Interoception relates to sleep and sleep disorders
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The central nervous system senses and responds to afferent signals arising from the body. These interoceptive afferents are essential to physiological homeostatic control and are known to influence an individual’s momentary affect, cognition, motivation, and conscious experiences. Both sleep and interoception are tightly connected to physical and mental well-being. This review outlines the current knowledge about the interactions between interoception and sleep. It is demonstrated that there are complex, dynamic relations between sleep and sensory processes within each modality of interoception, including thermoception, nociception, visceral sensations, and subjective feelings about these sensations. A better understanding and appreciation of the intricate interrelations may facilitate management of functional somatic symptoms, chronic pain, insomnia, and other sleep and mental disorders.

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Introduction
Central nervous system (CNS) processing of bodily signals, broadly known as interoception, has become an integral topic in the current discourse of affective, cognitive, behavioral, social, and clinical neurosciences [¹,²,³]. The notion of interoception was traditionally confined to visceral sensations but has expanded to encompass other sensory modalities that inform the CNS about the physiological states across the body, most notably thermoception and nociception [¹**,²]. Interoceptive information arising from body tissues is conveyed to the CNS via neural and humoral pathways as well as through indirect signaling involving immune cells and neurovascular coupling [⁴,⁵]. Ascending neural pathways interface with the central autonomic network at multiple spinal and subcortical levels and ultimately deliver interoceptive information to the ‘neuromatrix’ within the cerebral cortex [⁵,⁶]. Neuronal signaling along the pathways is subject to descending facilitation and inhibition from the brain and modulated by assorted hormonal and inflammatory factors [⁷]. Interoceptive sensitivity is thus determined by not only the neuro-endocrino-immunological condition but also the affective, cognitive, motivational, and arousal state of the individual.

The aim of this review is to provide a synopsis of the current knowledge about the interactions between sleep—which has prominent bidirectional relationship with all of the mentioned factors [⁸,⁹]—and the interoceptive systems. Both sleep and interoception are multi-dimensional constructs. For instance, subjective sleep quality and interoceptive feelings⁴ are often uncorrelated with objective measures of sleep and interoception. Thus far the relationship between each dimension of sleep and each dimension of interoception has not been equally investigated. The present review discusses the most representative themes in the current literature, including: impacts of interoception on sleep initiation, the roles of interoception during sleep, impacts of sleep deprivation on interoception, associations between interoception and habitual sleep, and altered interoception in sleep disorders (notably insomnia disorder).

Interoception affects sleep initiation
Noxious or stressful stimuli naturally increase arousal and hinder sleep. In contrast, certain types of interoceptive stimuli appear somnogenic. For example, gastrointestinal stimulation has been shown to reduce sleep onset latency, mirroring the familiar phenomenon of postprandial sleepiness [²,¹⁰]. It has also been observed in both animals and anesthetized humans that carotid sinus stimulation

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¹ Following the nomenclature recently proposed by the Human Affectome Project, we use the term interoceptive feelings to refer to subjective experiences regarding body parts (or the body as a whole) that may derive from interoceptive afferents but may also integrate other sensory (e.g., tactile [⁶⁹]) information and may even originate within the CNS itself [¹**]. Interoceptive feelings can manifest as symptoms or complaints in clinical settings.
triggers EEG activity resembling slow waves that are characteristic of sleep [2,11].

The link between thermoception and the sleep–wake behavior has attracted particularly widespread attention [12,13*14]. Mild skin warming within the thermoneutral zone during wakefulness reduces vigilance and promotes sleep onset [13*], although the effect appears compromised in the elderly, likely due to the age-related decline in thermosensitivity [15]. More intense heat as well as cold exposure at bedtime impedes sleep. However, body heating a few hours before bedtime reduces sleep onset latency and increases slow-wave sleep (SWS), colloquially known as the ‘warm bath effect’ and likely to involve a cascade of thermoregulatory processes [14]. This shows that sleep propensity depends on both magnitudes and timing of the thermal stimuli.

Based on these findings, an extension of the traditional two-process model of sleep has been proposed [14]. In the extended model, sleep propensity is not only determined by homeostatic sleep pressure and the circadian phase but also dependent on sensory gating signals. An interesting hypothesis is that sleep homeostasis may itself involve interoceptive mechanisms. For instance, sleep deprivation is known to elevate blood pressure and distal skin temperature [11,13*]. These changes could in turn be picked up by carotid baroreceptors and skin thermoreceptors, generating feedback input that promotes sleepiness. Likewise, the circadian component may itself also involve interoceptive mechanisms, for example, through the thermoregulatory effects of melatonin [13*].

Interoception during sleep

Stable sleep is marked by profound suppression of various behavioral defense responses (e.g., hypoxic/hypercapnic ventilatory responses, coughing, swallowing, shivering, and withdrawal reflexes) against adverse conditions or stimuli, and occurrences of such responses typically involve arousals or awakenings [8,10,12,16]. In addition to sleep-induced muscle hypotonia, changes associated with sleep within the sensory systems are believed to contribute to suppression of these responses [8,12,16]. The changes in interoceptive sensitivity prevent arousals and protect sleep. Unfortunately, such mechanisms necessarily render body tissues vulnerable to adverse physiological conditions or events (e.g., gastroesophageal reflux [10]), which could lead to severe clinical complications should those events become frequent during sleep.

It has been shown that manipulation of ambient temperature during sleep is able to alter the core body temperature rhythm as well as sleep architecture. As a result of the use of insulating clothing and bedding, sleep is more easily disturbed by heat than by cold exposure [12]. At present it is unclear whether alterations in skin temperature or in core body temperature exert more influences on sleep. However, it has been demonstrated that subtle skin warming during sleep can promote SWS without changing core body temperature [17], thus supporting direct impacts of skin temperature on SWS expression.

Studies on the nociceptive laser-evoked potential (LEP) and the heartbeat-evoked potential (HEP) during sleep have shown that cortical processing of interoceptive information is present but attenuated as compared to wakefulness [18,19]. Interestingly, the presence of a late positive component of the LEP predicts a subsequent arousal, indicating that nociceptive input can elicit higher order cognitive evaluation even during sleep [18].

The roles of interoception in dreams and rapid eye movement (REM) sleep are particularly elusive. Interoceptive feelings in dreams are rare [1*,18]. REM sleep is characterized by apparently CNS-initiated autonomic swings with minimal interoceptive feedback control, giving rise to erratic heart rate, blood pressure, and breathing patterns [8,11,12,16]. The HEP however indicates increased cortical processing of cardiovascular input during REM sleep relative to non-REM sleep [19]. This processing during REM sleep has been found to be elevated in people with nightmare disorder—regardless of whether a nightmare during the assessment night actually occurred [20]. Interoception, interoceptive feelings, and autonomic output thus seem dissociated during dreams and REM sleep.

Sleep deprivation

Acute or chronic sleep deprivation results in alterations in interoceptive feelings. This is most clearly demonstrated in the pain literature, where various sleep deprivation paradigms (e.g., total sleep deprivation, sleep restriction, SWS disruption, and sleep fragmentation) have been shown to increase sensitivity to painful stimuli as well as spontaneous pain [21]. An increase in somatic complaints besides pain following sleep deprivation has also been reported [22]. More generally, the ‘feeling of sleep deprivation’ that many readers are familiar with can be characterized by fatigue, negative mood, and an overall perception of unwellness [23], resembling in several respects the feeling state of sickness [1*,4,9]. Interestingly, a sleep-deprived person is indeed likely to be judged as being sick by others [24].

A recent study evaluated the effects of chronic sleep restriction with intermittent weekend recovery sleep for up to three weeks. Multiple measures tapping different pain-related processes were assessed. It was found that the heat pain threshold is lowered by sleep restriction during the first week but normalizes afterwards. In contrast, increased CNS cold pain facilitation and reduced cold pain habituation could only be observed in the later weeks of sleep restriction [25*]. The study highlights that the observed effects of acute sleep deprivation may not
generalize to chronic sleep deprivation, as each type of sleep deprivation may differentially affect the multiple processes involved in pain perception.

Sleep deprivation may induce hyperalgesia through several neurochemical pathways including the opioid, monoamine, orexin, and endocannabinoid systems as well as endocrine and immune mechanisms [26**]. Neuroimaging studies probing the brain substrates of sleep deprivation-induced changes in pain processing have just begun to emerge. One recent study found amplified reactivity of the primary somatosensory cortex and blunted reactivity of the nucleus accumbens (NAcc), thalamus, and insula in response to heat pain stimulation following a night of total sleep deprivation. Moreover, the sleep deprivation-induced changes in reactivity of the primary somatosensory cortex and thalamus predict corresponding lowering of the heat pain threshold [27]. Another study reported that a night of fragmented sleep attenuates and delays NAcc responses to heat pain stimulation [28]. Involvement of the NAcc as implicated by both studies suggests that processes related to affective valuation and cognitive control are likely to be engaged in the relationship between sleep and pain.

**Interoception covaries with habitual sleep**

It is not uncommon to find sleep disturbances to accompany somatic complaints. The experimental evidence summarized above would imply bidirectional relations between somatic discomfort and poor sleep. Longitudinal studies have repeatedly shown that self-reported sleep disturbances predict new-onset pain conditions and *vice versa* [29]. Conversely, good sleep quality has been shown to predict (partial) resolution of pain [30]. Pain does not seem to predict persistence versus remission of insomnia [31]. Longitudinal data for the bidirectional relationship between poor sleep and somatic complaints besides pain are lacking, but cross-sectional data have demonstrated robust associations between them across different populations [32–34,35*].

A recent population-based study conducted in Japan indicated that pain symptoms are more reliably associated with self-reported sleep insufficiency than with self-reported sleep duration *per se* [36]. This result is interesting in light of a recent interventional study showing that sleep extension benefits (cold) pain tolerance, more so in people who report to habitually sleep less than needed [37]. In a neuroimaging study, reporting to habitually sleep more than needed (termed ‘sleep credit’) was found to be associated with increased gray matter volume in part of the medial orbitofrontal cortex, which is in turn associated with less somatic complaints, depression, and paranoia [38]. These converging findings suggest that subjective sleep insufficiency is an especially important factor involved in somatic complaints, with the medial orbitofrontal cortex being the common neural substrate.

Investigating the intra-individual relationship between fluctuations in sleep and somatic complaints could provide more mechanistic insights into their interactions. Several studies in the pain literature, mostly carried out in patients with assorted somatic pain conditions, have consistently pointed to sleep (assessed with daily self-reports and sometimes with actigraphy) as a more reliable predictor of subsequent pain than *vice versa* [39]. The same ‘microlongitudinal’ paradigm has also been applied to the study of irritable bowel syndrome, a functional gastrointestinal disorder characterized by hypersensitivity [7]. It was found that poor self-reported sleep quality is associated with next-day abdominal pain but not with non-pain gastrointestinal symptoms [40]. Therefore, across heterogeneous conditions, it seems that the association between poor self-reported sleep and next-day pain is especially robust.

A recent community-based study assessed how people themselves perceive daytime pain to associate with subsequent sleep and *vice versa*. Interestingly, the perceived sleep–pain associations are asymmetric: Sleep worsens more after a day with more-than-usual pain than it improves after a day with less-than-usual pain. Also, pain worsens more after a night of worse-than-usual sleep than it improves after a night of better-than-usual sleep. This asymmetry becomes stronger in people with more severe habitual insomnia (Figure 1) or pain [35*]. The study highlights the possibility that the effects of better and worse nights of sleep on pain are not of equal magnitudes, which could potentially explain why treatments targeting insomnia only marginally alleviate pain in patients with comorbid insomnia and chronic pain [41].

Studies have also linked habitual sleep to laboratory test results on interoceptive feelings. One seminal population-based study found reduced cold pain tolerance in people reporting longer sleep onset latency, lower sleep efficiency, and more severe and frequent insomnia [42]. In another study, healthy volunteers reporting more sleep difficulties were shown to perform worse on the interoceptive cardiac discrimination task. Surprisingly, the association is reversed in people with affective disorders [43].

**Sleep disorders**

Diagnosed sleep disorders are common among patients with chronic pain. The most prevalent comorbid sleep disorder is insomnia disorder (ID). A recent meta-analysis estimated that the prevalence of comorbid ID among patients with chronic pain is 72%, much higher than the prevalence of comorbid restless legs syndrome (RLS, 32%) or obstructive sleep apnea (OSA, 32%) [44*]. Notably, laboratory quantitative sensory testing has confirmed increased pain sensitivity and implicated altered CNS
Etiological theories of ID hypothesize that attention to selective interoceptive or exteroceptive stimuli together with other cognitive activities could lead to a hyperarousal state at bedtime that interferes with sleep initiation or maintenance [46,47]. Somatic discomfort around bedtime can be assessed with the Pre-Sleep Arousal Scale—Somatic subscale [48], which has indeed been found to distinguish between people with ID, subclinical poor sleepers, and normal sleepers and to independently contribute to self-reported nocturnal wake time and poor sleep quality [49]. Some studies, however, suggested that insomnia symptoms are more closely related to pre-sleep cognitive activities than to pre-sleep somatic discomfort [48,50]. It has been proposed instead that perhaps arousal-promoting interoceptive input at bedtime is not maximally consciously recognized by people with ID [51].

Altered interoceptive feelings in ID beyond the pre-sleep period have also been demonstrated. During wakeful rest, people with ID report aberrant spontaneous mental content along several dimensions assessed by the Amsterdam Resting-State Questionnaire (ARSQ) [52] including reduced comfort, heightened health concern, heightened subjective sleepiness, and heightened somatic awareness as compared to healthy controls [53]. Reduced comfort in people with ID is further corroborated by their deficient ‘liking’ feelings throughout the day [54]. A detailed analysis of many dimensions of subjective thermoception also revealed a very different profile between people with probable ID and people without sleep complaints [55].

Strong differences between people with ID and people without sleep complaints are also reflected in an objective measure of interoception. The later part of the frontal HEP is enhanced in people with ID during wakeful rest in the evening, suggesting increased processing of cardiac signals [56] (Figure 2a). In a follow-up study, it was found that mean EEG microstate duration specifically for microstate class C is shortened in people with ID [57] (Figure 2b). As duration of class C microstates has been shown to negatively correlate with the somatic awareness dimension of the ARSQ [52], this microstate alteration could be a marker of heightened somatic awareness in ID.
In sum, it is important to note an unfortunate disbalance. While people with ID show increased interoceptive awareness across modalities, they are actually less likely to either sense comfort or to label experiences as comfortable or pleasant [51,53–55]. Neuroimaging studies have commenced to find neural correlates of this disbalance and suggested that increased reactivity may relate to hyperconnectivity of the angular gyrus while deficient comfort sensing likely involves suboptimal orbitofrontal processing [58,59]. The disbalance toward negative experiences may have long-standing consequences, as recent studies have found that the affective signatures of negative emotional experiences could persist through extinction learning, across the night, and over the long term in people with ID [60–63].

With respect to sleep disorders other than ID, accumulating evidence suggests that OSA is associated with impaired mecano- and thermosensitivity of the upper airway resulting from local neuropathy [64,65]. A recent study systematically examined the functional integrity of afferent neural pathways from the palate by means of electrical stimulation with alternating currents at different frequencies and found in patients with OSA impaired perception specifically of large fiber-mediated afferents at the soft palate [66]. In comparison, others applying the same method to the toes showed reduced current perception thresholds in people with RLS for both large fiber-mediated and small fiber-mediated afferents during the symptomatic period [67]. Because participants with abnormal test results indicative of peripheral neuropathy were excluded, the authors concluded that CNS mechanisms are likely to underlie hyperesthesia in RLS, a conclusion also corroborated by earlier studies using other methodologies [68].

**Conclusion**

To our knowledge, this is the first review that attempts to synthesize the vast literature on the links between sleep and sensory processing across a wide range of interoceptive modalities. The state of science has really only scratched the surface of their complex, dynamic interactions. We hope that our synopsis has presented a coherent account of their intricate relationship and will inspire innovative future research on this important topic.

**Conflict of interest statement**

Nothing declared.
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References and recommended reading
Papers of particular interest, published within the period of review, have been highlighted as:
● of special interest
●● of outstanding interest


An extensive review of the construct of interoception and in particular its relationship with emotion.


An up-to-date review of experimental and observational evidence supporting the connection between skin temperature and sleep.


A community-based observational study showing that the acute within-day mutual reactivity of pain and sleep is modulated by habitual insomnia severity and habitual pain intensity.


