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To sleep or not to sleep, that is the question: A systematic review and meta-analysis on the effect of post-trauma sleep on intrusive memories of analog trauma

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ABSTRACT

Distressing intrusive memories of a traumatic event are one of the hallmark symptoms of posttraumatic stress disorder. Thus, it is crucial to identify early interventions that prevent the occurrence of intrusive memories. Both, sleep and sleep deprivation have been discussed as such interventions, yet previous studies yielded contradicting effects. Our systematic review aims at evaluating existing evidence by means of traditional and individual participant data (IPD) meta-analyses to overcome power issues of sleep research. Until May 16th, 2022, six databases were searched for experimental analog studies examining the effect of post-trauma sleep versus wakefulness on intrusive memories. Nine studies were included in our traditional meta-analysis (8 in the IPD meta-analysis). Our analysis provided evidence for a small effect favoring sleep over wakefulness, log-ROM = 0.25, $p < .001$, suggesting that sleep is associated with a lower number of intrusions but unrelated to the

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occurrence of any versus no intrusions. We found no evidence for an effect of sleep on intrusion distress. Heterogeneity was low and certainty of evidence for our primary analysis was moderate. Our findings suggest that post-trauma sleep has the potential to be protective by reducing intrusion frequency. More research is needed to determine the impact following real-world trauma and the potential clinical significance.

Abbreviations

AIC	Akaike information criterion
AG	actigraphy
BIC	Bayesian information criterion
CD	Cook's distance
CI	confidence interval
COVRATIO	covariance ratio
GRADE	Grading of Recommendations, Assessment, Development and Evaluations
ID	intrusion distress
IF	intrusion frequency
IPD	individual participant data
ITT	Intrusion Triggering Task
OSF	Open Science Framework
log-ROM	log-transformed ratio of means
LRT	likelihood ratio test
PI	prediction interval
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSG	polysomnography; PTSD: posttraumatic stress disorder
REM	rapid eye movement
SDR	studentized deleted residuals
SMD	standardized mean difference
SWS	slow wave sleep

1. Introduction

The majority of the world's population will experience at least one potentially traumatic event during their lifetime (e.g., physical or sexual assault, natural disasters, war; Kessler et al., 2017). Following trauma, up to 59% of survivors experience stress-related symptoms (Kliem & Kröger, 2013). In most survivors, these symptoms remit naturally over time. However, a significant subgroup (15–30%) experiences ongoing and chronic stress-related symptoms, manifesting in the form of post-traumatic stress disorder (PTSD; Kessler, Sonnega, Bromet, Hughes, & Nelson, 1995). PTSD is characterized by spontaneous, involuntary (intrusive) memories of the traumatic event, which are highly distressing, vivid, and feature a sense of "nowness" (i.e., events seem to be happening in the present). By continuously intruding into the everyday life of trauma survivors, intrusive memories lead to a sense of continuous threat and are hypothesized to trigger hyperarousal (e.g., irritability, sleep disturbances) and avoidance of trauma reminders (i.e., self-isolation; Ehlers & Clark, 2000). This hypothesis is supported by longitudinal research showing that early intrusion characteristics (i.e., frequency, distress, and "nowness"; Kleim, Graham, Bryant, & Ehlers, 2013; Michael, Ehlers, Halligan, & Clark, 2005) predict persistent PTSD symptoms making them one of the hallmark symptoms of PTSD (Iyadurai et al., 2019).

PTSD patients experience on average 17 intrusive memories over one week (Pfaltz, Michael, Meyer, & Wilhelm, 2013). This high symptom frequency results in severe decrements of functioning (Alonso et al., 2010), comorbid physical (e.g., cardio-respiratory diseases) and mental disorders (e.g., depression), and impairments of quality of life (Alonso et al., 2004; Olatunji, Cisler, & Tolin, 2007). Critically, many patients (48–82%) experience a chronic course of PTSD, retaining their diagnosis for decades (Perkonigg et al., 2005; Zlotnick et al., 2004). Research efforts are thus focused on developing effective prevention strategies, which can be deployed in proximity to the traumatic event.

To divert the path from early intrusive memories to persistent PTSD, intervention strategies target at their underlying memory processes (Iyadurai et al., 2018, 2019; Pace-Schott, Seo, & Bottary, 2023). According to the cognitive model of PTSD (Ehlers & Clark, 2000), intrusive memories arise from the impact of traumatic stress on memory formation. That is, traumatic stress is proposed to enhance data-driven processing (i.e., bottom-up processing that relies heavily on perceptual and sensory information) which, in turn, strengthens associative learning and reduces the elaboration of explicit trauma memories as well as the integration of the trauma into the autobiographical memory system. As a result, trauma reminders trigger implicit - but not explicit - memory recall, facilitating the emergence of spontaneous, involuntary trauma memories. Moreover - due to the deficient explicit recall - trauma survivors lack awareness that their current sensory impressions derive from a past event (i.e., autonoetic awareness). In a similar vein, Brewin, Gregory, Lipton, and Burgess (2010) propose that traumatic stress reduces the formation of contextual representations of the traumatic event, which impairs voluntary, explicit memory retrieval. Conversely, they suggest that stress enhances the formation of sensory representations, which drive intrusive trauma memories. Intrusion development is assumed to be further facilitated by weak contextual representations, which fail to exert top-down control over strong sensory representations (Bisby & Burgess, 2017).

Based on these models, prevention strategies have been focused on reducing implicit (sensory) trauma memories and strengthening explicit (contextual) trauma memories in the post-encoding phase by targeting either consolidation or reconsolidation processes (Deeprose, Zhang, DeJong, Dalgleish, & Holmes, 2012; Hørlyck, Bisby, King, & Burgess, 2019; Krans, Näring, Holmes, & Becker, 2009). One line of research has specifically focused on a prolonged stage of consolidation, referred to as 'systems consolidation' (Kleim, Wysokowsky, Schmid, Seifritz, & Rasch, 2016). During systems consolidation, new memory representations are redistributed from short-term storage in the hippocampus to neocortical long-term stores (Diekelmann & Born, 2010). This process is assumed to occur during sleep. Accordingly, research shows that sleep - as opposed to wakefulness - enhances the retention of previously acquired emotional memories (Sopp, Michael, & Mecklinger, 2018). These effects are evident across different memory domains but are most pronounced for episodic memories, facilitating explicit, contextually rich memory recall (Atienza & Cantero, 2008; Drosopoulos, Wagner, & Born, 2005). However, specific studies also found the opposite pattern, indicating that a lack of sleep reduces implicit fear memories without affecting explicit memory recall (Kuriyama, Soshi, & Kim, 2010).

On a neurophysiological level, memory redistribution is assumed to occur during slow wave sleep (SWS), mediated by the propagation of slow oscillations and sleep spindles (Diekelmann & Born, 2010). However - in the context of emotional memory consolidation - empirical findings also suggest an involvement of rapid eye movement (REM) sleep (Hutchison & Rathore, 2015; Schäfer et al., 2020). Consonantly, REM theta activity (4–7 Hz) - the oscillatory signature of REM sleep - has

been shown to correlate with post-sleep emotional memory performance (Nishida, Pearsall, Buckner, & Walker, 2008; Sopp, Michael, Weess, & Mecklinger, 2017). Beyond sleep's impact on memory retention, studies have also indicated that consolidation processes occurring during sleep may affect the emotional tone of memories. On the one hand, these processes have been suggested to reduce the affective tone of emotional memories (van der Helm & Walker, 2009). On the other hand, empirical findings have found sleep to preserve or even intensify the affective charge associated with emotional stimuli (Jones & Spencer, 2019; Pace-Schott et al., 2011).

Based on these findings, researchers have considered sleep after trauma as a potential target for reducing intrusive trauma memories (Pace-Schott et al., 2023). However, in light of the heterogeneity of empirical findings, the underlying assumptions and suggested interventions differ dramatically. One line of research (Kuriyama et al., 2010; Porcheret, Holmes, Goodwin, Foster, & Wulff, 2015) hypothesizes that sleep-related consolidation mechanisms strengthen implicit memory processes, thereby facilitating intrusion development after trauma. Consequently, sleep deprivation during the night after trauma is proposed as a prevention strategy (Cohen et al., 2023). Another line of research (e.g., Kleim et al., 2016; Sopp, Brueckner, Schäfer, Lass-Hennemann, & Michael, 2019; Zeng, Lau, Li, & Hu, 2021) suggests that - by selectively strengthening explicit rather than implicit trauma memories - sleep may reduce intrusion development. These effects are assumed to emerge because facilitating explicit, contextually rich recall should - in turn - inhibit stimulus-driven reactivation of sensory representations (Bisby & Burgess, 2017). Moreover, explicit contextually rich recall supports autonoetic awareness, which may prevent the "nowness" quality of any arising intrusions (Ehlers, 2010). Based on these assumptions, interventions promoting restful post-trauma sleep are proposed to reduce intrusions, and thereby the development of persistent PTSD symptoms.

So far, experimental research on the effects of post-trauma sleep on PTSD symptoms is limited to studies from the field of experimental psychopathology that employ different variants of the analog trauma paradigm. This paradigm involves exposing non-clinical participants to aversive stimuli (e.g., film clips or aversive pictures; Holmes & Bourne, 2008; James et al., 2016). These materials contain scenes depicting highly stressful or traumatic events (i.e., actual or perceived threat and serious injuries; American Psychiatric Association, 2022), which cause significant distress in most people. Many studies showed that exposure to such materials reliably elicits PTSD-like symptoms (e.g., intrusive memories, physiological arousal, negative cognitions; James et al., 2016), which normally reside after a few days. The analog trauma paradigm provides a tool for studying cognitive, emotional and memory processes involved in the onset and persistence of PTSD symptoms under controlled laboratory conditions. Moreover, it allows examining potential targets of PTSD prevention and treatment (e.g., sleep manipulations). Beyond the advantage of high experimental control, previous research points to weaknesses of analog paradigms including ethical issues (Jaffe, DiLillo, Hoffman, Haikalis, & Dykstra, 2015; but see: Stirling, Nixon, & Takarangi, 2023) and a lack of ecological validity, preventing a transfer to real-world trauma (James et al., 2016). However, to date, analog trauma is the most widely used experimental paradigm to study processes involved in PTSD development and persistence, with a considerable number of successful translations to the clinical setting (Iyadurai et al., 2019; Woud et al., 2021). Also, in research on the potential impact of post-trauma sleep, these studies allow for highest experimental control and are thus able to provide insights on underlying memory processes when real-world studies using experimental designs are not yet available. Moreover, real world studies on this topic bring about several (ethical and practical) issues, most prominently acceptance of acutely traumatized individuals to wear polysomnography devices and to be randomized to a sleep deprivation intervention (Repantis et al., 2020). Hence, it is important to finetune such interventions in a non-clinical setting, prior to attempting replication in the context of real-world trauma.

Two recently published reviews (Davidson & Marcusson-Clavertz, 2023; Larson, Schapiro, & Gehrman, 2023) quantitatively summarized available evidence on the effects of post-trauma sleep on intrusive memories of analog trauma, both finding a small favorable effect of sleep over wakefulness on the number of intrusive memories (SMD = 0.26 in Davidson & Marcusson-Clavertz, 2023, based on 367 participant from 6 studies; SMD = 0.29 in Larson et al., 2023, based on 437 participants from 8 studies), and no effect of sleep for intrusion-related distress (SMD = 0.14 in Davidson & Marcusson-Clavertz, 2023). However, both reviews suffered from the small number of primary studies (with small sample sizes per study) and the unavailability of individual participant data (IPD), which prevented both a more in-depth analysis of the effects on intrusion frequency and intrusion distress as well as moderator analyses examining divergent findings from primary studies. The present systematic review aimed at addressing these gaps to shed further light on the effects of post-trauma sleep compared to wakefulness on intrusive memory based on the whole body of available evidence from experimental analog studies.

For this summary, researchers of the field have provided primary datasets of their studies, which were analyzed on study level (traditional meta-analysis based on aggregated data) and on participant level (IPD meta-analysis). While most systematic reviews and meta-analysis rely on aggregated (or summary) data extracted from published primary studies, IPD analyses use original data from primary studies, which are re-analyzed in a combined model (Tierney, Stewart & Clark, 2022). These analyses have the potential to improve the quality of data and produce more reliable results (Stewart & Tierney, 2002). Among the greatest advantages of IPD analyses is their potential to examine participant-level moderators. While meta-analyses on aggregated data only examine the moderating effects of sample averages (e.g., mean sample age, gender balance per sample), IPD analyses have the potential to examine the association of participant-level moderators with individual-level effect estimates (Cuijpers et al., 2022). This is particularly promising in fields requiring high resources like sleep research, where statistical power in primary studies is often insufficient for complex statistical models and to examine participant-level moderators.

In our review, we replicate findings from Davidson and Marcusson-Clavertz (2023) as well as Larson et al. (2023) by means of traditional meta-analysis. However, beyond these traditional analyses, we conducted IPD analyses differentiating the involvement of sleep in the onset of intrusions (any vs. no intrusive memories) and the severity of intrusive memories among those who experience intrusions. In line with state-of-the-art approaches (Franke et al., 2021), we modelled two parameters; one estimating the probability of not experiencing (i.e. zero) vs. experiencing (i.e. non-zero) intrusions/intrusion distress; and the other estimating intrusion (distress) severity for individuals with intrusions >0 (see Fig. 1). Thereby, we provide insights into the question of whether sleep may protect trauma-exposed individuals from the experience of any intrusive memory and/or might reduce the severity of intrusions among those who are sensitive to potentially traumatic events. Moreover, we combine our quantitative analyses with an in-depth qualitative summary focusing on associations of sleep physiology and intrusive memory as well as on potentially underlying processes in implicit and explicit memory of (analog) trauma. Thereby, our review aims at summarizing what is known and what is still unknown on the effects of post-trauma sleep on intrusive memories in order to path the way for future research in the field.

2. Methods

This systematic review was prepared in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021) and recommendations for reporting IPD meta-analyses (Stewart et al., 2015). The review was registered retrospectively on the Open Science Framework (OSF;

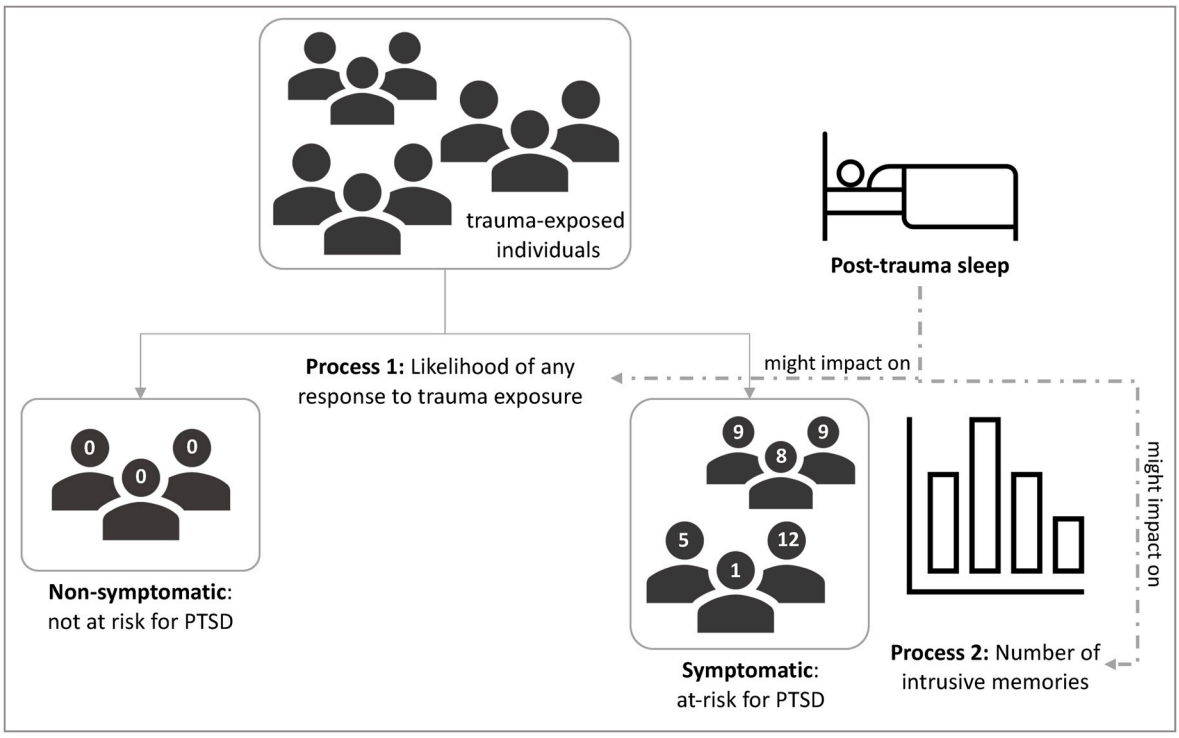

Fig. 1. Schematic illustration on the processes involved in the onset of intrusions. Post-trauma sleep could potentially impact on both, the likelihood of experiencing any versus no intrusion (process 1) and the severity of intrusions among those experiencing intrusive memories (process 2).

registration https://doi.org/10.17605/OSF.IO/4DH2V, link to OSF project: https://osf.io/j2av3/), where we also provide the protocol, materials and aggregated data relevant to this review. Changes from registration to final review were only minor and are presented in Supplementary Material SM1.

2.1. Literature search

Relevant search terms were identified by the research team to cover the most frequently used terms in the literature. Using these terms, a literature search based on title, abstract, and keywords was performed in six databases: EBSCOhost (PsycINFO and PsycARTICLES), PTSDpubs, PubMed, Scopus, and Web of Science (see Supplementary Material SM2 for search strings). Moreover, reference lists of included studies and related reviews were checked for eligible studies (Azza, Wilhelm, & Kleim, 2020; Davidson & Marcusson-Clavertz, 2023; Larson et al., 2023). Additionally, authors of studies included in the IPD analyses were asked if they were aware of other (un)published studies meeting our inclusion criteria. A date-of-publication criterion was not defined. The most recent literature search was run on May 16th, 2022.

2.2. Selection criteria

Studies meeting the following criteria were included: 1) The experimental study reported on a sample that encoded aversive visual stimuli (e.g., trauma film, aversive pictures). 2) One group of participants subsequently underwent a post-trauma (or post-aversive stimuli) sleep opportunity, while another group stayed awake during the daytime or was exposed to (partial) sleep deprivation during the nighttime (e.g., REM sleep deprivation). 3) Following sleep or wakefulness, the frequency of intrusive memories was assessed using an intrusion diary or a laboratory intrusion assessment (e.g., intrusion triggering task[a]). 4) Participants were mentally healthy adults. Samples were excluded if 1) they exclusively investigated the effect of sleep in the context of specific memory tasks (e.g., think-no-think paradigm), or 2) the necessary data for effect size calculation were not available by May 16th, 2022 (for the meta-analysis on aggregated data) or December 31st, 2021 (for IPD meta-analysis).

2.3. Study selection

Authors CL, EF, and SKS screened titles/abstracts and full texts in duplicate for inclusion eligibility. The interrater agreement achieved for inclusion/exclusion decisions was excellent, *kappa* = 1.0 at both levels. Corresponding authors of all eligible studies were contacted and asked to provide raw data from their study to perform the IPD meta-analysis.

[a] The intrusion triggering task (ITT) is a paradigm that simulates intrusive memories triggered by trauma reminders in everyday life of PTSD patients. During the ITT, auditory fragments of the aversive picture stories are presented while participants are engaged in an ongoing task (e.g., face rating test unrelated to the aversive material). While participants performed the rating task, sentence fragments from the picture stories or from an unrelated source are presented via headphones. Participants are instructed not to pay attention to these sounds. After the task ends, participants are asked to indicate the number of intrusions that they had experienced during the task. For more details see: Sopp et al. (2019); Sopp et al. (2021); Streb et al. (2017); Wegerer et al. (2013).

2.4. Data extraction

2.4.1. Meta-analysis on aggregated data

Using a standardized Excel form, data for each study was extracted by two independent coders (CL, EF). The interrater agreement for extracted data was excellent, *kappa* = 1.0 for *ns*, *M*s, and *SD*s. Data on intrusion distress were coded as a secondary outcome. For intrusion distress, we adopted the definition used in the original studies (e.g., Porcheret et al., 2015; participants were asked to rate the level of distress experienced with the intrusion from 0 = "not at all" to 10 = "extremely"). The only exception was the study by Werner, Schabus, Blechert, and Wilhelm (2021), for which aversiveness ratings served as an index of intrusion distress. Other coded variables were related to study characteristics (e.g., type of wake group) or sample characteristics (e.g., participants' mean age, percentage of female participants).

2.4.2. Individual participant data meta-analysis

Two independent team members (CL, student research assistant) extracted IPD based on generic standardized Excel forms and integrated single study datasets into one individual participant dataset. All disagreements between coders were resolved through discussion or consultation of a third reviewer (RS, SKS), and in unclear cases, study authors were contacted to provide additional information. All data were checked for integrity by one team member (e.g., data for primary and secondary outcomes within reasonable range, consistent reporting of covariates), with no evidence for issues with data quality.

2.5. Data synthesis

2.5.1. Qualitative synthesis

We performed a narrative synthesis of study findings on intrusion frequency and intrusion distress. For this purpose, we clustered studies based on different study designs: 1) sleep versus total sleep deprivation during nighttime; 2) sleep versus wakefulness during daytime (and nighttime); 3) sleep versus partial sleep deprivation during nighttime; and 4) nap versus wakefulness. Subsequently, we summarize associations between sleep physiology and intrusions narratively and report on effects on explicit and implicit trauma memory based on the differentiation proposed by Kuriyama et al. (2010). The narrative synthesis was performed by the last author (RS) and was checked by the first author (SKS).

2.5.2. Quantitative synthesis

Combining meta-analysis on aggregated data and IPD, our analyses compared results from data reported in individual studies (i.e., meta-analysis on aggregated data) and those obtained from multilevel analyses (i.e., IPD meta-analysis). The former allowed for the inclusion of all eligible studies, while the latter allowed for modeling two processes (i.e., occurrence of intrusions and severity of intrusions) and participant-level moderators (e.g., participants' age, gender; Mathew & Nordström, 2010). All analyses were performed in *R* version 4.1.3 (R Core Team, 2020). Analytic code and aggregated data are available at the OSF (https://osf.io/j2av3/). Due to data privacy reasons, data for the IPD analyses will be made available upon reasonable request by the study authors.

2.5.2.1. Manipulation check for negative mood. First, we used IPD to check whether the exposure to analog trauma resulted in a significant increase in negative mood. This analysis was performed using the *R* package *lme4* (Bates, 2010) and employed a multilevel model with time and group as fixed effects and a random intercept and slope for study. We expected negative mood to increase from pre-to-post exposure to the traumatic material, without any difference between experimental groups (i.e., sleep vs. wake group).

2.5.2.2. Meta-analysis on aggregated data. Meta-analyses on aggregated data were performed using the *R* package *metafor* (Viechtbauer, 2010). To mirror findings from a meta-analysis solely based on published findings, these analyses used data reported in published articles (e.g., *M*s reported in a table of the publication). *M*s and *SD*s were only calculated from IPD in case no other information was available.

2.5.2.2.1. Effect size calculation. For effect size calculation, experimental groups per study were chosen to be as similar as possible across studies. In case there was more than one condition relevant to our research question, they were either combined or we selected the one that was most comparable to other studies. As most of the studies did not comprise more than two conditions, we decided not to use multilevel meta-analyses (van den Noortgate, López-López, Marín-Martínez, & Sánchez-Meca, 2015). The meta-analyses used log-transformed *ratio of means* (log-ROMs) and corresponding sampling variances as effect size measures (Friedrich, Adhikari, & Beyene, 2011), with positive log-ROMs indicating that intrusion frequency or distress were lower in the sleep as compared to the wake group. For illustrative purpose, we transformed log-ROMs to ROMs that express the percentage increase in the mean value of intrusion frequency and distress of the wake group relative to the sleep group. We decided to use log-ROMs instead of *standardized mean differences* (SMDs) as our IPD analyses revealed that raw data for intrusion frequency and intrusion distress followed non-normal distributions and recent simulation studies found non-normality from primary studies to bias SMD estimates (Sun & Cheung, 2020). We used 95% confidence intervals (CIs) as indicator of significance. For all analyses, we used forest plots for visualization.

2.5.2.2.2. Main analyses and heterogeneity. All analyses used maximum likelihood estimations, weighted studies based on an inverse-variance approach, and relied on random-effects models that allow for true between-study variance (Field & Gillett, 2010). Residual heterogeneity of study effects was indicated by Cochran's *Q* statistic (i.e., weighted sum of squared differences between the observed effects and the weighted mean effect size, which can be tested for statistical significance, whereby a significant *Q* statistics indicates the presence of heterogeneity), and I^2, which expresses heterogeneity as percentage (0–100%; Higgins, Thompson, Deeks, & Altman, 2003). I^2 reflects the proportion of variance that reflects true variance in effect sizes rather than sampling error (Borenstein, Higgins, Hedges, & Rothstein, 2017), with values of 50% and above indicating substantial between-study heterogeneity (Deeks, Higgins, & Altman, 2022).

2.5.2.2.3. Outliers and influential cases. Outliers and influential cases were identified based on studentized deleted residuals (SDRs), Cook's distances (CD), and covariance ratios (COVRATIO). SDRs below and above ±1.96, CD values >0.45, and COVRATIOs <1 were considered as outlier or influential case (Cook & Weisberg, 1982; Viechtbauer & Cheung, 2010).

2.5.2.2.4. Moderator analyses. The impact of study-level moderators (i.e., mean age, gender distribution, number of follow-up assessments in days) was investigated by meta-regressions for continuous variables, with significance being assessed using *QM* statistics. Subgroup analyses for categorical moderators (e.g., study design) were not performed due to the small number of studies per subgroup.

2.5.2.3. Meta-analysis on individual participants data

2.5.2.3.1. Effect size calculation. Analyses followed a one-step approach, that is, analyses were performed on a merged dataset containing all IPD with participants being clustered in studies (Mathew & Nordström, 2010). IPD meta-analysis was performed using the *R* packages *GLMMapdative* (Rizopoulos, 2019), *glmmTMB* (Brooks et al., 2017), and *DHARMa* (Hartig, 2020). We conducted separate multilevel analyses to examine the effect of sleep versus wakefulness on intrusion frequency (Model 1, primary outcome) and intrusion distress (Model 2, secondary outcome). Intrusion frequency and intrusion distress were used as dependent variables and group as the independent variable. For

intrusion frequency, we used the absolute number of reported intrusions. For intrusion distress, we divided the severity of reported distress levels by the number of intrusions, whose result was further divided by the range of distress assessment (i.e., intrusion distress = [total score of reported distress/frequency of intrusions]/range of distress assessment). This resulted in scores ranging from 0 to 1, with 1 indicating maximum distress for each intrusion on the respective scale. Participants who did not experience any intrusion were removed from this analysis.

2.5.2.3.2. Model selection and diagnostics. All models were examined to fit our data based on residual distributions (i.e., under- and over-dispersion, zero-inflation, normal distribution [Kolmogorov-Smirnov]; Borhan et al., 2020; Perumean-Chaney, Morgan, McDowall, & Aban, 2013). For intrusion frequency as count variable, our analyses used zero-inflated negative binominal models (see SM3 for details on model selection). For intrusion distress as a continuous variable, we employed a hurdle model for semi-continuous data. Those models allowed to differentiate two processes: First, the occurrence of any vs. no intrusion/intrusion distress; and second, the number of intrusion or the severity of intrusion distress (in cases where at least one intrusion/at least some distress was present; see Fig. 1 for an illustration). All models allowed for random intercepts per study. The inclusion of random slopes per study was evaluated based on the change in model fit using a likelihood ratio test (LRT).

2.5.2.3.3. Outliers. Outliers were examined as part of the residual diagnostics.

2.5.2.3.4. Moderator analyses. We examined the effects of participant-level variables on the intrusion frequency, intrusion distress and their interaction with the group (moderator effect). The moderators include age, gender, depressive symptoms at baseline, and increases in negative mood due to aversive stimuli. Cluster mean centering was applied for all participant-level moderators.

2.6. Risk of bias assessment

2.6.1. Publication bias

Results of meta-analyses may overestimate the true population effect due to publication bias (DeVito & Goldacre, 2019). To reduce its potential impact, our search also included grey literature (i.e., dissertations, preprints) and study authors were asked for available unpublished data. Although the number of studies was small ($k = 9$), publication bias was assessed on an exploratory basis for the meta-analysis on aggregated data using visual inspection of funnel plots and rank correlation tests (Kendall's τ) to examine their symmetry (Egger, Smith, Schneider, & Minder, 1997). A significant rank correlation test provides evidence for the presence of a publication bias. In addition, we used contour-enhanced funnel plots to examine if "missing" studies would fall into the area of non-significant findings (Peters, Sutton, Jones, Abrams, & Rushton, 2008).

2.6.2. Internal risk of bias

Meta-analytical findings can be biased by insufficient study quality such as flaws in study design, analysis, or reporting (Higgins et al., 2011). Since standard internal-bias assessment checklists were not applicable, we used an adapted version of a quality checklist developed for a meta-analysis on the impact of sleep on emotional memory (Schäfer et al., 2020). The 11-item checklist is based on state-of-the-art criteria in sleep research (e.g., study design, control of wake/sleep deprivation conditions). Study quality as indicator of internal risk of bias was rated independently by two raters (CL, student research assistant). Ratings could range between 0 and 1, with higher scores indicating better quality (i.e., lower risk of bias). Meta-regression was used to statistically examine the impact of internal risk of bias on effect estimates.

2.7. Certainty of evidence

The certainty of evidence for intrusion frequency and intrusion distress was assessed in duplicate using an adapted version of GRADE (Grading of Recommendations, Assessment, Development and Evaluations; Schünemann et al., 2022). We used the internal risk of bias assessment described above for the GRADE domain "risk of bias". To assess imprecision, we calculated optimal information sizes based on standard recommendations (Garcia-Alamino, Bankhead, Heneghan, Pidduck, & Perera, 2017). Certainty of evidence can either be very low, low, moderate, or high.

2.8. Sensitivity analyses

To examine the robustness of our findings, we performed sensitivity analyses investigating the impact of analytic decisions. We decided to use log-ROMs as effect size measure of our meta-analysis. However, we re-ran our meta-analyses on aggregated data using SMDs as check for robustness. Moreover, as statistical approaches varied between primary studies (i.e., Poisson regressions; Porcheret et al., 2015; *t*-tests; Sopp et al., 2021), we examined if our results from the IPD meta-analysis depended on modeling decisions. For this purpose, we recalculated our analyses based on comparable distributions (i.e., intrusion frequency: negative binominal hurdle model; intrusion distress: zero-inflated gamma model).

3. Results

3.1. Search results and study characteristics

The study selection procedure is illustrated in the PRISMA flowchart (see Fig. 2). Our search in six databases yielded 623 records, of which 220 were removed as duplicates. Four-hundred-three records were screened at title/abstract level and another 184 records were identified via citation searching, with 10 being assessed at full-text level. Nine studies were included in our review and meta-analysis on aggregated data (see Table 1); eight in our meta-analysis on IPD. Data of one study (Kleim et al., 2016) could not be obtained for IPD meta-analysis. All studies were published between 2015 and 2021. Three studies (Porcheret et al., 2015; Porcheret et al., 2019; Zeng et al., 2021) examined the effects of sleep versus total sleep deprivation during nighttime. Two studies investigated the effect of sleep versus wakefulness during the daytime (or daytime *and* nighttime; Kleim et al., 2016; Sopp et al., 2021). Another two trials studied the effects of sleep versus partial sleep deprivation during nighttime (Sopp et al., 2019; Werner et al., 2021) and two studies examined the effects of nap sleep versus wakefulness (Wilhelm et al., 2021; Woud et al., 2018).

3.2. Qualitative summary

3.2.1. Effects on intrusion frequency and intrusion distress

Effects on intrusion frequency and intrusion distress as reported in primary studies are summarized based on different study designs.

3.2.1.1. Sleep versus total sleep deprivation during nighttime. Three studies investigated the effect of total sleep deprivation versus sleep during the first night after analog trauma on subsequent intrusive memories (Porcheret et al., 2015, 2019; Zeng et al., 2021). In the first study on this subject, Porcheret et al. (2015) exposed participants to a traumatic film after which they either returned home to sleep or underwent a full night of sleep deprivation in the laboratory (see Table 1 for study characteristics). Results demonstrated significantly higher intrusion frequencies in the sleep group than in the sleep deprivation group. These effects were evident on the first two days after exposure to the trauma film including the period of acute sleep deprivation. In

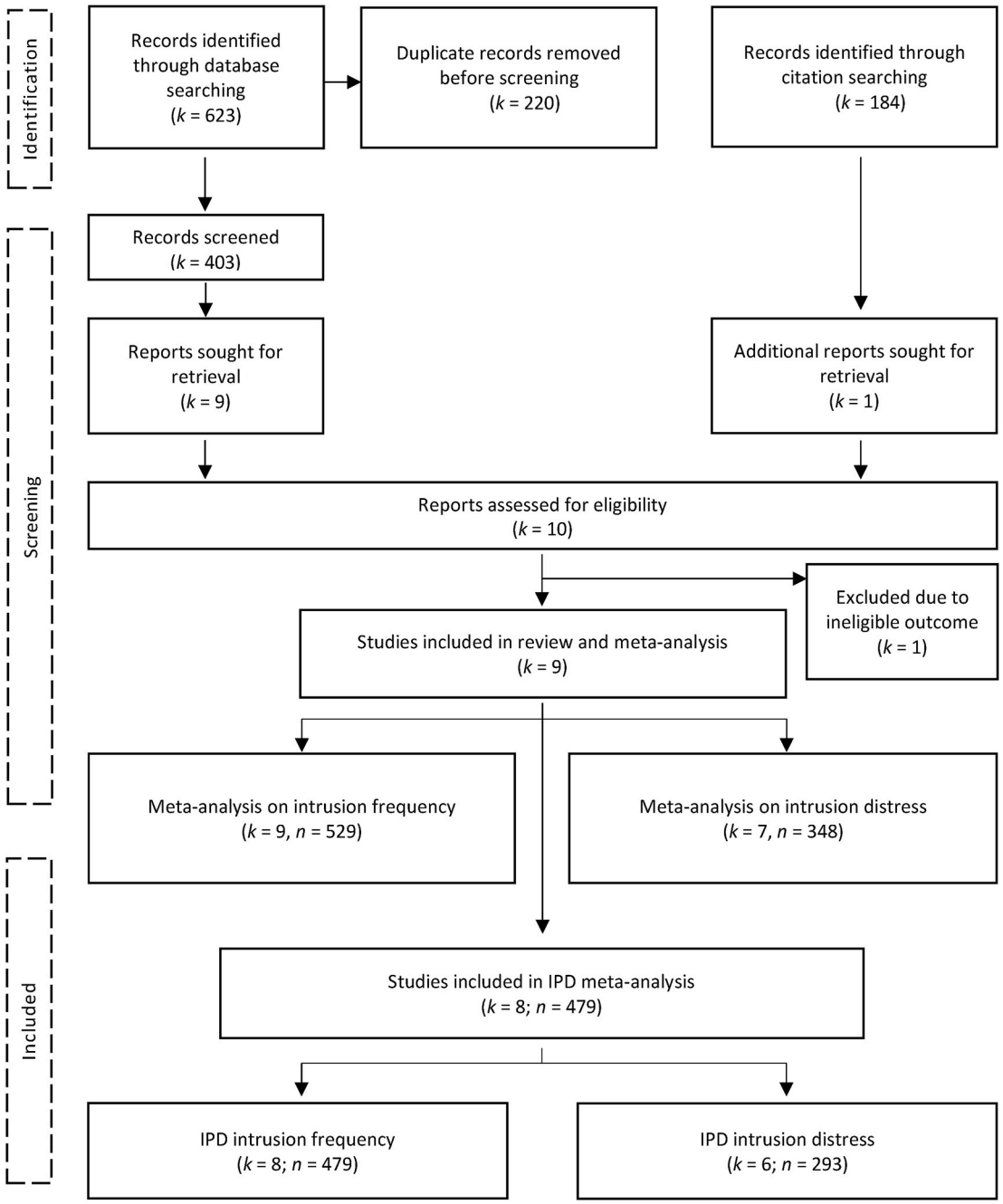

Fig. 2. PRISMA Flowchart of the Study Selection Process. *Note*. Lastly updated on May 16th, 2022. IPD = individual participant data, k = number of studies, n = number of participants.

addition, distress ratings as assessed by the Impact of Event Scale-Revised (Weiss, 2007) were significantly higher in the sleep than in the sleep deprivation group. In a follow-up study to their first experiment, Porcheret et al. (2019) reinvestigated the effects of sleep as opposed to sleep deprivation on analog intrusions. Their design was largely identical to their 2015 study with the exception that sleep deprivation was conducted at home rather than at the lab. Analyses revealed different effects, depending on the inclusion of the high rate of participants who slept to some extent in the sleep deprivation group. Without excluding these participants, results did not reveal any consistent differences between groups. After their exclusion, analyses showed significantly lower intrusion frequencies in the sleep group than in the sleep deprivation group. No differences emerged for intrusion distress. Finally, using a similar design, Zeng et al. (2021) reinvestigated the impact of sleep versus full night sleep deprivation at the lab on intrusive memories of a traumatic film. Results showed fewer intrusions in the sleep than in the sleep deprivation group but revealed no difference in intrusion distress.

3.2.1.2. Sleep versus wakefulness during daytime. Two studies investigated the effects of sleep as opposed to wakefulness during daytime or both day- and nighttime. In the study of Kleim et al. (2016), participants were exposed to a traumatic film and either had a full night of sleep at home afterwards or were deprived of sleep. Half of the wake group was exposed to the trauma film in the evening and was subsequently sleep deprived during the night, whereas the other half was exposed to the trauma film in the morning and subsequently remained awake during the day. Wakefulness during the daytime versus nighttime did not affect

Table 1
Study and sample characteristics of studies included in meta-analysis on aggregated data.

Study	Participants	$n_{sleep,}$ ($n_{intrusion}$)	$n_{wake,}$ ($n_{intrusion}$)	Age *M* (*SD*)	% female	Aversive stimuli	Outcome assessment	Follow-up (days)	Sleep duration (min)	Sleep design	Sleep recording	Sleep context	Results as reported	Risk of bias[e]
1. Sleep vs. total sleep deprivation during nighttime														
Porcheret et al., 2015	mentally healthy students with normal sleep quality and no extreme diurnal preference, no participation in a similar study	21 (17; 81%)	18 (12; 67%)	21.53 (1.95)	70.73	Trauma film (15-min compilation of traumatic and distressing clips depicting scenes like suicide, bullying, injury, cutting to the face)	IF/ID: paper-and-pencil diary	6	NA	Nocturnal sleep	AG	home	IF: ↓; ID: ↓	low
Porcheret et al., 2019	mentally healthy young adults with normal sleep quality and no extreme diurnal preference, no participation in a similar study	24 (17; 71%)	26 (22; 85%)	24.18 (3.73)	54.00	Trauma film (15-min compilation of 11 traumatic and distressing clips depicting scenes of a car crash, self-harm and genocide)	IF/ID: paper-and-pencil diary	6	433.20	Nocturnal sleep	AG, PSG	home	IF: - (↓)[f]; ID: -	low
Zeng 2021 [a]	mentally and physically healthy young adults (mostly university students) with normal sleep quality	30 (15; 50%)	30 (18; 60%)	20.50 (2.02)	68.33	Trauma film a 14-min film of 9 aversive clips depicting fatal accidents (e.g., car and plane crashes, train wreck)	IF/ID: online diary (and lab-based intrusion monitoring task)	7	403.62	Nocturnal sleep	AG	home	IF: ↑; ID: -	high
2. Sleep vs. wakefulness during daytime or day- and nighttime														
Kleim et al., 2016 (not included in IPD)	mentally healthy young females, recruited via newspapers, no lifetime trauma exposure	32 (32; 100%)	33 (33; 100%)	23.80 (3.09)	100	Trauma film (12 min from 'Irreversible' showing physical and sexual violence)	IF/ID: paper-and-pencil diary	7	420.00	Nocturnal sleep	PSG	home	IF: ↑; ID: ↑	high
Sopp 2021	mentally and physically healthy students with normal sleep quality and no extreme diurnal preference, no lifetime trauma exposure	38 (34; 89%)	37 (35; 95%)	22.51 (2.98)	82.66	Traumatic picture stories (including 12 negative pictures from the International Affective Picture System and the Nencki Affective Picture System database showing a mutilated or heavily injured person)	IF: ITT	1	447.70	Nocturnal sleep	PSG	lab	IF: ↑; ID: not assessed	high
3. Sleep vs. partial sleep deprivation														
Sopp 2019 [b]	mentally healthy students with normal sleep quality and no extreme diurnal preference, no participation in a similar study	21 (12; 57%)	20 (16; 80%)	22.44 (2.50)	65.85	Traumatic picture stories (including five negative pictures from the International Affective Picture System showing a mutilated or heavily injured person)	IF: ITT	1	217.86	Nocturnal sleep	PSG	lab	IF: ↑; ID: not assessed	low
Werner 2021 [c]	mentally healthy young females (mostly university students) with normal sleep quality	28 (23; 82%)	21 (19; 90%)	22.32 (3.16)	100	Aversive pictures (20 negative pictures from the International Affective Picture System, mean valence 1.64 [range 1–9])	IF/ID: Intrusion Memory Questionnaire (paper-and-pencil)	3	26.58	Nap	PSG	lab	IF: ↑; ID: ↑	low
4. Nap sleep vs. wakefulness														
Wilhelm 2021	mentally healthy young females, recruited at the university, no lifetime trauma exposure and normal sleep quality	33 (33; 100%)	23 (23; 100%)	23.50 (0.70)	100	Trauma film (12 min from 'Irreversible' showing physical and sexual violence)	IF/ID: paper-and-pencil diary	7	64.42	Nap	PSG	lab	IF: -; ID: - (↑)[g]	low

(*continued on next page*)

Table 1 (*continued*)

Study	Participants	n_{sleep}, ($n_{intrusion}$)	n_{wake}, ($n_{intrusion}$)	Age *M* (*SD*)	% female	Aversive stimuli	Outcome assessment	Follow-up (days)	Sleep duration (min)	Sleep design	Sleep recording	Sleep context	Results as reported	Risk of bias[e]
Woud et al., 2018 [d]	mentally healthy young adults, no lifetime trauma exposure and normal sleep quality	51 (42; 82%)	43 (39; 91%)	23.09 (3.65)	76.60	Trauma film (a compilation of distressing clips depicting serious and life-threatening injuries and violence)	IF/ID: paper-and-pencil diary	7	41.42	Nap	PSG	lab	IF: ↑; ID: -	high

Note. ↑: effect in favor of sleep over wakefulness/sleep deprivation, i.e., fewer intrusive memories or less severe intrusion distress; ↓: effect in favor of wakefulness/sleep deprivation over sleep, i.e., fewer intrusive memories or less severe intrusion distress; –: no evidence for a difference between sleep and wakefulness/sleep deprivation. AG = Actigraphy; IF = intrusion frequency; ID = intrusion distress; ITT = Intrusion Triggering Task (based on Streb et al., 2017; Wegerer et al., 2013); *n* = number of participants; NA = not available; PSG = polysomnography.

[a] The study by Zeng et al. (2021) reported data on more than one intrusion measure. In this case, we chose the diary assessment as most similar to the majority of included studies.

[b] Due to the partial nighttime sleep deprivation design employed by Sopp et al. (2019), second night half sleep duration is reported as sleep duration.

[c] The study of Werner et al. (2021) comprised more than one group that underwent post-trauma sleep or sleep deprivation. For the purpose of our meta-analysis, we chose the groups most similar to other studies (i.e., REM sleep deprivation and REM sleep) to reduce between-study heterogeneity. For our moderator analysis on sleep duration, we subtracted the sleep duration of the REM sleep deprivation group from the sleep duration of the REM sleep group (i.e, 80.38 min–53.80 min = 26.58 min).

[d] The study by Woud et al. (2018) reported data on participants that received either positive or negative cognitive bias modification training. As this intervention was not of interest for our meta-analysis, both sleep and wake groups were combined.

[e] Risk of bias ratings reflect inverse measures of study quality, that is, 1 – study quality. Studies with quality ratings >0.77 were assumed to have low risk of bias, studies with quality ratings <0.77 were rated as high risk of bias.

[f] Porcheret et al. (2019) found evidence for a difference in favor of sleep deprivation over sleep when they excluded participants from analyses that slept at least for short periods during sleep deprivation at home.

[g] Wilhelm et al. (2021) found in a secondary analysis that participants in the sleep group that reached REM sleep reported lower intrusion distress.

outcome measures, allowing to collapse these subgroups for further analyses. Analyses of 7-day diary data revealed lower intrusion frequencies in the sleep than in the wake group, with the effect being most pronounced on days 3–7 indicating a delayed benefit of sleep. Groups also differed in intrusion distress with the sleep group reporting significantly lower ratings than the wake group. Sopp et al. (2021) investigated the impact of sleep as opposed to wakefulness on analog intrusions during the daytime. After being exposed to traumatic picture stories, participants either had a full night of sleep (50% at the lab, 50% at home) or a 12-h period of wakefulness during daytime. Groups did not differ in intrusion frequency in an intrusion triggering task.

3.2.1.3. Sleep versus partial sleep deprivation. Two studies investigated the effect of sleep as opposed to partial sleep deprivation on analog intrusions. In the study by Sopp et al. (2019), participants viewed traumatic picture stories prior to a full night sleep or a limited sleep opportunity with sleep deprivation during the second night half systematically reducing the amount of REM sleep (Ekstrand, Barrett, West, & Meier, 1977). Intrusions were assessed in the morning using an intrusion triggering task showing lower intrusion frequency in the sleep than in the partial sleep deprivation group. Werner et al. (2021) similarly manipulated sleep duration to compare participants that underwent a nap with REM sleep, a nap with REM awakening, and a nap without REM sleep at the lab after having been exposed to traumatic pictures. Analyses revealed significantly reduced intrusions (number and duration) in the REM sleep group and REM awakening group as compared to the no REM sleep group on day 3. Groups also differed in intrusion distress (i.e., aversiveness), with the REM sleep and the REM awakening group showing lower distress.

3.2.1.4. Nap sleep versus wakefulness. Finally, two studies compared the effects of nap sleep with wakefulness during the daytime. Wilhelm et al. (2021) investigated the effect of a 90-min nap in the lab as opposed to a 90-min wake period during the daytime on intrusive memories of a trauma film. Intrusion frequency and distress did not differ between groups. In a secondary analysis, the authors found that participants who reached REM sleep reported lower intrusion distress than those with no REM sleep or no sleep at all. There was no evidence for an effect of sleep on intrusion frequency. In another study by Woud et al. (2018), participants viewed a traumatic film and were then subjected to a cognitive bias modification training. Subsequently, they were either given a nap opportunity of 90 min at the lab or remained awake. Collapsing effects across training groups provided evidence for an effect of nap sleep on intrusive memories, with participants of the nap group reporting fewer intrusions than their wake counterparts. No differences emerged for intrusion distress.

3.2.2. The relationship between sleep physiology and intrusions

Four studies assessed polysomnography and reported on associations of sleep physiology and intrusions (see SM4 for detailed results). Of these, one study provided support for a role of slow wave sleep (SWS) in intrusive memories. Sopp et al. (2021) found that a longer SWS duration (% and min) was associated with fewer intrusions ($n = 38$). Werner et al. (2021) provided support for the involvement of REM sleep, finding longer REM sleep duration (% and min) to be associated with fewer and less aversive intrusions (on day 3) as well as shorter intrusion duration ($n = 68$). Two studies provided evidence for the involvement of both Non-REM and REM sleep. Kleim et al. (2016) found evidence for negative correlations between stage 2 sleep and parietal fast sleep spindles (13–15 Hz) and intrusion frequency ($n = 18$). By contrast, they found that stage 1 sleep, more time spent awake after sleep onset, and REMs were linked to more intrusions. Wilhelm et al. (2021) reported that more REM sleep and higher slow wave activity were correlated with less intrusion distress ($n = 32$).

3.2.3. Effects on explicit and implicit analog trauma memory

Our summary follows the differentiation of explicit and implicit trauma memory by Kuriyama et al. (2010). A more detailed version of this summary can be found in Supplementary Material SM5.

3.2.3.1. Effects of sleep on explicit analog trauma memory. Two studies investigated the impact of sleep during the nighttime on explicit trauma memory using a visual recognition memory test (Porcheret et al., 2019; Zeng et al., 2021). Porcheret et al. (2019) examined visual recognition memory for the trauma film at day 2 using images from the trauma film and new images. Analyses indicated that participants of the sleep group recognized more images from the trauma film than participants from the sleep deprivation group. Zeng et al. (2021) conducted an immediate (day 1) and delayed (day 8) recognition memory test using screenshots from the trauma film as old stimuli (50% aversive scenes, 50% neutral scenes) together with screenshots from similar, but unwatched films as new stimuli. Analyses revealed that participants of the sleep group had better recognition memory (i.e., higher rate of correct rejection to new pictures) than participants of the sleep deprivation group on day 1, while no differences emerged on day 8.

Two studies investigated the impact of sleep on explicit trauma memory using a visual recognition memory test that differentiated between divergent retrieval processes, that is, recollection- and familiarity-based retrieval (Yonelinas, 2002). Sopp et al. (2019) assessed explicit memory of traumatic picture stories by presenting objects that had been embedded into the picture stories and new objects. After awakening or sleep deprivation in the second night half, participants were asked to indicate for each object whether it had been presented in the picture stories ('old') or not ('new'). For each object that they identified as 'old', they were asked to indicate whether their recognition judgement was based on *remembering* details of its previous presentation or on a feeling of *knowing*. Analyses revealed that participants of the sleep group showed higher recollection-based recognition memory than participants of the partial sleep deprivation group, while no difference emerged for familiarity-based recognition. In a follow-up study, Sopp et al. (2021) investigated explicit memory for relevant and irrelevant objects presented in the traumatic picture stories. Participants were exposed to picture stories with relevant and irrelevant objects, which were supplemented with new items during a recognition test. Results revealed higher recognition memory for relevant, but not for irrelevant objects in the sleep as compared to the wake group.

Two studies investigated the impact of (nap) sleep as opposed to wakefulness during the day- or nighttime on explicit trauma memory using a verbal recognition memory test based on questions or statements on the trauma film (Porcheret et al., 2019; Woud et al., 2018). Both studies found no differences between sleep and wake groups.

3.2.3.2. Effects of sleep on implicit analog trauma memory. One study investigated the impact of sleep on implicit trauma memory, assessed in terms of processing fluency. Sopp et al. (2019) presented half of the objects from the traumatic picture stories and distractor objects in a blurred picture identification task, where participants should label the blurred objects as soon as they recognized them. No evidence for a between-group difference emerged.

Four studies investigated the impact of (nap) sleep on implicit trauma memory, assessed in terms of fear ratings (Porcheret et al., 2019; Werner et al., 2021; Wilhelm et al., 2021; Zeng et al., 2021), with no strong evidence for between-group differences. Wilhelm et al. (2021) used pictures from the trauma film to assess emotional responses 8 days after exposure. Before and after viewing aversive pictures, subjective mood and arousal were measured by visual analog scales as well as current affective state using a questionnaire. Analyses revealed that mood generally decreased across presentation and that this effect was less pronounced in the nap group as compared to the wake group.

3.3. Quantitative summary

3.3.1. Sample characteristics

The final meta-analysis on aggregated data comprised nine studies ($N = 529$, $n_{sleep} = 278$, $n_{wake} = 251$) for intrusion frequency and seven for intrusion distress ($N = 348$, $n_{sleep} = 179$, $n_{wake} = 169$). The meta-analysis on IPD comprised eight studies ($N = 479$, $n_{sleep} = 247$, $n_{wake} = 232$) for intrusion frequency and six studies for intrusion distress ($N = 293$, $n_{sleep} = 150$, $n_{wake} = 143$). The weighted mean age was 22.71 years ($SD = 2.73$) for the meta-analysis on aggregated data (22.53 years, $SD = 3.34$, for the IPD meta-analysis), and 80.60% were female (78.03% for the IPD meta-analysis).

3.3.2. Manipulation check for negative mood

Our meta-analysis on IPD allowed us to examine whether the exposure to aversive stimuli resulted in an increase in negative mood. Across all studies, negative mood increased by 23.6% from pre-to-post exposure. A linear mixed model with random intercept and slope per study revealed a significant increase in negative mood, $b = 0.11$, 95% CI [0.06, 0.15], $p = .002$, that was independent from experimental group, $b = 0.00$, 95% CI [−0.02, 0.03], $p = .724$.

3.3.3. Meta-analysis on aggregated data

3.3.3.1. Main analyses

3.3.3.1.1. Intrusion frequency. The forest plot presented in Fig. 3a displays the effect estimates and CIs of all samples. Effect estimates ranged from −0.50, 95% CI [–1.20, 0.20] to 0.76, 95% CI [–0.01, 1.52]. Most effect estimates (8 out of 9; 89%) were numerically positive, that is, participants who underwent post-trauma sleep as compared to wakefulness experienced fewer intrusions. Table 2 presents the results of the main meta-analysis using a random-effects model. The analysis provided evidence for an effect of sleep on intrusion frequency, log-ROM = 0.25, 95% CI [0.10, 0.39], $p < .001$. Participants in the sleep groups experienced 28% fewer intrusions than those in the wake groups. There was no evidence for heterogeneity of effect sizes as indicated by a non-significant Q statistic, $Q(8) = 8.88$, $p = .352$, and a I^2 of 10.0%. This absence of heterogeneity supports the generalizability of the findings beyond the included studies to the wider population. Certainty of evidence for the primary outcome was moderate due to the increased risk of bias resulting from the inclusion of nonrandomized studies (see Supplemental Material SM6).

3.3.3.1.2. Intrusion distress. The forest plot presented in Fig. 3b shows the effect estimates and CIs of all samples included in the analysis on intrusion distress. Effect estimates ranged from −0.23, 95% CI [–0.64, 0.19], to 0.40, 95% CI [0.03, 0.76]. Five out of seven effect sizes (71%) were numerically positive, that is, participants who were in the post-trauma sleep group reported lower levels of distress than those in the wake group. The meta-analysis provided no evidence for an effect of sleep compared to wakefulness on intrusion distress, log-ROM = 0.09, 95% CI [–0.03, 0.22], $p = .145$. There was no significant heterogeneity as shown by a non-significant Q statistic, $Q(6) = 6.00$, $p = .423$, and a I^2 of 0.1%. Certainty of evidence for intrusion distress was very low due to the inclusion of nonrandomized studies and imprecision (see SM6).

3.3.3.2. Outlier and influence analyses. Fig. 4a and b displays outlier and influence analyses based on SDRs, Cook's distances (CD), and covariance ratios (COVRATIO). For both outcomes, none of the studies was identified as outlier or influential case.

3.3.3.3. Moderator analyses. Given the homogeneous results for both outcomes, it is debatable if moderator analyses should be performed. However, most recommendations suggest performing a-priori planned analyses even in absence of heterogeneity (Geyskens, Krishnan, Steenkamp, & Cunha, 2009). For intrusion frequency, there was no moderator

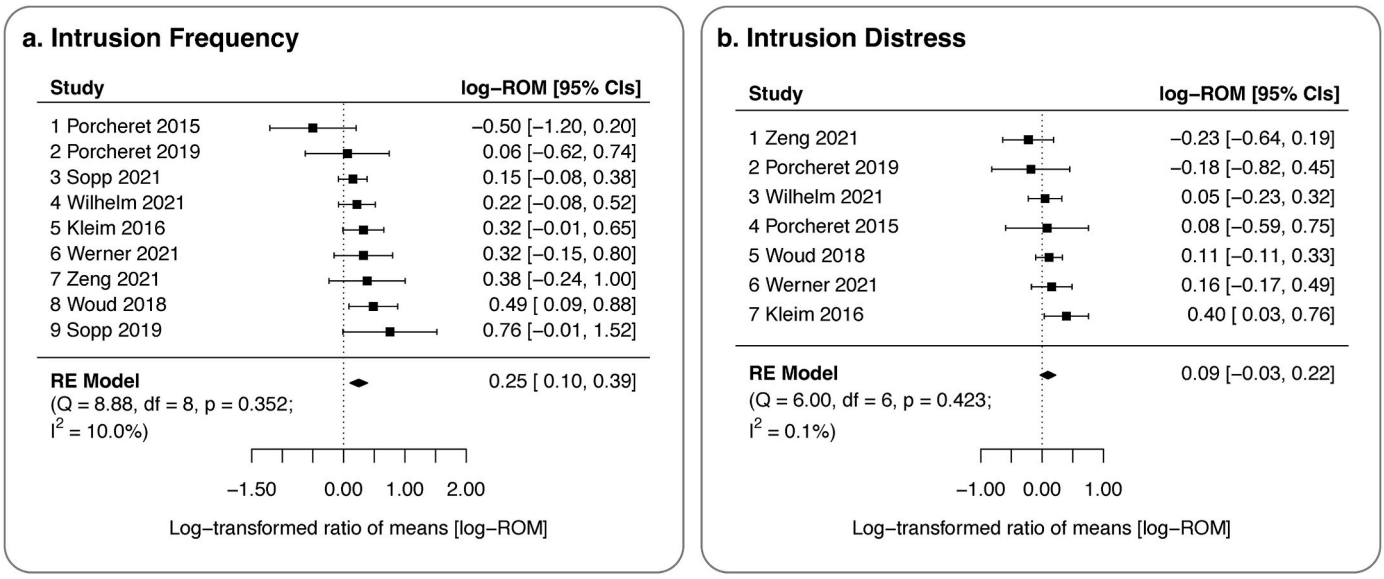

Fig. 3. Forest Plots of Meta-Analyses on Intrusion Frequency and Intrusion Distress. *Note.* Forest plots of the meta-analysis on aggregated data on (a.) intrusion frequency and (b.) intrusion distress. CI = confidence interval; M(log-ROM) = log-transformed ratio of means; RE Model = random effects model.

Table 2
Results of the meta-analysis on aggregated data.

Analysis	95% CI										
	N/n	*k*	EE	lower	upper	*p*	*Q*	df	*p(Q)*	I^2	Certainty
1. Main analysis (log-ROM)											
Intrusion frequency	529	9	0.25	0.10	0.39	<.001	8.88	8	.352	10.0	⊕⊕⊕◯ **Moderate**
			ROM = 1.28	1.11	1.48						
Intrusion distress	348	7	0.09	−0.03	0.22	.145	6.00	6	.423	0.1	⊕◯◯◯ **Very low**
			ROM = 1.10	0.97	1.25						
2. Sensitivity analysis (SMD)											
Intrusion frequency	529	9	0.31	0.13	0.48	<.001	8.08	8	.426	0.94	⊕⊕⊕◯ **Moderate**
Intrusion distress	348	7	0.15	−0.06	0.36	.168	5.86	6	.439	0.00	⊕◯◯◯ **Very low**

Note. EE = effect estimate; *N/n* = number of participants; *k* = number of studies; log-ROM/SMD = log-transformed ratio of means/standardized mean difference; ROM = ratio of means; *p* = significance value of log-ROM/SMD; 95% CI = 95% confidence interval; *Q* = *Q* statistic; df = degrees of freedom of *Q* statistic; *p(Q)* = significance value of *Q* statistic; I^2 = percentage of heterogeneity reflecting true effect estimate variance. The certainty column shows the overall GRADE rating (see Supplementary Material SM3 for details).

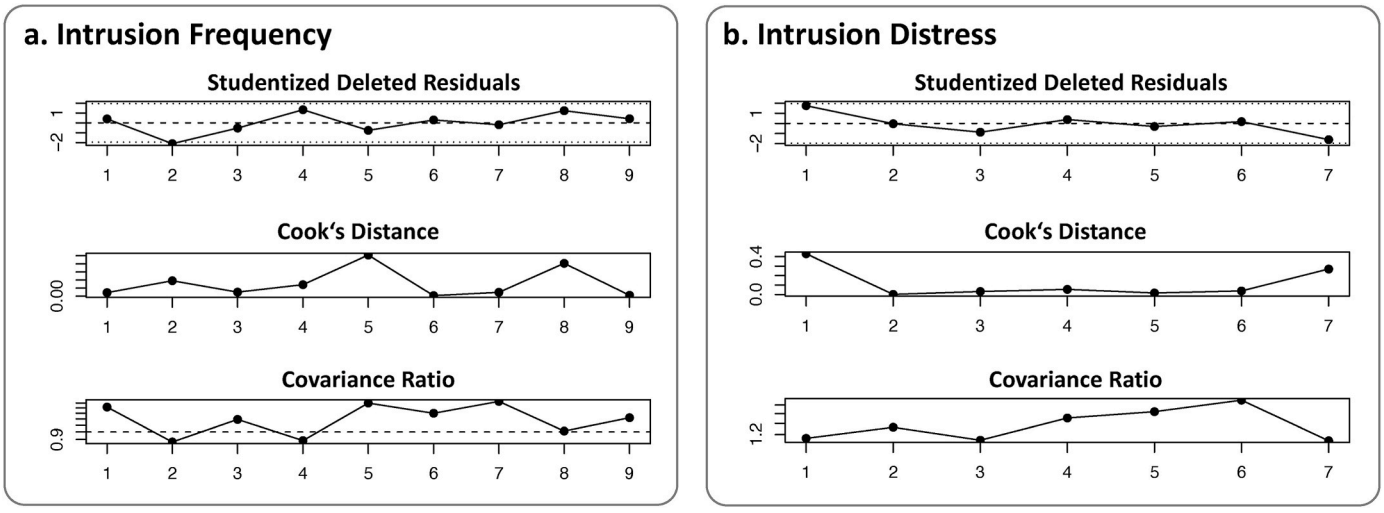

Fig. 4. Outlier and Influence Diagnostics for the Meta-Analyses on Intrusion Frequency and Intrusion Distress. *Note.* Influence diagnostics of the meta-analysis on aggregated data on (a.) intrusion frequency and (b.) intrusion distress. Study numbers per outcome correspond to those presented in Fig. 2.

effect of the samples' mean age, $QM(1) = 0.23$, $p = .633$, or gender, $QM(1) = 0.07$, $p = .785$. Also, neither the number of follow-up assessments in days, $QM(1) = 0.24$, $p = .622$, nor the average duration of post-trauma sleep, $QM(1) = 0.81$, $p = .369$, significantly predicted effect estimates. For intrusion distress, there was neither a moderator effect of mean age, $QM(1) = 1.43$, $p = .232$, gender, $QM(1) = 1.69$, $p = .194$, number of follow up-assessments in days, $QM(1) = 0.07$, $p = .788$, nor average post-trauma sleep duration, $QM(1) = 0.04$, $p = .838$.

3.3.3.4. Publication bias. Visual inspections and non-significant rank correlation tests indicated symmetry of the funnel plots for intrusion frequency, Kendell's $\tau = 0.11$, $p = .761$ (see Fig. 5a), and intrusion distress, Kendell's $\tau = -0.14$, $p = .773$ (see Fig. 5b). Also, the contour-enhanced funnel plot did not indicate that non-significant findings were more likely to be missing.

3.3.3.5. Internal risk of bias. For our analyses on intrusion frequency, study quality ratings ranged between 0.50 and 1.00, with median study quality rating at 0.77. For intrusion distress, the range of quality ratings of the included studies was between 0.50 and 0.92, and median study quality was at 0.77. For both outcomes, effect estimates were not significantly related to study quality [intrusion frequency: $QM(1) = 0.03$, $p = .870$; intrusion distress: $QM(1) = 1.70$, $p = .193$].

3.3.3.6. Sensitivity analyses. To examine if our findings were dependent on our decision to choose log-ROMs instead of SMDs as effect measure, we re-ran our analyses by using SMDs as the effect measure. For intrusion frequency, this analysis provided evidence for an effect of sleep on intrusion frequency, SMD = 0.31, 95% CI [0.13, 0.48], $p < .001$, suggestion fewer intrusions after post-trauma sleep compared to wakefulness, which was numerically - but not significantly - larger than the effect found using log-ROMs (see Table 2). For intrusion distress, consistent with the analysis using log-ROMs, there was no evidence for an effect of post-trauma sleep, SMD = 0.15, 95% CI [−0.06, 0.36], $p = .168$.

3.3.4. Meta-analysis on individual participant data

3.3.4.1. Main analyses

3.3.4.1.1. Intrusion frequency. As models based on zero-inflated Poisson distributions showed significant overdispersion, $p < .001$, and models based on negative binominal distributions indicated significant zero-inflation, $p = .016$, we employed a zero-inflated binominal model. Including group as fixed effect in both parts of the model improved model fit when compared to a model that only included a random intercept for study in both model parts, $LRT(2) = 8.69$, $p = .013$, while including a random slope did not result in a better model fit, $LRT(7) = 1.65$, $p = .977$. Residual diagnostics of the final model indicated a good fit (Kolmogorov-Smirnov test: $p = .747$) and identified no outliers ($p = .062$). The zero part of the model showed no between-group difference, $b = 0.53$, 95% CI [−0.40, 1.46], $p = .266$, that is, the occurrence of any intrusions was equally likely in both groups (see Table 3). In the count part of the model, there was evidence for a between-group difference, $b = -0.19$, 95% CI [−0.35, −0.03], $p = .020$, indicating that the number of intrusions was higher in the wake groups as compared to the sleep groups. A sensitivity analyses based on a hurdle model did not change our results.

3.3.4.1.2. Intrusion distress. As a model based on a Gaussian distribution indicated significant zero inflation, $p < .001$, we employed a lognormal hurdle model for semi-continuous data. When we compared a model including group as fixed effect in both parts of the model with a random intercept only model, there was no increase in fit, $LRT(2) = 0.51$, $p = .775$. The same applied to the inclusion of a random slope, which also did not improve model fit compared to the random intercept-only model, $LRT(9) = 6.78$, $p = .660$. Although the inclusion of group did not improve model fit, we present a model including a fixed effect for

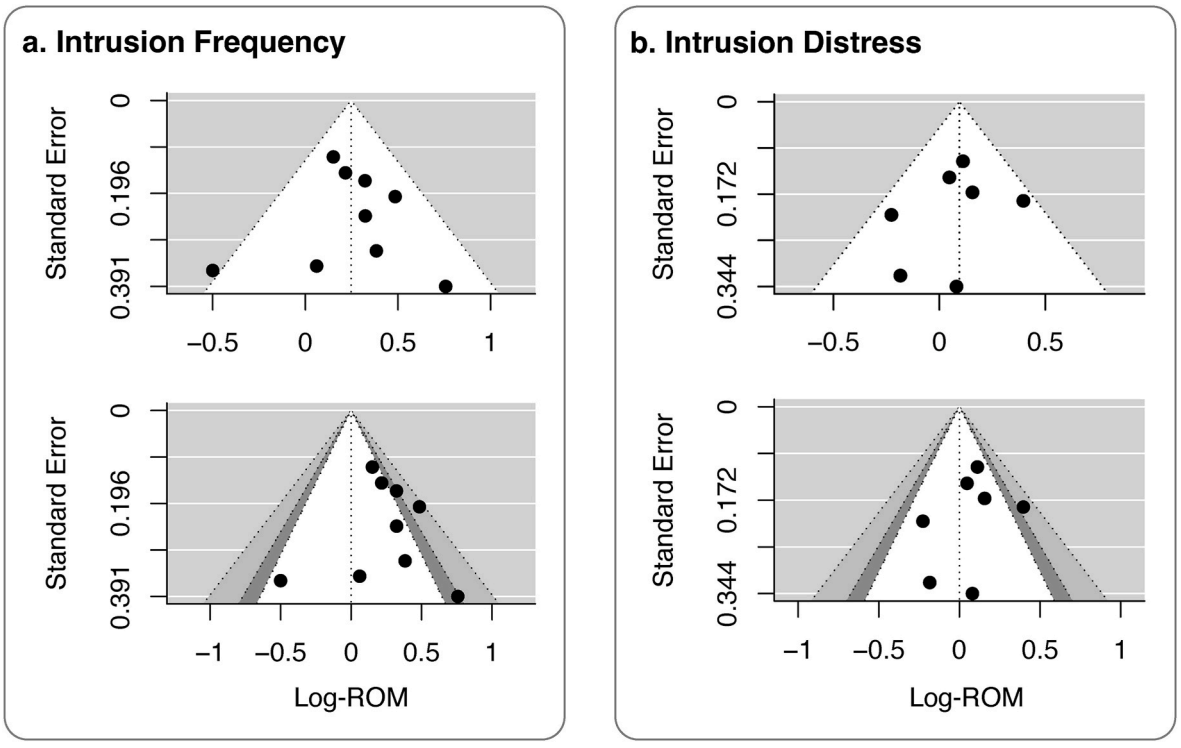

Fig. 5. Funnel Plots for the Meta-Analyses on Intrusion Frequency and Intrusion Distress. *Note*. Funnel plots and contour-enhanced funnel plots of all studies included in the analysis on intrusion frequency (a.) and intrusion distress (b.). For the contour-enhanced funnel plots, the white area indicates findings being insignificant at $p \geq .10$, the darker grey areas indicate p-values between $.05 < p \leq .10$ (marginally significant findings), while the lighter grey areas mirror p-values between $.01 < p \leq .05$. All studies following beyond these boundaries would be significant at $p \leq .001$. log-ROM = log-transformed ratio of means.

Table 3
Results of multilevel models for intrusion frequency and intrusion distress.

	Model 1			Model 2		
	b	*95% CI*	*p*	*b*	*95% CI*	*p*
a. Intrusion frequency						
Count part						
(Intercept)	1.49	1.09, 1.88	<.001	1.48	1.10, 1.87	<.001
Group	−0.19	−0.35, −0.03	.020	−0.19	−0.35, −0.03	.017
Age				0.01	−0.01, 0.03	.354
Gender				0.21	−0.02, 0.44	.070
Group x Age				−0.05	−0.10, 0.00	.038
Group x Gender				0.28	−0.18, 0.74	.237
Age x Gender				0.05	−0.02, 0.12	.139
Group x Age x Gender				0.01	−0.13, 0.15	.878
Zero part						
(Intercept)	−2.40	−3.29, −1.50	<.001	−2.46	−3.37, −1.55	<.001
Group	0.53	−0.40, 1.46	.266	0.41	−0.56, 1.40	.413
Age				−0.05	−0.21, 0.11	.547
Gender				−0.24	−1.47, 0.99	.703
Group x Age				−0.07	−0.39, 0.25	.671
Group x Gender				−0.40	−3.00, 2.21	.766
Age x Gender				−0.17	−0.52, 0.18	.345
Group x Age x Gender				−0.33	−1.02, 0.36	.346
k_{Study}	8				8	
$n_{Participants}$	478				476	
b. Intrusion distress						
Continuous part						
(Intercept)	−1.55	−1.85, −1.26	<.001	−1.56	−1.84, −1.27	<.001
Group	−0.06	−0.22, 0.11	.522	−0.05	−0.22, 0.11	.525
Age				−0.01	−0.04, 0.01	.353
Gender				0.04	−0.21, 0.28	.764
Group x Age				0.02	−0.03, 0.07	.396
Group x Gender				0.33	−0.17, 0.83	.193
Age x Gender				−0.04	−0.12, 0.04	.311
Group x Age x Gender				0.09	−0.07, 0.25	.280
Zero part (hurdle)						
Intercept	−2.83	−3.61, −2.06	<.001	−3.14	−4.16, −2.12	<.001
Group	−0.15	−1.15, 0.86	.773	−0.53	−1.88, 0.83	.447
Age				−0.09	−0.32, 0.15	.467
Gender				−1.22	−2.54, 0.10	.070
Group x Age				−0.30	−0.79, 0.19	.228
Group x Gender				−1.62	−4.31, 1.08	.239
Age x Gender				−0.40	−0.85, 0.05	.085
Group x Age x Gender				−1.05	−1.98, −0.12	.026
k_{Study}		6			6	
$n_{Participants}$		293			292	

Note. k = number of effect sizes; n = number of participants.

group in both model parts for comparison with the meta-analysis on aggregated data (see Table 3, Model 1). Residual diagnostics of this model demonstrated good fit (Kolmogorov-Smirnov test: $p = .122$) and identified no outliers ($p = .509$). The zero part of the model showed that the occurrence of any intrusion distress was equally likely in both groups, $b = -0.15$, 95% CI [−1.15, 0.86], $p = .773$, and the continuous part of the model demonstrated that the severity of intrusion distress did not differ between groups, $b = -0.06$, 95% CI [−0.22, 0.11], $p = .522$ (see Table 3, Model 1). When we employed a zero-inflated gamma distribution for sensitivity analyses, our results remained unchanged, pointing to the robustness of our findings.

3.3.4.2. *Moderator analyses*

3.3.4.2.1. Intrusion frequency. We examined moderator effects of age, gender, depressive symptoms, and increases of negative mood from pre-to-post exposure. Age and gender showed no moderator effects in the zero part of the model, $ps \geq .346$ (see Table 3, Model 2), while age significantly moderated the effect of group (sleep vs. wake) in the count part, $b = -0.05$, 95% CI [−0.10, 0.00], $p = .038$, indicating that the protective effect of sleep was more pronounced with increasing participant age. Depressive symptom levels had no moderator effect, neither in the zero part, $b = -1.32$, 95% CI [−4.52, 1.88], $p = .417$, nor in the count part of the model, $b = -0.02$, 95% CI [−0.08, 0.05], $p = .600$ (see Table 4). Larger increases of negative mood from pre-to-post exposure were associated with more severe intrusions in the count part of the model, $b = 0.61$, 95% CI [0.22, 1.01], $p = .002$, but did not moderate the impact of sleep on intrusion frequency, $b = -0.02$, 95% CI [−0.81, 0.77], $p = .963$. No moderator effect emerged in the zero part of the model.

3.3.4.2.2. Intrusion distress. For intrusion distress, there were no moderator effects of age and gender, neither in the count nor the zero part of the model, $p \geq .193$, except for a three-way interaction between group, age, and gender in the zero part, $b = -1.05$, 95% CI [−1.98, −0.12], $p = .026$ (see Table 3, Model 2). However, neither for females nor males of all ages, there was evidence for an effect of group on the occurrence of any (vs. no) intrusion distress. Depressive symptoms had no significant moderator effect in the zero part of the model but showed a significant interaction with group in the continuous part of the model, $b = 0.06$, 95% CI [0.00, 0.11], $p = .048$, with numerically larger effect estimates for group when depressive symptoms were less severe (see Table 4). However, even when limiting our sample to those with below median depressive symptoms for illustrative purpose, the effect of group remained non-significant. Moreover, increases in negative mood from pre-to-post exposure had no moderator effect in both model parts, $p \geq .676$, but a significant main effect on intrusion distress in the count-part, $b = 0.82$, 95% CI [0.45, 1.18], $p < .001$, with stronger increases being associated with more intrusion distress.

4. Discussion

This review aimed to provide a qualitative and quantitative summary of the current state of research on the effect of sleep versus wakefulness after exposure to experimental analog trauma on subsequent intrusive memories. Specifically, we aimed to answer the question of whether research supports a beneficial or detrimental effect of post-trauma sleep on subsequent intrusive memories. In line with two recent reviews (Davidson & Marcusson-Clavertz, 2023; Larson et al., 2023), our meta-analyses on aggregated data showed that sleep as opposed to wakefulness is associated with fewer intrusive memories, while there was no evidence for an impact of sleep on intrusion distress. Study-level moderators such as the number of assessment days had no impact on effect estimates. Beyond previous reviews, the availability of individual participant data (IPD) allowed us to perform more in-depth analyses.

Table 4
Details of moderator analyses.

	Depressive symptoms				Increase of negative mood		
	b	95% CI	*p*		*b*	*z*	*p*
a. Intrusion frequency							
Count part				**Count part**			
(Intercept)	1.55	0.83, 2.28	<.001	(Intercept)	1.49	1.11, 1.87	<.001
Group	−0.25	−0.47, −0.02	.030	Group	−0.19	−0.35, −0.04	.015
Depressive symptoms	−0.01	−0.04, 0.02	.421	Increase in negative mood	0.61	0.22, 1.01	.002
Group x Depressive symptoms	−0.02	−0.08, 0.05	.600	Group x Increase in negative mood	−0.02	−0.81, 0.77	.963
Zero part				**Zero part**			
(Intercept)	−5.14	−12.19, 1.91	.153	(Intercept)	−2.38	−3.29, −1.47	<.001
Group	−0.02	−5.58, 5.53	.994	Group	0.51	−0.41, 1.43	.273
Depressive symptoms	−0.32	−1.47, 0.84	.589	Increase in negative mood	0.31	−2.34, 2.97	.817
Group x Depressive symptoms	−1.32	−4.52, 1.88	.417	Group x Increase in negative mood	0.22	−4.86, 5.31	.932
k_{Study}	4				8		
$n_{Participants}$	271				478		
b. Intrusion distress							
Continuous part				**Continuous part**			
(Intercept)	−1.53	−1.95, −1.12	<.001	(Intercept)	−1.55	−1.85, −1.26	<.001
Group	0.00	−0.19, 0.19	.989	Group	−0.06	−0.22, 0.10	.473
Depressive symptoms	0.00	−0.03, 0.03	.916	Increase in negative mood	0.82	0.45, 1.18	<.001
Group x Depressive symptoms	0.06	0.00, 0.11	.048	Group x Increase in negative mood	−0.15	−0.90, 0.59	.676
Zero part (hurdle)				**Zero part (hurdle)**			
(Intercept)	−3.32	−4.46, −2.19	<.001	(Intercept)	−2.84	−3.62, −2.06	<.001
Group	1.25	−0.25, 2.75	.102	Group	−0.16	−1.18, 0.85	.766
Depressive symptoms	0.04	−0.17, 0.25	.733	Increase in negative mood	−0.69	−3.52, 2.15	.656
Group x Depressive symptoms	−0.09	−0.52, 0.35	.693	Group x Increase in negative mood	−0.96	−6.72, 4.80	.890
k_{Study}	4				6		
$n_{Participants}$	220				293		

Note. k = number of effect sizes; n = number of participants.

While we found evidence that sleep as opposed to wakefulness was related to a lower number of intrusions in participants experiencing at least one intrusion, sleep was unrelated to the occurrence of intrusions, i.e., sleep did not affect the likelihood of experiencing any versus no intrusions. Moreover, IPD also allowed us to perform participant-level moderator analyses showing that a higher age may be associated with a more pronounced protective effective effect of sleep. However, these findings need further replication in larger, more diverse samples.

Our qualitative summary showed that of nine studies investigating the impact of post-trauma sleep versus wakefulness on intrusive memories, five found evidence for a positive impact of sleep on analog intrusions (Kleim et al., 2016; Sopp et al., 2019; Werner et al., 2021; Woud et al., 2018; Zeng et al., 2021). One study found evidence for a positive impact of sleep deprivation on analog intrusions (Porcheret et al., 2015), and three studies provided inconclusive results (Porcheret et al., 2019; Sopp et al., 2021; Wilhelm et al., 2021). We also examined the effect of post-trauma sleep on explicit and implicit trauma memory: Of five studies investigating the impact of sleep versus sleep deprivation on explicit trauma memory, three found evidence for sleep significantly enhancing explicit trauma memory as compared to sleep deprivation (Sopp et al., 2019, 2021; Zeng et al., 2021). One study provided mixed evidence, indicating that sleep enhanced visual memory but not verbal memory (Porcheret et al., 2019). Correspondingly, one study found no evidence for an impact of sleep on explicit trauma memory using a verbal memory test (Woud et al., 2018). Of five studies investigating the impact of sleep versus sleep deprivation on implicit trauma memory, four did not find any evidence for group differences (Porcheret et al., 2019; Sopp et al., 2019; Werner et al., 2021; Zeng et al., 2021). One study found that sleep compared to wakefulness reduced implicit memory as evident in mood responses (Wilhelm et al., 2021). Finally, four studies investigated associations between Non-REM and REM sleep physiology and analog intrusions. Two studies found evidence for an involvement of both Non-REM and REM sleep (Kleim et al., 2016; Wilhelm et al., 2021). Only single studies found evidence for an involvement of REM sleep (Werner et al., 2021) and SWS (e.g., Sopp et al., 2021).

Across both analytical approaches chosen for our quantitative summary, we found evidence in favor of a beneficial rather than a detrimental effect of post-trauma sleep on subsequent intrusion frequency. That is, participants experienced fewer intrusions if they had slept after exposure to analog trauma than if they remained awake or were partially sleep deprived. Due to the lack of heterogeneity, these effects can be generalized beyond the current samples to the wider population of healthy young adults experiencing analog trauma. IPD analyses further suggest that sleep does not affect the occurrence of any versus no intrusive memories per se. However, in the subgroup of individuals who experienced any intrusions after exposure to analog trauma, post-trauma sleep compared to wakefulness was associated with fewer intrusions.

Overall beneficial effects of post-trauma sleep on intrusion frequency may emerge because post-trauma sleeping reduces the frequency of intrusions in participants that are prone to develop intrusions in response to analog trauma. If confirmed by further research, these findings suggest that prevention strategies that aim to improve sleep should be developed and tested on individuals at-risk for intrusion development and later onset of PTSD. Such individuals could be identified based on pre-trauma (e.g., trait rumination, prior psychopathology; Schultebraucks et al., 2021) and/or peri-trauma (e.g., peritraumatic distress, dissociation; Massazza, Joffe, & Brewin, 2021; Massazza, Joffe, Hyland, & Brewin, 2021) risk factors. However, such an approach would require a strong (empirical) consensus on primary risk factors that should be targeted, which does not exist at present (Bonanno, 2021; Kalisch et al., 2017).

Moreover, it must be noted that our analyses revealed small-to-medium effect sizes reflecting a small difference of average intrusion frequency between sleep and wake groups. Given the high individual and societal burden associated with PTSD (Davis et al., 2022; Olatunji et al., 2007; Pacella, Hruska, & Delahanty, 2013), even small-to-medium effect sizes of prevention measures could make a great difference as they may prevent a substantial number of PTSD cases when delivered to a larger population of traumatized individuals. However, studies translating other interventions found to be effective in experimental

psychopathology to clinical populations provided evidence for potential decreases of effect sizes and point to the importance of distinguishing lab-based research from randomized controlled trials with clinical samples (Wiers, Boffo, & Field, 2018). Moreover, a recent meta-analysis on the effectiveness of consolidation/reconsolidation interventions for the prevention and treatment of PTSD provided evidence for smaller effect sizes in real-world settings for PTSD prevention (Astill Wright, Horstmann, Holmes, & Bisson, 2021). Hence, further research in clinical populations needs to establish whether the magnitude of effects is sufficient to justify a clinical implementation of sleep-enhancing interventions. These studies may also examine whether sleep, mainly targeting the process of memory consolidation, might be used as a mechanism-focused adjunct of other interventions (Kleim et al., 2014; see Blackwell, 2020; for a similar idea on cognitive bias modification).

While our analyses support a beneficial effect of sleep on intrusion frequency, we did not find evidence for sleep-related effects on intrusion distress. On the one hand, this lack of evidence may have emerged since these analyses relied on a smaller subsample of studies and participants. On the other hand, our results could indicate that the sleep-related processes that modulate intrusion frequency do not affect distress levels. In fact, there have been different accounts as to how sleep may reduce intrusions (Azza et al., 2020; Germain, Buysse, & Nofzinger, 2008), with one assuming that sleep supports memory consolidation, thereby strengthening explicit trauma memory and inhibiting the occurrence of intrusions (based on e.g., Diekelmann & Born, 2010). The other account proposed a role of sleep in reprocessing and weakening of the affective component of traumatic memories, resulting in reduced intrusion distress (based on van der Helm & Walker, 2009). The current results seem to support the first hypothesis while providing no support for the second. However, since our analyses did not focus on underlying processes, caution is warranted in drawing strong conclusions. Some additional insights can be gathered from our qualitative synthesis. That is, four of five studies (i.e., Porcheret et al., 2019; Sopp et al., 2019; Sopp et al., 2021; Zeng et al., 2021) investigating the effect of sleep on explicit trauma memory found an enhancing effect of sleep. Implicit trauma memory - mostly assessed by pre-to-post-sleep changes in mood/affective ratings during presentation of traumatic stimuli - was only found to be reduced after sleep in one of five studies (i.e., Wilhelm et al., 2021). These findings support the notion that sleep influences intrusions by modulating explicit trauma memory, rather than supporting the reprocessing of the affective component of traumatic memories. The neurophysiological underpinning of this process requires further investigation. Our qualitative synthesis showed mixed evidence for an involvement of Non-REM and REM sleep. However, this evidence is based on correlational findings in very small samples, which - so far - have not been replicated across studies. For the current review, we were not able to perform meta-analyses on sleep characteristics and their association with intrusion frequency or intrusion distress due to substantial between-study heterogeneity of sleep assessments (home vs. lab-based) and reported associations. However, building on findings of the current review, future studies may explicitly focus on memory processes and their neurophysiological correlates, and thus make them a potential target for future meta-analyses.

Although our analyses provided evidence for sleep having a beneficial impact on intrusion frequency, one of the included studies has revealed opposing findings (Porcheret et al., 2015). We aimed to find the source of these discrepancies by exploring differences between studies that could account for opposing effects (see e.g., Schenker et al., 2021). Traditional meta-analytical moderator analyses on study characteristics did not reveal any significant findings, which was not surprising as the main analyses pointed to homogeneous effect estimates. Participant-level moderator analyses only revealed one robust finding, which was that the beneficial effects of sleep tended to be larger with increasing participant age. However, it must be noted that the age range across studies was restricted (*Range* = 18–35 years), which limits the interpretation and generalization of this finding. Reasons for the divergent finding by Porcheret et al. (2015) may lie in the fact that the assessment of intrusions included the acute period of sleep deprivation, whereas this phase was excluded in other studies. Alternatively, the use of the total sleep deprivation may have elicited these effects, since they were reproduced in their follow-up study, albeit only in a secondary analysis (Porcheret et al., 2019; but see: Zeng et al., 2021, who employed a similar design finding a medium-sized favorable effect of sleep). Other factors that may have introduced variance between studies are type of recruitment (university vs. community sample), stimulus material (trauma film vs. aversive pictures), and intrusion assessment (paper-pencil or electronic). To date, the small number of studies does not allow for subgroup analyses, however, future meta-analyses based on a larger number of primary studies should examine those variables by means of moderator analyses. Statistically, our results might also point to the fact that differences in observed effect estimates may be explained by sampling error and divergent findings can be viewed as upper and lower end of a single distribution of effect estimates. At the same time, the number of included studies was low, which limits the power of heterogeneity tests (von Hippel, 2015), and may have resulted in overlooked true between-study differences. Moreover, it is important to note that our moderator analyses in both meta-analyses only included variables that were available for a relevant number of included studies, limiting the scope of these analyses and thus our ability to clarify the emergence of opposing effects of sleep. Further research investigating multiple potentially relevant moderators, ideally in sufficiently powered studies and more heterogeneous samples (e.g., with respect to gender and age), is thus needed to characterize potential boundary conditions of the detrimental or beneficial impact of sleep on intrusive memories.

Beyond the limitations noted above, several others need to be considered. First, our project involved into a systematic review over time, therefore, it was not prospectively preregistered. There were no major changes with respect to research questions and modelling decisions in the course of our project, however, we cannot exclude that the retrospective registration biased our findings. Second, our analyses aggregated data across studies with very different designs (e.g., [partial] sleep deprivation, nap sleep) and assessment methods (e.g., intrusion triggering task, intrusion diary). However, the lack of significant heterogeneity supports the notion that - despite procedural differences - effect estimates were eligible for meta-analyses. Another limitation concerns the fact that the number of studies included in our analyses ($k = 9$) is low compared to other meta-analyses in the trauma field (e.g., Clark, Mackay, & Holmes, 2015; Schäfer, Becker, King, Horsch, & Michael, 2019). However, the limited number of studies gave us the unique opportunity to gather almost all primary datasets ($k = 8$) and conduct an IPD meta-analysis. These analyses strongly improved interpretation beyond previous work in the field (Davidson & Marcusson-Clavertz, 2023; Larson et al., 2023) by showing that sleep is not a significant predictor of any (vs. no) intrusions but of the number of intrusions. As such, the current study constitutes an example of how collaboration can advance the field beyond the contributions of individual studies. This is especially important in the field of sleep research that is often limited by small sample sizes. Collaborative efforts and meta-analytical data analyses may help to answer questions that cannot be addressed by individual studies, while increasing the replicability of findings, which is essential to translate findings from experimental to clinical research. However, the sample size of our meta-analysis is still small, which may limit the validity of our findings. Sample sizes of primary studies ranged between 39 and 94 participants, while our meta-analysis included 529 participants (or 479 participants, respectively). There is still a strong need for large multi-lab replication studies running a single experimental design at different sites. Previous research showed that meta-analysis and multi-lab replication projects may yield different results, with effects tending to be larger in meta-analysis compared to multi-lab replication studies due to (small) differences in statistical analyses, publication bias, potential method- and context sensitivity and experimenter effects (Lewis, Mathur, VanderWeele, &

Frank, 2022). Finally, it is important to emphasize that all included studies investigated analog symptoms in healthy participants. Although this approach is commonly used in PTSD research (Iyadurai et al., 2019), it prevents us from drawing strong inferences on how effects may unfold after real-world trauma exposure – effects may be different for different types of trauma and may also differ in size. It is one of the major strengths of analog trauma that such paradigms allow for (partly) causal modelling of processes involved in the onset, persistence and treatment of PTSD (James et al., 2016). However, doubts have been raised about their ecological validity (Lau-Zhu, Holmes, & Porcheret, 2018). In case of our research, one may question whether processes involved in the occurrence of intrusions during an intrusion triggering task (Streb, Conway, & Michael, 2017; Wegerer, Blechert, Kerschbaum, & Wilhelm, 2013) are the same as those eliciting intrusions in everyday life of PTSD patients. Moreover, research indicates that disturbed sleep may have a different impact on emotional processing in those with mental disorders than in healthy individuals, thus putting into question whether findings from healthy samples can be generalized to clinical populations (van Someren, 2021). Bridging the gap between experimental research in the lab and clinical research in the field thus constitutes an important next step (Blackwell & Woud, 2022), for which the present review may provide a base. Nevertheless, one must consider that hypotheses derived from analog studies may not prove to be valid in real-world settings.

Future research should focus on investigating the effects of sleep on intrusions in the immediate aftermath of real-world trauma. So far, only one longitudinal observational study examined the link between post-trauma sleep and intrusive memories after real-world trauma (Porcheret et al., 2020), finding a U-shaped association between sleep duration in the first night post-trauma and intrusive memories in the first week post-trauma, with both "too little" and "too much" sleep being associated with more intrusive memories in the first week posttrauma. Moreover, also both an increase and decrease from pre-to-post-trauma sleep duration were associated with more intrusive memories. However, no associations emerged between post-trauma sleep and PTSD symptoms after two months. Other studies (e.g., Neylan et al., 2021; Schenker et al., 2023) examined the association of subjective and objective sleep data with subsequent PTSD symptoms. Schenker et al. (2023) found a link between subjective sleep disruptions and next-day PTSD symptoms, while objective sleep data was unrelated to PTSD symptoms. Similary, Zhou et al. (2023) found an association between subjectively perceived sleep distrubances within two weeks after trauma and PTSD symptoms 3-months post-trauma. Neylan et al. (2021) showed a link between retrospectively reported pre-trauma insomnia, sleep-stress reactivity and nightmares, and post-trauma symptoms of PTSD and depression. Similarly, Reffi et al. (2023) found that pre-pandemic sleep reactivity predicted stress reactions and depression during the COVID-19 pandemic. Future studies should employ experimental designs in clinical contexts (within existing ethical boundaries) and may also examine how different sleep-related interventions may be used to reduce intrusions. Generally speaking, interventions could comprise elements of evidence-based treatment of insomnia like cognitive behavioural techniques and relaxation as well as evidence-based interventions to promote sleep health (e.g., Buysse, 2014; Edinger et al., 2021). Future studies will provide insights on whether these interventions are also suitable for reducing post-trauma sleep disturbances, which may be qualitatively different from sleep problems related to insomnia, requiring a focus on issues such as PTSD-related nighttime hyperarousal psychoeducation, identification of alternatives to PTSD-related safety behaviours, nightmare psychoeducation, psychoeducation about PTSD avoidance in the context of substance/medication use, cognitive techniques, and behavioural tracking to challenge beliefs and avoidance behaviours (Carlson et al., 2022). These treatment targets may require including non-standard components such as sleep-directed hypnosis (Cordi, Rossier, & Rasch, 2020; Friesen, Sopp, Cordi, Rasch, & Michael, 2023), which has been shown to be effective in alleviating sleep problems and depression in PTSD patients (Galovsky et al., 2016). Due to the high level of standardization, such interventions could be disseminated in a self-guided web-based format, which would allow targeting traumatized individuals in the immediate aftermath of trauma.

One may also think that the use of sleep-inducing medication might help to promote post-trauma sleep. However, a robust evidence base challenges the use of sleep-inducing medication for improving sleep quality (Solomon et al., 2021) and shows that sleep medication negatively impacts on sleep-related memory processes (Leong et al., 2022; Seibt et al., 2008). Thus, future research should focus on non-pharmacological sleep-inducing interventions, while pharmacological interventions may increase the risk of long-term alterations of sleep.

Future studies may also examine the complex interplay of intrusive reexperiencing with other PTSD symptom clusters (i.e., avoidance, numbing, hyperarousal, negative cognitions, and mood; American Psychiatric Association, 2022). Due to the critical role of sleep in memory consolidation, intrusive memory is the most proximal outcome of sleep interventions. However, future studies should investigate whether and how sleep-related processes may affect other symptom domains that are found to be highly influential in PTSD development (e.g., trauma-related alterations in cognition; Kube, Berg, Kleim, & Herzog, 2020) as well as a potential mediating role of intrusive memories.

5. Conclusion

The present systematic review summarized evidence on the effect of sleep versus wakefulness on intrusive memories after experimental analog trauma. By means of traditional meta-analysis, we found evidence for a small effect of sleep as compared to wakefulness on intrusive memory, with sleep being associated with a lower number of intrusions but unrelated to intrusion distress. Our meta-analyses on IPD supported these findings and provided additional insights such that sleep was related to lower intrusion frequency but did not affect the occurrence of any versus no intrusive memory. Despite divergent findings of individual studies employing different study designs, our meta-analyses yielded homogeneous results pointing to a small beneficial effect of sleep after analog trauma. Future studies should critically examine the clinical significance of this effect as well as its association with memory processes and their neurophysiological underpinning based on larger and more diverse samples.

Authors contributions

SKS: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Visualization; CL: Formal analysis, Data curation, Writing – review & editing, Project administration; KP: Data curation, Resources, Writing – review & editing; XH: Data curation, Resources, Writing – review & editing; JM: Data curation, Resources, Writing – review & editing; TM: Conceptualization, Resources, Writing – review & editing, Supervision; EH: Data curation, Resources, Writing – review & editing; GW: Data curation, Resources, Writing – review & editing; MW: Data curation, Resources, Writing – review & editing; IW: Data curation, Resources, Writing – review & editing; SZ: Data curation, Resources, Writing – review & editing; EF: Data curation, Writing – review & editing, Project administration, SHM: Data curation, Writing – review & editing; JLH: Conceptualization, Writing – review & editing; KL: Methodology, Resources, Writing – review & editing; AK: Methodology, Writing – review & editing; BW: Conceptualization, Methodology, Formal analysis, Writing – review & editing; RS: Conceptualization, Methodology, Resources, Supervision, Writing – original draft

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Declaration of competing interest

All authors declare to have no conflict of interest.

Data availability

The data is available from the Open Science Framework. Links are provided.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.brat.2023.104359.

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