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REVIEW ARTICLE

Hyperarousal in insomnia disorder: Current evidence and potential mechanisms

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Summary

Insomnia disorder is among the most frequent mental disorders, making research on its aetiology and pathophysiology particularly important. A unifying element of many aetiological and pathophysiological models is that they support or even centre on the role of some form of hyperarousal. In this theoretical review, we aim to summarise the current evidence on hyperarousal in insomnia. Hyperarousal is discussed as a state of relatively increased arousal in physiological, cortical and cognitive-emotional domains. Regarding physiological hyperarousal, there is no conclusive evidence for the involvement of autonomous variables such as heart rate and heart rate variability, whereas recent evidence points to a pathophysiological role of neuroendocrine variables. In addition, current literature supports a central involvement of cortical arousal, that is, high-frequency electroencephalographic activity. An increasingly important focus in the literature is on the role of other microstructural sleep parameters, especially the existence of microarousals during sleep. Beyond that, a broad range of evidence exists supporting the role of cognitive-emotional hyperarousal in the form of insomnia-related thought and worries, and their concomitant emotional symptoms. Besides being a state marker of insomnia, hyperarousal is considered crucial for the predisposition to insomnia and for the development of comorbid mental disorders. Thus, beyond presenting evidence from cross-sectional studies on markers of hyperarousal in insomnia, hypotheses about the mechanisms of hyperarousal are presented. Nevertheless, longitudinal studies are needed to further elucidate the mechanism of hyperarousal throughout the course of the disorder, and future studies should also focus on similarities and differences in hyperarousal across different diagnostic entities.

KEYWORDS
hyperarousal, insomnia, sleep

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1 | INTRODUCTION

Insomnia disorder (ID) is defined by problems initiating or maintaining sleep, or by early morning awakening. These sleep-related symptoms have to occur at least 3 nights per week over a period of at least 3 months, and must be accompanied by significant distress or impairments of daytime functioning (American Psychiatric Association, 2013). The prevalence of ID is highly dependent on the diagnostic criteria used, but is estimated to be about 10% of the adult population in industrialised countries (Morin et al., 2015; Roth et al., 2011). ID is among the most frequent mental disorders in the European Union (Wittchen et al., 2011), and is accompanied by high economical and societal costs (Kessler et al., 2011; Wickwire et al., 2016).

This highlights the need for appropriate treatments, for which a profound understanding of pathophysiological aspects as well as their causes and consequences is important.

During the past decades, several aetiological and pathophysiological models of insomnia have been proposed. These include the neurocognitive model of insomnia (Perlis et al., 1997), the AIE (attention, intention, effort) model (Espie et al., 2006), the cognitive model of insomnia (Harvey, 2002), as well as models focusing on impaired emotion regulation or rapid eye movement (REM) sleep instability (Feige et al., 2008; Riemann et al., 2012; Van Someren, 2021). A unifying element of all these models is that they propose or centre on some type of increased arousal in cognitive/emotional, cortical and/or physiological domains. Increased arousal has indeed been one of the most consistent findings in insomnia research, summarised in profound reviews (Bonnet & Arand, 2010; Riemann et al., 2010). However, these reviews are more than 10 years old—a time when knowledge in the insomnia field started to grow rapidly. To our knowledge, there is no current attempt to provide a comprehensive overview on the model. The following review aims to summarise new findings on hyperarousal in insomnia, and to extend the model by focusing on potential causes and consequences of hyperarousal in insomnia. For this purpose, starting from a general definition of the term *hyperarousal*, the various manifestations of hyperarousal in insomnia as well as its role in different phases of the disorder will be discussed in depth.

2 | WHAT IS HYPERAROUSAL? ATTEMPT AT A DEFINITION

One of the earliest findings in patients with insomnia complaints is a frequent presence of metabolic changes that can be linked to high levels of arousal. These include early reports of increases in body temperature, cortisol and adrenaline levels, heart rate and skin resistance (Adam et al., 1986; Haynes et al., 1981; Johns et al., 1971; Monroe, 1967).

In line with this, Bonnet and Arand (1997b, 2010) define hyperarousal in insomnia primarily as a physiological disturbance that is the precursor of other insomnia symptoms (including emotional symptoms). This assumption is based on the observation that inducing symptoms of physiological arousal in healthy sleepers can cause decreased sleep efficiency, but also other symptoms commonly observed in patients with insomnia, such as daytime fatigue and dysphoria (Bonnet & Arand, 1992).

Besides that, there is a long tradition pointing to a specific role of cognitions, emotions and (personality) traits (e.g. neuroticism, trait anxiety) in the aetiology of insomnia, and their role in possibly triggering physiological aspects of arousal (Adam et al., 1986; Kales et al., 1976). In line with this, Riemann et al. (2010) define the hyperarousal concept more broadly by also discussing cognitive/emotional and cortical arousal, and their close interplay with physiological aspects of hyperarousal.

Following this perspective, we define hyperarousal as a state of relatively increased 24-hr cognitive, emotional, physiological and cortical arousal, the signs or antecedents of which are found in all phases of the disorder, and contribute to the manifestation of symptoms at both the subjective and objective levels. This definition includes the following aspects. (1) Hyperarousal in ID is present both during the day and at night. (2) Hyperarousal is defined relatively. Which state is qualified as hyperaroused usually cannot be determined in absolute terms. (3) Hyperarousal occurs in different domains that interact with each other in a complex manner. (4) Signs of hyperarousal can be found before initial manifestation of symptoms in terms of predisposing factors, as maintaining factors during chronic insomnia, as well as crucial factors in the potential transition to comorbid disorders.

The different components of this definition will be subsequently described in more detail.

3 | HYPERAROUSAL IS PRESENT BOTH DURING THE DAY AND AT NIGHT

When discussing potential causes of hyperarousal in ID, a key question is whether increased levels of arousal occur only during the presleep period and at night or also during the day. In particular, potential causes of hyperarousal such as conditioning effects in the bed environment (Perlis et al., 1997), sleep effort (Espie et al., 2006) and worries about potential consequences of not being able to sleep (Harvey, 2002), as well as a failure to de-arouse (Espie, 2002) should not occur or be largely reduced during the day.

Nevertheless, signs of increased daytime arousal in patients with insomnia have been found in many studies. These include increases in cortisol levels (Dressle et al., 2022), metabolic rate (Bonnet & Arand, 1997a) and cognitive arousal (Kallestad et al., 2010; Palagini et al., 2015). In a study by Feige et al. (2017), 10 patients with insomnia and 10 good sleeper controls were investigated in a study involving simultaneous functional magnetic resonance imaging and electroencephalography (EEG) in a resting state wake condition. In patients with insomnia, increases in absolute alpha power and alpha attenuation were found, which was interpreted as potentially indicating increased levels of wakefulness (i.e. arousal) during the day.

Besides that, one of the most common and widely used approaches to assess arousal during the day is the Multiple Sleep

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Latency Test (MSLT). The MSLT is an approach to measure daytime sleepiness, that is, the physiological tendency to fall asleep in the absence of alerting environmental factors. It is therefore assumed to capture an intrinsic arousal state (Carskadon & Dement, 1982).

3.1 | Multiple Sleep Latency Test

Bonnet and Arand (2010) reviewed 12 studies investigating MSLT scores in patients with insomnia. Contrary to the expectation of reduced sleep latency due to impaired night-time sleep, none of these studies confirmed this assumption. Rather, six studies found a significantly increased sleep latency in patients with insomnia. A subsample of four studies that reported mean values and standard deviations was included in a meta-analysis. This meta-analysis confirmed the finding of significantly increased MSLT scores in patients with insomnia (Bonnet & Arand, 2010).

In another study including 95 patients with insomnia and 55 good sleeper controls, Roehrs et al. (2011) found a significantly increased MSLT score in patients with insomnia. In addition, this score was higher in patients with insomnia with shorter total night-time sleep duration and relatively stable over an 8-month period, even under treatment with zolpidem (Roehrs et al., 2011). The finding of increased MSLT scores in patients with insomnia and higher MSLT scores in patients with less objective sleep was also confirmed in a large study including 122 patients with insomnia and 48 good sleeper controls (Huang et al., 2012). Besides demonstrating significantly increased MSLT scores in patients with insomnia compared with good sleeper controls, Kalmbach et al. (2020) also found a relationship between longer sleep latencies in the MSLT and higher pre-sleep cognitive arousal.

Taken together, these results support the notion that increased arousal in insomnia not only occurs during or just before the night but also during the day, characterising it as a stable, 24-hr pathophysiological feature. Nevertheless, future studies should further investigate the mechanisms behind increased sleep latencies in the MSLT, which are increased on average, but not in all patients with insomnia (Roehrs et al., 2011) and thus might be associated with specific insomnia subtypes. In addition, it should be noted that this approach confronts patients with a sleep-related environment and the prompt to fall asleep, which may result in an arousal level that resembles bedtime arousal and may not be representative of actual daytime hyperarousal. Therefore, studies assessing arousal levels during daily routines might be more appropriate.

4 | HYPERAROUSAL IS DEFINED RELATIVELY

In the following sections, hyperarousal is discussed in three different ways: As a *predisposing factor* (see Section 6.1); as a *state* marker for insomnia; and as a component of pathophysiological processes that potentially leads to or causes various insomnia-related symptoms (mechanistic component). A proper understanding of the concept requires a careful separation of these different manifestations of hyperarousal. It is important to note that most studies referring to the hyperarousal concept involve cross-sectional comparisons between patients with insomnia and good sleeper controls (Riemann et al., 2010), and thus refer to the state component of hyperarousal. This is especially important when considering the question to what "hyper" (from ancient Greek hupér = over, above) actually refers to, in particular, whether absolute standards for *hyper*arousal can be applied. Regarding arousal levels in patients with insomnia, Espie (2002) states that "it cannot be stated with conviction that they are hyper-aroused in any absolute sense" (p. 233), which has led to critical remarks about whether *hyper*arousal in insomnia really exists or if patients with insomnia only suffer from a *loss of de-arousal* (Espie, 2002; Vargas et al., 2020). Nevertheless, this refers to a mechanistic component of hyperarousal. If hyperarousal is considered a state, less de-arousal in a situation where de-arousal is expected could be just one way of achieving this state. Describing the *state* of hyperarousal in an absolute sense would, in most cases, require clear threshold for what is *normal* under certain circumstances and certain times. Because these thresholds usually do not exist, they could reasonably be derived only by establishing standard values from large samples of healthy sleepers. This again amounts to a relative comparison (using a standard sample instead of a control group). Thus, we do not see the relative definition of hyperarousal as a deficiency, but rather as a basal and elementary component of the concept. Beyond that, our definition of hyperarousal and the idea of a loss of de-arousal are not mutually exclusive. Rather, it could be speculated that processes related to an increase of arousal (hyperarousal as mechanism), and those related to an inhibition of de-arousal operate in parallel to achieve the state of hyperarousal (Figure 1). Indeed, this view might best explain why many results point to increased arousal during the day (i.e. when an effect of potential loss of de-arousal cannot be expected), whereas the effects for increased arousal in the evening/at night are usually larger (Dressle et al., 2022).

These complex mechanisms through which a state of hyperarousal can be achieved are also illustrated by studies showing evidence of decreased activity in brain regions associated with executive control (Altena et al., 2008; Drummond et al., 2013; Kay & Buysse, 2017). As a consequence of these findings, it has been inferred that, for example, results on high-frequency EEG activity in insomnia are not due to a hyperarousal process but to impaired inhibitory processes, and that the notion of a global, CNS-wide hyperarousal mechanism is too simplistic (Bastien et al., 2008; Kay & Buysse, 2017). Indeed, we posit that hyperarousal in this case does not initially occur as a pathophysiological mechanism, but as a *state*, potentially caused by disturbed inhibitory processes. However, in a next step, this state may in turn act as a mechanism that can cause further arousal in other domains (e.g. cognitive arousal; Perlis et al., 1997) and may also be associated with further insomnia symptoms (e.g. sleep state misperception; Harvey & Tang, 2012).

From this perspective, it can be concluded that although a state of increased arousal is a consistent finding in insomnia research, there are many ways to achieve this state, not all of which are directly linked to an arousal mechanism. Future studies should focus more on

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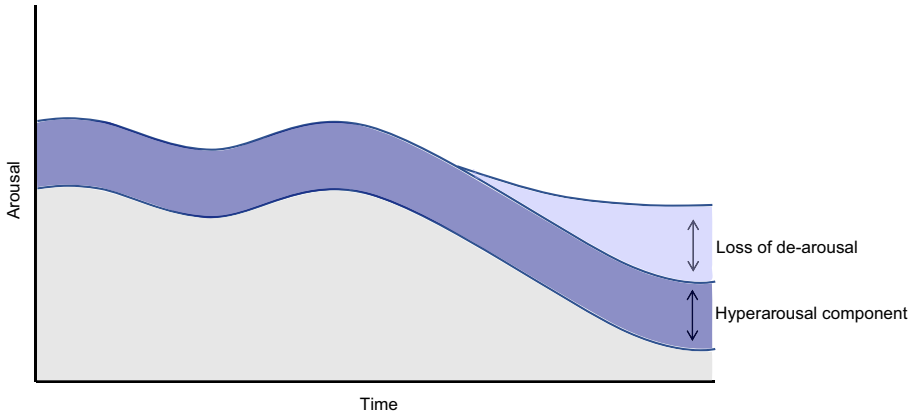

FIGURE 1 Relationship between mechanisms of impaired de-arousal and hyperarousal in insomnia disorder (ID). Both might act in parallel to achieve a state of hyperarousal [Color figure can be viewed at wileyonlinelibrary.com]

the complex interactions of arousal and de-arousal, also combining different methodological approaches to capture hyperarousal in its various manifestations beyond the investigation of physiological arousal markers (see also Section 5).

5 | HYPERAROUSAL OCCURS IN DISTINCT BUT INTERRELATED DOMAINS

In the current literature, hyperarousal is sometimes discussed predominately or exclusively from a physiological (autonomous or CNS-related) perspective (Bonnet & Arand, 1997b, 2010; Kay & Buysse, 2017), whereas other conceptualisations also incorporate cognitive and emotional aspects (Riemann et al., 2010). Treating arousal as a multidimensional construct has a long tradition in insomnia research (Coren, 1988; Nicassio et al., 1985; Tang & Harvey, 2004). This is also reflected in major theoretical models of insomnia that treat physiological and cognitive-emotional aspects not only as two levels of analysis, but as distinct but interrelated pathophysiological dimensions (Harvey, 2002; Perlis et al., 1997), a view also supported by empirical studies showing a pattern of dissociation between different arousal domains. For example, Wassing, Benjamins et al. (2019) confronted patients with insomnia and good sleeper controls with a distress-inducing stimulus before and after a night of sleep. They found increased self-reported physiological distress when patients were re-exposed to the distress-inducing stimulus after sleep, while emotional distress did not change. The opposite was found in good sleepers, with a decrease in both physiological and emotional distress.

Therefore, to gain a comprehensive impression of arousal-related processes in insomnia, we will adhere to the multidimensional view on hyperarousal in this article.

6 | EVIDENCE OF HYPERAROUSAL CAN BE FOUND IN ALL PHASES OF THE DISORDER

While hyperarousal has traditionally been discussed in the context of perpetuating factors (Riemann et al., 2022), we argue that evidence of hyperarousal or its immediate precursors in patients with ID can also be found among important predisposing and precipitating factors, and in the context of possible transition to other mental disorders.

6.1 | Predisposing factors and their interaction with precipitating events

Several lines of research suggest that hyperarousal is not only a state marker in chronic insomnia, but also plays a key role as a baseline characteristic of those at increased risk for developing ID. Predisposing factors for chronic insomnia include genetic and epigenetic factors as well as personality characteristics (Riemann et al., 2022). The role of hyperarousal in the predisposition to insomnia can be globally divided into two broad domains (see Figure 2). First, there is evidence that people prone to insomnia have increased tonic arousal levels premorbidly and, second, there is evidence of increased arousability, that is, a tendency to respond to (specific) stressors with high levels of arousal (dynamic component). Of course, both aspects are closely related, as increased arousability to naturally recurring (daily) stressors probably also leads to tonically increased arousal levels. The latter could result from several mechanisms, including impaired feedback regulation of the hypothalamic–pituitary–adrenocortical (HPA) axis system (for a review, see Dressle et al., 2022).

Regarding tonically increased baseline levels of arousal, large genome-wide association studies were able to identify more than 550 loci associated with ID (Watanabe et al., 2022). Interestingly, clusters of insomnia risk loci have been identified that are only modestly associated with sleep traits, but are associated with either metabolic disturbances or psychiatric traits including anxiety and neuroticism (Jansen et al., 2019; Watanabe et al., 2022). Metabolic disturbances are directly linked to physiological hyperarousal (Bonnet & Arand, 2010; Watanabe et al., 2022), and increased baseline levels of physiological arousal have been found to increase the risk of developing acute symptoms of insomnia as a result of stressful conditions (Bonnet & Arand, 2003). The psychiatric traits implicated in genetic studies are closely related to the dynamic component of increased arousability. Neuroticism is traditionally conceptualised as a state of "nervousness" and increased responsiveness of the emotional and

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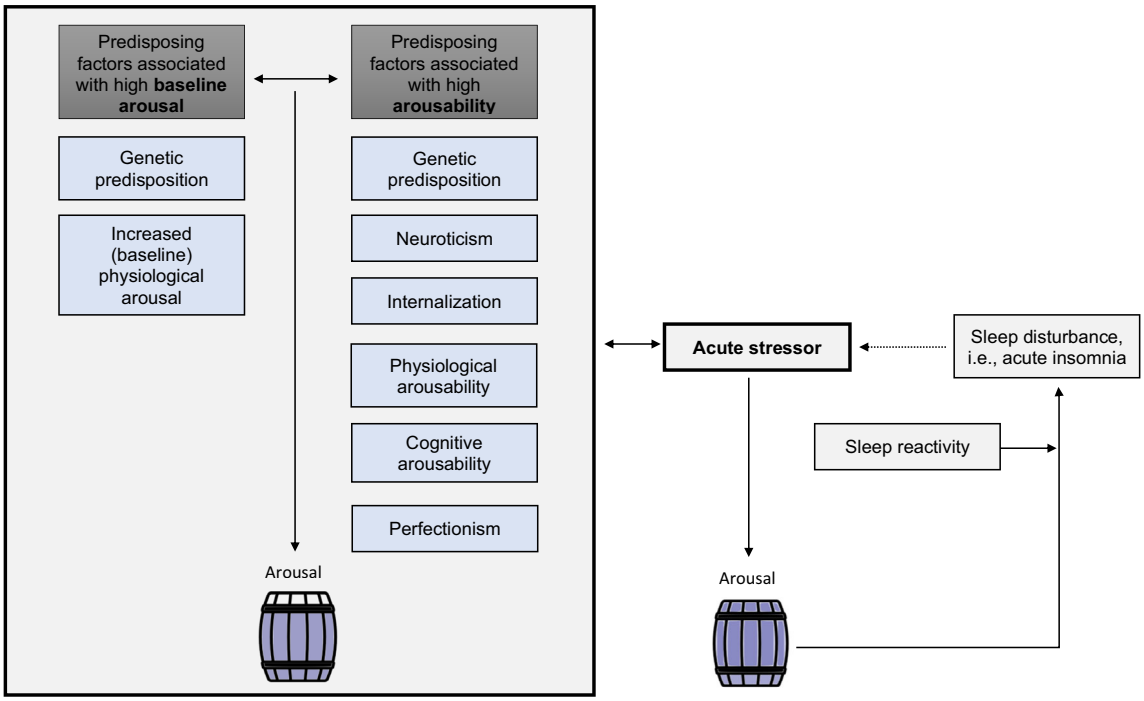

FIGURE 2 The role of hyperarousal in predisposition to insomnia. People who are predisposed to insomnia suffer from both an increased baseline level of arousal and increased arousability. Acute stressors lead to an arousal excess with sleep-disturbing effects, which in turn act as stressors [Color figure can be viewed at wileyonlinelibrary.com]

autonomic nervous systems, leading to a tendency to experience negative emotions more frequently (Barlow et al., 2014; Fahrenberg, 1987). Although the association between neuroticism and insomnia has frequently been established cross-sectionally (Dekker et al., 2017; Gurtman et al., 2014; LeBlanc et al., 2007), neuroticism has also been shown to be related to insomnia symptoms longitudinally in a large sample of shift workers (Larsgård & Saksvik-Lehouillier, 2017). Furthermore, in healthy sleepers, neuroticism has been shown to be a vulnerability factor for the development of acute insomnia as a result of stressful conditions (Fernández-Mendoza et al., 2010), and that higher levels of neuroticism are a characteristic feature of individuals suffering from acute insomnia, as opposed to healthy sleepers (Ellis et al., 2021).

In addition to neuroticism, frequently discussed personality traits in insomnia include a tendency towards internalisation and perfectionism (van de Laar et al., 2010). The internalisation hypothesis, although still poorly investigated, suggests that patients with insomnia are characterised by suppression of negative emotions rather than acting out or expressing them, leading to emotional arousal, which in turn leads to physiological arousal (Kales et al., 1976; Park et al., 2012; van de Laar et al., 2010). A more complicated picture emerges when considering perfectionism, that is, a stable tendency toward very high standards of performance (van de Laar et al., 2010). Besser et al. (2008) found that perfectionism is generally related to physiological arousal in performance situations, in which subjects receive negative feedback. In this regard it has been speculated that the subjectively perceived "failure to sleep" might correspondingly cause physiological arousal in people prone to develop insomnia (van de Laar et al., 2010). Although perfectionism has been shown in a longitudinal design to be associated with insomnia at the 1-year follow-up in a large sample from the general public, this relationship disappeared when accounting for emotional distress (anxiety and depression) in the analysis (Jansson-Fröjmark & Linton, 2007). Thus, perfectionistic thinking may be at least in part secondary to emotional arousal, which is also supported by a study by Akram et al. (2015), who demonstrated that baseline anxiety partially mediates the relationship between insomnia symptoms and future perfectionistic thinking (Akram et al., 2015).

Furthermore, while partly overlapping with the construct of neuroticism, cognitive and physiological arousability as a trait-like construct has been found to be related to insomnia symptoms (Coren, 1988; Coren & Mah, 1993; Fernández-Mendoza et al., 2010).

Thus, it can be summarised that in individuals prone to develop insomnia, a pattern of increased baseline physiological arousal as well as increased arousability exists. The acute onset of insomnia is then usually related to negatively valanced stressful life events (Riemann et al., 2022). Due to the described arousal profile, these situations result in an excess of arousal with ultimately sleep-disturbing effects, the latter being boosted by the capacity of strong emotions to overcome homeostatic sleep pressure (Saper et al., 2005). In addition, evidence suggests that it may also be a stable and predisposing trait to respond to stressful events with sleep disturbances (sleep reactivity; Drake et al., 2004, 2014; Palagini et al., 2016). The sleep disturbance is then itself a stressor that may be dysfunctionally processed due to the predisposing profile. At the same time, poor sleep in turn negatively affects emotion regulation (Baglioni et al., 2010; Vandekerckhove & Cluydts, 2010; see also Section 6.2.4).

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Subsequently, various physiological (e.g. neuroendocrine, see meta-analysis by Dressle et al., 2022), behavioural and cognitive alterations contribute to a maintenance of hyperarousal characteristic of chronic insomnia. These perpetuating factors will be discussed in more detail in the following sections.

6.2 | Hyperarousal and perpetuating factors

6.2.1 | Autonomous variables

Riemann et al. (2010) proposed several autonomous variables that indicate hyperarousal in insomnia: these include altered heart rate and heart rate variability (HRV), increased body temperature and metabolic rate.

Heart rate and HRV

The sympathetic and parasympathetic nervous systems together regulate heart rate on a beat-to-beat basis. HRV reflects variations in heart rate over time, and is considered an indicator of autonomic function/dysfunction (Stein & Pu, 2012). It is therefore plausible to expect changes in these parameters as a marker of physiological arousal in ID. Indeed, Bonnet and Arand (1998) were able to find a significant increase in heart rate in a sample of 12 patients with insomnia and 12 age- and gender-matched controls. Regarding HRV, an increase in low-frequency and a decrease in high-frequency power were found, which was interpretated as indicative of increased sympathetic nervous system activity (Bonnet & Arand, 1998). Other studies were able to partially replicate these results. Spiegelhalder et al. (2011) found a decreased reduction in heart rate from wakefulness to sleep in patients with insomnia, and a significantly reduced nocturnal parasympathetic activity (decreased high-frequency activity) in a subgroup of patients with insomnia with short sleep duration, as determined by a sleep efficacy of less than 85% (Spiegelhalder et al., 2011). Another study investigating patients with insomnia with objective short sleep duration of less than 6 hr also found a significantly decreased high-frequency activity during sleep along with an increase in heart rate (Jarrin et al., 2016). In a sample of 85 patients with insomnia and 55 good sleeper controls, Farina et al. (2014) found a significant increase in heart rate and sympathetic activity in patients with insomnia in the pre-sleep period and during non-rapid eye movement (NREM)-2 sleep (Farina et al., 2014). Nevertheless, several studies were not able to find changes in heart rate or HRV in patients with insomnia (Maes et al., 2014; Monroe, 1967; Varkevisser et al., 2005). In addition, successful treatment with cognitive-behavioural therapy for insomnia had no effect on heart rate or HRV (Johann et al., 2020).

In a systematic review including 22 studies, Dodds et al. (2017) concluded that assumptions about altered HRV are not confirmed by the existing literature. A recent meta-analysis of 17 studies on HRV in patients with insomnia yielded the same conclusion (Zhao & Jiang, 2022).

Body temperature

A review by Lack et al. discusses increased core body temperature as a marker of physiological arousal in patients with insomnia (Lack et al., 2008). Based on a limited evidence base at that time, they concluded that elevated core body temperature affects elderly patients with sleep maintenance insomnia only during the night. In addition, one study (Gradisar et al., 2006) reported a 24-hr increase in core body temperature in nine middle-aged patients with insomnia compared with eight good sleeper controls. Since then, only a few additional studies have been conducted supporting the pathophysiological relevance of increased core body temperature in insomnia. Tracy et al. (2022), investigating 24-hr core body temperature in 37 older (> 60 years) patients with insomnia and 30 older good sleeper controls, found a significant increase in body temperature indicated by a higher meson (rhythm-adjusted mean) in older patients with insomnia. In line with this, Milller et al. found a significant decrease in core body temperature during the night following successful sleep restriction therapy in a small sample of 11 middle-aged patients with insomnia (Miller et al., 2015).

Metabolic rate

An early study by Bonnet and Arand (1995) investigated the metabolic rate of patients with insomnia by measuring oxygen consumption and CO_2 production at several times of the day and during the night. They found significant 24-hr increases in metabolic rate. A systematic review by Chapman et al. (2018) on metabolic rate in insomnia identified another study showing an increase in oxygen use both during the day and at night (Bonnet & Arand, 1997a). One study found no significant differences when only a single time point in the morning was considered (Seelig et al., 2013), and another study investigated the effects of lorazepam on oxygen use in patients with insomnia and found a significant decrease during the night after treatment with lorazepam compared with placebo treatment (Bonnet & Arand, 1999). Thus, although there is some evidence for an increase in metabolic rate, the overall evidence base is still scarce (Chapman et al., 2018).

Overall, the evidence base regarding changes in autonomous variables in insomnia remains scarce and inconclusive. Furthermore, it is difficult to draw clear conclusions from these studies because measurement methods, times and settings vary considerably, sample sizes are often small, and samples are inconsistently defined. There is still a need for larger, well-controlled studies. These studies should also consider objective sleep duration, as insomnia with short sleep duration may represent a distinct phenotype with alterations in autonomous variables (for a review, see Vgontzas et al., 2013).

6.2.2 | Neuroendocrine variables-HPA axis activity

Given the crucial role of the HPA axis in mediating human stress responses (Holsboer & Ising, 2010; Russell & Lightman, 2019), its investigation with respect to hyperarousal in insomnia seems obvious. In this regard, most studies focus on cortisol, the hormonal end-product of the HPA axis released by the adrenal cortex (Holsboer & Ising, 2010).

Vgontzas, Bixler, Lin et al. (2001) performed a comprehensive study investigating series 24-hr plasma cortisol levels (sampling every

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30 min) in 11 patients with insomnia and 13 good sleeper controls. They found significantly increased 24-hr cortisol levels in patients with insomnia, and a more pronounced effect before bedtime and during the first half of the night. In contrast, Riemann et al. (2002) found no significant differences between 10 patients with insomnia and 10 good sleeper controls in a study in which serum cortisol levels were measured every 30 min during the evening and night. Since these early and conflicting studies, cortisol levels in insomnia have been investigated by several other studies. Recently, Dressle et al. (2022) summarised these studies in a systematic review and meta-analysis. Twenty studies on cortisol levels in patients with insomnia were identified, 19 of which were suitable for quantitative synthesis. Overall, a significant increase in cortisol levels was found in patients with insomnia, although this increase was only moderate and high heterogeneity was found between studies. When considering cortisol levels at different times of the day, no significant effects were found on cortisol levels at morning. However, significant effects emerged on cortisol levels during daytime, the pre-sleep period, and during the night (Dressle et al., 2022). Although this supports the assumptions on 24-hr hyperarousal in insomnia, it remains crucial to further investigate the sources of heterogeneity (Dressle et al., 2022). In this regard, indications suggesting relevance of objective sleep duration (Vgontzas et al., 2013; Vgontzas, Bixler, Lin et al., 2001) have not yet been reliably confirmed (Dressle et al., 2022).

Furthermore, aside from HPA activity being a potential state marker of hyperarousal in insomnia, its precise role in potentially causing and maintaining insomnia-specific sleep impairments still needs further investigation. Most sleep-related effects of the HPA axis are thought to be mediated by corticotrophin-releasing hormone (CRH) rather than cortisol, and there is no 1–1 relationship between these two hormones (Buckley & Schatzberg, 2005; Russell & Lightman, 2019). CRH is released by the hypothalamus, and increases in CRH have been demonstrated to be related to increases in sleep EEG frequency and total wake time, and decreases in slow-wave sleep (Ehlers et al., 1986; Holsboer et al., 1988; Schüssler et al., 2016; Vgontzas, Bixler, Wittman et al., 2001). Nevertheless, only two studies directly assessed baseline CRH levels in patients with insomnia (Dressle et al., 2022). Both studies found significantly increased CRH levels when measured in a single morning blood sample (Chen et al., 2016; Xia et al., 2013).

6.2.3 | Hyperarousal and the microstructure of sleep in insomnia

It is a widely recognised phenomenon in insomnia research that subjective sleep complaints outweigh polysomnographically determined objective sleep loss, which is referred to as *paradoxical insomnia* or *misperception of sleep* (Harvey & Tang, 2012). Indeed, at a macrostructural level, a meta-analysis by Baglioni et al. (2014) showed only a significant decrease in total sleep time of about 23 min, a significant increase in sleep-onset latency of about 6 min, and a significant reduction in the duration of both slow-wave sleep and REM sleep in patients with insomnia (Baglioni et al., 2014). Thus, it has been suggested that looking more closely at the microstructural parameters of sleep may be helpful in understanding subjective insomnia complaints (Feige et al., 2013). Some of these mostly arousal-related microstructural changes are discussed in more detail in the following sections.

Cortical arousal–high-frequency EEG activity

Spectral analysis can be used to quantify EEG signals by separating different frequencies. It is among the earliest findings in insomnia research that patients with insomnia compared with good sleeper controls show an increase in fast-frequency EEG activity indicative of cortical arousal. Freedman (1986) investigated 12 patients with insomnia along with 12 age-matched good sleeper controls, and found an increase in beta power during wakefulness, NREM-1 sleep and the first REM period. This increase in beta power during wakefulness and NREM-1 was replicated by Jacobs et al. (1993), who also demonstrated a decrease in beta power after behavioural treatment. These and further results inspired theorising about the pathophysiology of insomnia (Perlis et al., 1997, 2001).

However, subsequent studies have also found contradictory results. In a study consisting of 48 patients with insomnia and 25 good sleeper controls, an increase in high-frequency EEG activity during NREM sleep was found only in women with insomnia (Buysse et al., 2008), and Cervena et al. (2014) found no significant differences between patients with insomnia with sleep-onset or sleep-maintenance problems and good sleeper controls in terms of spectral power in the pre-sleep period.

These inconsistent findings have been attributed to methodological inconsistencies and shortcomings of the different studies. For example, many studies investigated only very small sample sizes, which is especially problematic due to the stable and high interindividual variability in EEG power profiles during sleep (De Gennaro et al., 2008; Riemann et al., 2010), and many studies do not exclude medication intake, which complicates clear conclusions due to the influence, especially of benzodiazepines, on EEG frequency (Bastien et al., 2003; Feige et al., 1999). In addition, studies differ in reporting either relative or absolute spectral power values (Riemann et al., 2010; Zhao et al., 2021).

In an attempt to target these inconsistencies, Zhao et al. (2021) performed a meta-analysis that included 24 studies on EEG spectral analysis in insomnia. They found a significant and robust increase in absolute and relative beta power for NREM sleep, and evidence of a decrease in relative delta power. In addition, a significant but less robust increase in absolute alpha and sigma power was found for REM sleep (Zhao et al., 2021). Nevertheless, this meta-analytic approach is not able to solve all of the methodological problems. Besides heterogenous inclusion criteria for patients with insomnia in primary studies, this also refers to an inconsistent definition of frequency bands between studies (Zhao et al., 2021). In addition, there remains a lack of studies investigating spectral power during REM sleep (Riemann et al., 2010; Zhao et al., 2021).

Therefore, Dressle et al. (2023) investigated absolute spectral power in a large sample of 109 medication-free patients with

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insomnia and 109 good sleeper controls. They found an increase in gamma band power (32–48 Hz) during both NREM and REM sleep.

Overall, recent evidence shows increasing consolidation of assumptions regarding the occurrence of high-frequency EEG activity in insomnia, characterising it as a central arousal domain. Nevertheless, besides the finding of increased spectral power during sleep in patients with insomnia, its precise role in the pathophysiology of insomnia requires further clarification. In addition to the aforementioned studies showing increased spectral power after benzodiazepine intake (Feige et al., 1999), a recent study also shows increased gamma power in patients with insomnia along with a decrease in insomnia severity after mindfulness-based therapy (Goldstein et al., 2019), both of which indicate that high-frequency spectral power is not maladaptive per se. It is possible that it is an epiphenomenon of various processes that in turn determine its maladaptive character. Consistent with this, Dressle et al. (2023) were able to show a relationship with maladaptive pre-sleep cognitive arousal. In contrast to more adaptive cognitive processes as a result of mindfulness-based therapy, maladaptive cognitions that extend into sleep could contribute to the subjective impression of wakefulness and thus to paradoxical insomnia (Dressle et al., 2023; Feige et al., 2008).

Microarousals and REM sleep instability

Feige et al. (2008) were the first to highlight the importance of changes in REM sleep in patients with insomnia. In a large sample of 100 patients with insomnia and 100 matched good sleeper controls, they found a marked increase of arousals per time specifically in REM sleep. They also found a relationship between the duration of REM sleep and subjective wake time that was more pronounced for patients with insomnia (Feige et al., 2008). This led to the model of *REM sleep instability* in insomnia, which assumes that fragmentation of REM sleep contributes to subjective sleep impairments (Riemann et al., 2012). It is speculated that this fragmentation may result from insomnia-related stressors, such as worry about the daytime consequences of sleep disturbance (Riemann et al., 2012). This type of (pre-sleep) cognitive arousal could also shape REM sleep mentation, leading to the perception of wakefulness through its more wake-like content and easier recall due to arousals from REM sleep (Riemann et al., 2012). Indeed, Feige et al. (2018) found that when patients with ID were awakened from REM sleep, they were significantly more likely than healthy subjects to report that they had been awake before. No difference was found for NREM-2 sleep. In addition, patients with ID showed more negatively toned dream content during REM sleep (Feige et al., 2018). Wassing, Schalkwijk et al. (2019) were able to replicate the specific increase of microarousals during REM sleep in patients with ID. However, other studies failed to find a significant increase in microarousals during REM sleep in patients with insomnia (Andrillon et al., 2020; Feige et al., 2018, 2021; Hermans et al., 2019).

Wassing et al. extended the findings on REM sleep in insomnia by demonstrating that REM sleep fragmentation impedes the resolution of emotional distress during sleep, potentially contributing to the chronicity of hyperarousal (Wassing et al., 2016). In another study in which distress was experimentally induced before sleep (Wassing, Benjamins et al., 2019), patients with ID were even found to experience increased self-reported physiological distress when re-exposed to the distress-inducing stimulus after a night of sleep, while emotional distress did not change. The opposite, a decrease in both physiological and emotional distress, was found in healthy sleepers. It is assumed that distress may accumulate in this way over the course of the disorder, paving the way for comorbid mental disorders (Van Someren, 2021).

On a neurobiological level, fragmented REM sleep leads to a lower decline in amygdala reactivity during sleep (Wassing, Lakbila-Kamal et al., 2019). This is assumed to result from impeded silencing of the *locus coeruleus* during fragmented REM sleep, leading to maintenance of noradrenaline release, which is normally strongly reduced during healthy REM sleep and disrupts synaptic depotentiation (Swift et al., 2018; Van Someren, 2021; Wassing, Lakbila-Kamal et al., 2019). These assumptions are supported by the finding that in patients with ID, recall of shameful experiences from the distant past elicits activity in the limbic circuit that partially overlaps with activity elicited by a novel shameful experience. In contrast, healthy sleepers show no limbic activity in response to shameful experiences from the distant past (Wassing, Schalkwijk et al., 2019).

Besides these seminal studies supporting the importance of REM sleep-related disturbances in ID, precise mechanisms behind these disturbances still need further investigation.

Event-related potentials (ERPs) during sleep

The ERPs are characteristic EEG waves that follow the presentation of stimuli. The peaks are named according to their polarity (positive or negative) and the latency of their occurrence (Feige et al., 2013). The ERP components most commonly studied in insomnia research include the P1 and N1 components. A decrease in N1 amplitude and an increase in P2 amplitude is usually a hallmark of the pre-sleep period and sleep (Campbell & Colrain, 2002; Cote et al., 2002). Furthermore, increased N1 amplitudes have been shown to be associated with attention to a stimuli (Näätänen & Picton, 1987), whereas an increase in P2 amplitude is associated with a decrease in attention (Crowley & Colrain, 2004). Thus, P2 is assumed to be associated with inhibition of irrelevant stimuli (Bastien et al., 2013).

Over the past few years, progress has been made in the study of ERPs during sleep. In a recent study, Feige et al. (2021) presented highly frequent continuous low-intensity guitar tones to 100 participants (50 with ID and 50 good sleeper controls) during two entire nights of sleep. Compared with healthy subjects, patients with insomnia showed reduced P2 amplitudes in phasic REM sleep—a reduction that, interestingly, correlated negatively with sleep misperception. In a study investigating 13 subjects with poor sleep together with 12 good sleepers, a similar reduction in P2 amplitudes was found for standard stimuli of an oddball paradigm in the pre-sleep period (Kertesz & Cote, 2011). The auditory oddball paradigm is the standard method in research on auditory ERPs. It involves the presentation of a series of repetitive standard tones along with infrequently occurring deviant tones (oddball stimulus). Reduced P2 amplitudes were also found at

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sleep onset by Turcotte et al. (2011) in subjects with psychophysiological insomnia compared with those with paradoxical insomnia and good sleeper controls. This pattern of reduced P2 amplitudes was also found by Yang and Lo (2007) at the beginning of NREM-2 sleep, and by Cortoos et al. (2014) in the evening. In addition, Yang and Lo (2007) found larger N1 amplitudes to deviant tones along with smaller N350 amplitudes to standard stimuli. Overall, these results are interpreted in terms of increased attentiveness or failure to suppress irrelevant stimuli in patients with insomnia (Feige et al., 2021; Kertesz & Cote, 2011).

Nevertheless, besides smaller P2 amplitudes at sleep onset, Turcotte et al. (2011) also found *increased* P2 amplitudes during evening wakefulness and NREM-2 sleep in patients with psychophysiological insomnia compared with good sleeper controls. Similar results were found by Bastien et al. (2013), who demonstrated larger N1 amplitudes in subjects with psychophysiological and paradoxical insomnia as well as larger P2 amplitudes during REM sleep in subjects with psychophysiological insomnia compared with those with paradoxical insomnia and good sleepers, and Bastien et al. (2008), who found larger P2 amplitude in patients with insomnia and smaller N350 amplitude at sleep onset. During wakefulness in the evening and morning, patients with insomnia showed increased N1 amplitudes compared with good sleeper controls.

Sforza and Haba-Rubio (2006) found no significant alterations in N1, P2 and P3 amplitudes and latency during an auditory oddball task administered in the evening and morning during wakefulness in a sample of 15 patients with insomnia compared with 45 patients with sleep-related breathing disorder and 13 good sleeping control subjects.

In addition, Turcotte and Bastien (2009) investigated the association between different parameters of objective sleep quality and N1 and P2 latencies and amplitudes during an auditory oddball paradigm in the morning, evening and at sleep onset in 15 patients with insomnia and 16 good sleeping controls. For N1 amplitudes during the evening task, significant negative correlations with wake after sleep onset as well as a significant positive correlation with sleep efficacy were found in patients with insomnia. For P2 amplitude in the morning, a significant negative association was found with total sleep time and sleep efficacy in patients with insomnia. For P2 amplitudes in the evening, there was also a significant negative association with sleep efficacy in patients with insomnia. Regarding N1 and P2 latencies, a significant negative association was found between N1 latency at sleep onset and sleep-onset latency, as well as a negative association between P2 latency at sleep onset and wake time after sleep onset in patients with insomnia (Turcotte & Bastien, 2009).

Ceklic and Bastien (2015) applied an auditory oddball paradigm during NREM sleep, and found significantly larger N350 amplitudes during NREM-2 sleep in the second half of the night in good sleeper controls and significantly larger N350 amplitudes during slow-wave sleep in patients with insomnia. Interestingly, they also found a general influence of sleep quality. In both groups, objective good sleep quality was associated with smaller N350 amplitude. Good subjective sleep quality was associated with smaller P2 and N350 amplitudes. The latter also applied to subjects who objectively slept poorly but reported good sleep (Ceklic & Bastien, 2015). This has been interpreted in terms of the need to inhibit sensory stimuli being lower in subjects with good sleep. Furthermore, it is concluded that the P2 component is specifically related to subjective sleep quality, and that the subjective impression of good sleep emerges when less energy needs to be invested to inhibit information processing (Ceklic & Bastien, 2015).

Hairston et al. (2010) investigated sensory gating directly in 18 patients with insomnia and 20 good sleepers. Pairs of identical white-noise clicks were presented during wakefulness and during six–eight blocks of 11 min in NREM-2 sleep. As a measure of sensory gating, that is, the capacity to filter out irrelevant stimuli (Kisley et al., 2001), the ratio between the two clicks was calculated for each component. There was no significant difference in ERP components during wakefulness. During sleep, reduced sensory gating was found for the N350 and P450 components in patients with insomnia (Hairston et al., 2010).

In general, it can be concluded from these studies that patients with insomnia appear to lack the ability or have a reduced capacity to inhibit sensory stimulation both during wakefulness and sleep, resulting in greater permeability to external sensory stimuli. Discrepant findings regarding P2 amplitude (i.e. increase versus decrease) have been attributed to stimulus characteristics (Feige et al., 2021). Besides that, clear-cut conclusions about the precise mechanisms are difficult due to the high variability between studies in terms of times (during wakefulness, the sleep-onset period, different sleep stages) and frequency of stimulus presentation, as well as sample composition, especially applying to the degree of sleep state misperception.

With respect to the hyperarousal concept, in addition to increased sensitivity to sensory stimuli being a state marker of hyperarousal in insomnia, it should be noted that the subjective and objective sleep disturbances caused by this may further trigger and maintain hyperarousal processes (e.g. through increased worries about not getting enough sleep).

In addition to these findings, other sleep phenomena are discussed as indicative of hyperarousal in insomnia. These include increases in cyclic alternating pattern (CAP) during sleep (Terzano et al., 2003), and increases in spontaneous K-complexes (Forget et al., 2011) as well as a decrease in density of sleep spindles (Besset et al., 1998; for a general review, see Feige et al., 2013).

6.2.4 | Cognitive and emotional hyperarousal

Consistent with the clinical impression of patients with insomnia frequently complaining of an overactive mind, cognitive arousal is a central feature of many insomnia models (Espie et al., 2006; Harvey, 2002; Perlis et al., 1997). It is generally defined as a tendency toward excessive worry and rumination, and frequently occurs more intensely during the pre-sleep period (Harvey, 2002), is influenced by dysfunctional beliefs about sleep (Carney, Edinger et al., 2010; Harvey, 2002; Hertenstein et al., 2015; Jansson & Linton, 2007),

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dysfunctional strategies for coping with cognitive arousal such as thought suppression (Harvey, 2001), and by meta-cognitions regarding its functions and consequences (Palagini et al., 2016; Waine et al., 2009). Most studies use questionnaires to assess the level of cognitive activity in patients with insomnia (for an overview, see Hiller et al., 2015). One of the most frequently used measures is the Pre-Sleep-Arousal Scale (PSAS), which consists of a subscale for self-reported cognitive and another subscale for self-reported somatic arousal (Nicassio et al., 1985). Indeed, numerous studies have demonstrated that patients with insomnia show increased pre-sleep cognitive activity compared with good sleeper controls (Dressle et al., 2023; Hertenstein et al., 2015; Kalmbach et al., 2020; Nicassio et al., 1985; Palagini et al., 2016, 2017; Robertson et al., 2007; Vochem et al., 2019). In accordance with the concept of 24-hr hyperarousal, this increase in cognitive activity also occurs during the day (Harvey, 2002; Kallestad et al., 2010; Palagini et al., 2015). Furthermore, many studies point to an association with objectively determined sleep latency (Kalmbach et al., 2020; Wicklow & Espie, 2000), as well as sleep efficacy and sleep maintenance (Kalmbach et al., 2020; Spiegelhalder et al., 2012).

It is assumed that this cognitive arousal leads to emotional distress, and that altered emotional reactivity mediates the relationship between cognitive and physiological arousal (Baglioni et al., 2010; Harvey, 2002). Likely, this emotional distress is then exacerbated by deficits in emotion regulation (for reviews, see Schiel et al., 2020; Van Someren, 2021). Of note, further processes central to the pathophysiology of insomnia are also assumed to stem from this cognitive-emotional overactivity. These include selective attention to sleep-related cues (for a review, see Harris et al., 2015) and safety behaviours (Perlis et al., 1997), both of which further amplify cognitive arousal, leading to a vicious circle (Harvey, 2002; Perlis et al., 1997).

Nevertheless, cognitive arousal is a broad construct, and research suggests that it might be crucial to distinguish between different contents of cognitive activity. Wicklow and Espie (2000) investigated the content of pre-sleep cognitive arousal in 21 patients with insomnia. They instructed participants to express their thoughts while having trouble falling asleep. This was recorded and subjected to content analysis. A total of eight distinct categories of thoughts were identified. Interestingly, while many thoughts were related to the topic of sleep and adverse consequences of not getting enough sleep, this was only the second most frequent thought content. More frequently, subjects were preoccupied with thoughts related to general problem-solving and rehearsing of past events (Wicklow & Espie, 2000).

Spiegelhalder et al. (2012) found that although both were significantly increased in patients with insomnia, only sleep-related, but not the general level of cognitive arousal, were related to polysomnographically determined sleep efficacy and wake time after sleep onset.

Carney, Harris et al. (2010) tried to distinguish between the concepts of worry and rumination. Rumination was operationalised in terms of *thinking* about symptoms, whereas worry was thought to be more focused on the future consequences of mood and sleep disturbances. It was found that only the rumination component was associated with subjective sleep parameters (Carney, Harris et al., 2010).

In addition, different modalities of processing, that is, a more verbal- or imagery-based form, might be important (Harvey, 2002; Nelson & Harvey, 2003). Verbal processing is suggested to be able to suppress unpleasant images and physiological arousal by shifting cognitive activity to less concrete processing that also leads to less unpleasant emotions (Davey & Wells, 2006; Stöber et al., 2000). A lack of cognitive capacity, in turn, could lead to more imagery-based thinking, which has the opposite effect of increasing negative emotions and physiological arousal (Toh & Vasey, 2017; Vasey et al., 2017). Dressle et al. (2023) found that pre-sleep cognitive arousal was positively, whereas self-reported somatic arousal was negatively associated with gamma power during sleep. Because gamma power has been associated with cognitive control (Cho et al., 2006; Minzenberg et al., 2010), the effect of cognitive arousal on gamma power could also be influenced by applying cognitive control. Dressle et al. (2023) further speculate that these different types of cognitive processing might have different effects on sleep. More precisely, verbal cognitive arousal might primarily affect the microstructure of sleep. This is supported by the association between thought-like cognitive processes during the night and restlessness of REM sleep (Wassing, Benjamins et al., 2019). The high physiological arousal associated with imagery-based processing could interfere with the macrostructural dimensions of sleep initiation and/or maintenance, which could provide an explanation for the relationship between objective short sleep duration and physiological arousal suggested by Vgontzas et al. (2013). In line with this, shorter sleep duration and problems with sleep onset were associated with a reduced capacity to control attention to negatively valanced stimuli in subjects who scored high on a questionnaire assessing negative repetitive thinking (Nota & Coles, 2018). Furthermore, Cox et al. (2019) found that the effects of insomnia symptoms at baseline on negative repetitive thinking 3 months later were significantly mediated by executive (dys)function 1 month after baseline measurement and problems in emotion regulation 2 months after baseline measurement.

It can be generally concluded that cognitive-emotional hyperarousal is central to the pathophysiology of insomnia. It plays a role in causing objective and subjective sleep complaints (and possibly also in sleep state misperception; Tang & Harvey, 2004), which in turn acts as a major concern leading to perpetuating vicious circles. Beyond that, cognitive arousal seems to be closely related to cortical arousal and emotional arousal aspects to physiological or somatic arousal. However, future studies should more closely focus on precise cause–effect relationships. In addition, cognitive arousal is a broad and heterogenous construct, and more studies are needed that distinguish between the effects of different cognitive content or modalities.

7 | SYNTHESIS

The concept of hyperarousal has been proven fruitful in recent years and has stimulated much research. Therefore, a large proportion of findings in insomnia research has been related to it. The discussed findings on hyperarousal thus necessarily remain a selection, which is

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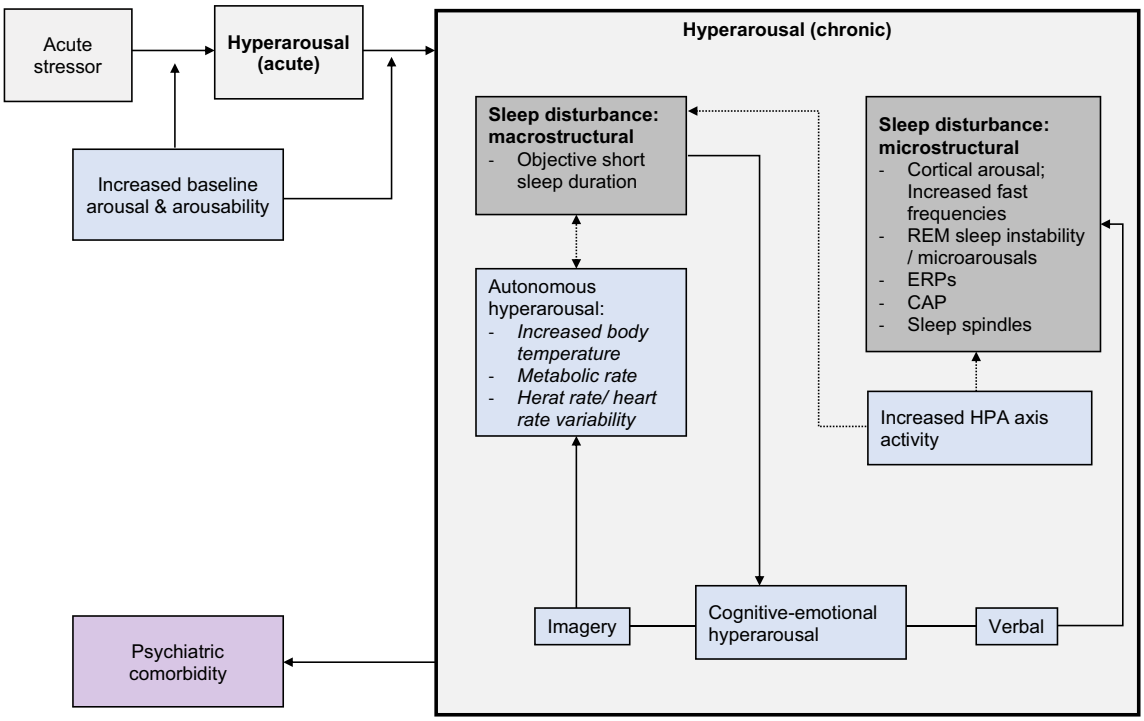

FIGURE 3 The role of hyperarousal in the maintenance of insomnia. Insomnia is maintained by the mutual reinforcement of arousal in different domains. CAP, cyclic alternating pattern during sleep; ERPs, event-related potentials; REM, rapid eye movement [Color figure can be viewed at wileyonlinelibrary.com]

intended to illustrate mechanisms that are assumed to be central. Furthermore, studies on neuroimaging in insomnia are not discussed in this article, as this is the focus of another article in this special issue.

Hyperarousal has been discussed as a 24-hr disturbance in ID that plays a key role in the context of predisposition to insomnia, as a state in patients with chronic insomnia, as a maintaining factor, and a factor critically involved in the transition to other psychopathologies. Thus, it has become apparent that the term hyperarousal is used in many different ways, which may lead to confusion and misunderstanding. Most importantly, future studies should more carefully distinguish between the cross-sectional comparison of hyperarousal states and the pathophysiological consequences of hyperarousal (mechanistic component).

Furthermore, hyperarousal has been shown to occur in cognitive-emotional, cortical and physiological domains. While cognitive and emotional alterations play a major role in the development and maintenance of insomnia, they can only be adequately understood if their consequences are considered at the physiological/cortical level. Therefore, the notion that insomnia is a psychobiological disorder (Riemann et al., 2010) still holds true.

Regarding its role in predisposition to insomnia, it has been demonstrated that people who are vulnerable to insomnia already have an increased baseline level of arousal. Moreover, many traits associated with predisposition to insomnia are associated with increased arousability, that is, the tendency to respond to stressors with high levels of cognitive-emotional and physiological arousal. As (mild) stressors occur regularly, the baseline level of arousal is also boosted by increased arousability. Confrontation with acute stressors then leads to an excess of arousal, with sleep-disturbing consequences that are exacerbated by sleep reactivity and themselves act as a stressor that is dysfunctionally processed due to the high arousability. Thus, hyperarousal becomes chronic.

Chronic hyperarousal is then accompanied by sleep disturbances at a macrostructural level (i.e. objective short sleep) and/or a microstructural level (Vgontzas et al., 2013). Evidence suggests that macrostructural sleep changes are more closely related to physiological arousal (both as cause and consequence), and microstructural changes are bidirectionally related to cognitive aspects of arousal (see Figure 3). Hypothetically, the nature of processing and cognitive content could be relevant in this regard. Nevertheless, especially the evidence base on autonomous arousal parameters is still inconclusive, which warrants further research in this area.

Whether insomnia with micro- versus macrostructural changes reflects stable subtypes remains to be investigated. In this regard, it might be also interesting to investigate whether the nature of the disorder could change with duration (e.g. starting with objective short sleep and then gradually evolve to more microstructural sleep changes).

8 | FUTURE PERSPECTIVES

A majority of studies investigate hyperarousal in a cross-sectional manner. Although the present review also attempts to present mechanisms of hyperarousal during the course of the disease, most of these are theoretical assumptions. More longitudinal studies are therefore

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needed to investigate the role of hyperarousal in the predisposition to insomnia and, in particular, in the transition from acute to chronic symptoms. This research should not treat insomnia as a uniform construct, but should consider different domains of arousal, their characteristics and interactions. In this regard, it would be interesting to see whether subtyping the heterogenous condition of insomnia along different arousal foci (e.g. predominance of physiological arousal, predominance of cognitive arousal, etc.) might be suitable. Related to this, the development of a hyperarousal test, perhaps even applicable during the day, could be useful and improve insomnia diagnosis (Riemann et al., 2022).

By defining hyperarousal as a broad construct that also incorporates cognitive-emotional alterations, the question of whether hyperarousal mechanisms are specific to insomnia necessarily arises. Indeed, hyperarousal has been demonstrated in many other mental disorders, including depression (Ulke et al., 2019; Wenzler et al., 2017), PTSD (Weston, 2014) and anxiety disorders (Geiger et al., 2014; van Veen et al., 2008). In particular, aspects of cognitive-emotional hyperarousal such as the tendency to be excessively ruminative is a major transdiagnostic feature in many mental disorders (McEvoy et al., 2013). It might not be the fact of cognitive-emotional arousal per se that is specific to insomnia, but the sleep-related content. Similar to processes in the context of anxiety disorders (Casey et al., 2004), the fear of not getting enough sleep may develop into a real sleep impairment, which in turn becomes a source of further concern. Future research should more closely consider similarities and differences in hyperarousal across different diagnostic entities. This could also help to better understand common comorbidities between insomnia and other mental disorders as well as the transition from insomnia to other mental disorders.

AUTHOR CONTRIBUTIONS

Conceptualisation: Raphael J. Dressle and Dieter Riemann. Writing, original draft: Raphael J. Dressle. Writing, review and editing: Raphael J. Dressle and Dieter Riemann.

CONFLICT OF INTEREST STATEMENT

Raphael J. Dressle does not report any financial or non-financial conflicts of interest. Dieter Riemann is member of the Executive Board of FAVT (Freiburger Ausbildungsinstitut für Verhaltentherapie/Freiburg Institute for Behavioural Therapy; non-profit organisation). In this function he receives honoraria for running examinations, giving lectures, attending board meetings, and participating in the selection of candidates. Dieter Riemann receives royalties for authored books and book chapters from several publishing companies (Elsevier, Thieme, Hogrefe, Kohlhammer, etc.). Dieter Riemann is Editor-in-Chief of the *Journal of Sleep Research*, which is owned by the European Sleep Research Society (non-profit organisation)–he receives monthly payments for this task. Dieter Riemann frequently lectures at conferences, meetings, seminars, mostly invited by the organising bodies (no pharmaceutical industry)–sometimes honoraria are paid for his engagement, and usually travel costs (if travelling is involved) are covered. Dieter Riemann receives honoraria from GAIA group (Germany), Meinstresscoach (Switzerland) and HelloBetter (Germany) for advising on the development of internet-based approaches to insomnia treatment.

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DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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