	Yes	Moderate
Tinaz et al. (2015)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Yang et al. (2023)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Yoris et al. (2017)	Unclear	Yes	Yes	Yes	Yes	Yes	No	Yes	Low

Appendix 4

Table 4 Risk of bias: JBI quasi-experimental checklist for primary studies

Authors (Year)	1. Is it clear in the study what is the 'cause' and what is the 'effect'?	2. Were the participants included in any comparisons similar?	3. Were the participants included in any comparisons receiving similar treatment/care, other than the exposure or intervention of interest?	4. Was there a control group?	5. Were there multiple measurements of the outcome both pre and post the intervention/ exposure?	6. Was follow up complete and if not, were differences between groups in terms of their follow up adequately described and analysed?	7. Were the outcomes of participants included in any comparisons measured in the same way?	8. Were outcomes measured in a reliable way?	9. Was appropriate statistical analysis used?	Overall risk of bias: Low, moderate high
Arbuzova et al. (2022)	Yes	Yes	Yes	Yes	N/A	N/A	Yes	Yes	Yes	Low
Beste et al. (2016)	Yes	Yes	Yes	Yes	N/A	N/A	Yes	Yes	Yes	Low
Bhikram et al. (2020b)	Yes	Yes	Yes	Yes	N/A	N/A	Yes	Yes	Yes	Low
Bragdon et al. (2023)	Yes	Yes	Yes	Yes	N/A	N/A	Yes	Yes	Yes	Low
Brown et al. (2019)	Yes	Yes	Yes	No	N/A	N/A	Yes	Yes	Yes	Low
Dieringer et al. (2019)	Yes	Yes	Yes	No	N/A	N/A	Yes	Yes	Yes	Low
Fornés-Romero & Belloch (2017)	Yes	Unclear	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Low
Friedrich et al. (2021)	Yes	Yes	Yes	Yes	N/A	N/A	Yes	Yes	Yes	Low
Gentsch et al. (2012)	Yes	Yes	Yes	Yes	N/A	N/A	Yes	Yes	Yes	Low
Houghton et al. (2019)	Yes	Yes	Yes	Yes	N/A	N/A	Yes	Yes	Yes	Low

Authors (Year)	1. Is it clear in the study what is the 'cause' and what is the 'effect'?	2. Were the participants included in any comparisons similar?	3. Were the participants included in any comparisons receiving similar treatment/care, other than the exposure or intervention of interest?	4. Was there a control group?	5. Were there multiple measurements of the outcome both pre and post the intervention/ exposure?	6. Was follow up complete and if not, were differences between groups in terms of their follow up adequately described and analysed?	7. Were the outcomes of participants included in any comparisons measured in the same way?	8. Were outcomes measured in a reliable way?	9. Was appropriate statistical analysis used?	Overall risk of bias: Low, moderate high
Schultchen et al. (2019)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Schunke et al. (2016)	Yes	Yes	Yes	Yes	N/A	N/A	Yes	Yes	Yes	Low
Stern et al. (2020)	Yes	Yes	Yes	Yes	N/A	N/A	Yes	Unclear	Yes	Low
Summers & Cougle (2017)	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Low
Summers et al. (2020)	Yes	Yes	Yes	Yes	N/A	N/A	Yes	Yes	Yes	Low
Wehmeyer et al. (2023)	Yes	Yes	Yes	Yes	N/A	N/A	Yes	Yes	Yes	Low

Appendix 5

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Abbreviations

AASP	Adolescent/Adult Sensory Profile
BDD	Body dysmorphic disorder
BFRBs	Body-focused repetitive behaviours
BINCS	Brown Incompleteness Scale
BPQ-BA	Body Awareness subscale of the Body Perception Questionnaire
CTD	Chronic tic disorders
DOCS	Dimensional Obsessive–Compulsive Scale
DSM-5	Diagnostical and Statistical Manual of Mental Disorders, 5th Edition
FSU-12	Feelings of Incompleteness Questionnaire
HD	Hoarding disorder
MAIA	Multidimensional Assessment of Interoceptive Awareness
MAIA-2	Multidimensional Assessment of Interoceptive Awareness, Version 2
NJRE-Q-R	Not Just-Right Experiences Questionnaire—Revised
NJREs	"Not just-right experiences"
OC-CDQ	Obsessive-Compulsive Core Dimensions Questionnaire
OCD	Obsessive-compulsive disorder
OCRDs	Obsessive-compulsive related disorders
PMUs	Premonitory urges
PUTS	Premonitory Urge for Tics Scale
S-Hab-Q	Sensory Habituation Questionnaire
SPQ	Sensory Processing Quotient
SGI	Sensory Gating Inventory
SP	Sensory phenomena
SPD	Skin picking disorder
TS	Tourette syndrome
TTM	Trichotillomania
USP-SPS	University of Sào Paulo Sensory Phenomena Scale

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Authors LW, IR and JS contributed to the study conception and design. Eligibility screening and risk of bias assessment was conducted by LW and MJ, with disagreements resolved through consultation with IR and JS. The first draft of the manuscript was written by LW and authors IR and JS drafted previous versions of the manuscript. All authors read and approved the final manuscript.

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