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Sleep differentially impacts involuntary intrusions and voluntary recognitions of lab-analogue traumatic memories

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Summary

Despite the critical role of sleep in memory and emotion processing, large remains unknown regarding how sleep influences trauma-related symptoms arising from maladaptive memory/emotional processes, such as those among patients with post-traumatic stress disorder. Employing a trauma film paradigm, we investigated how post-trauma sleep versus sleep deprivation influenced involuntary intrusions and voluntary recognition of traumatic memories. Sixty participants were randomly assigned to sleep or total sleep deprivation group following experimental trauma induction. Participants were assessed with: (a) lab-based and 7-day diary-based involuntary intrusions; (b) voluntary recognitions of traumatic memories 12-hr and 7-day post-trauma induction; and (c) post-traumatic stress disorder-like symptoms measured by the Impact of Event Scale-Revised. We found that compared with sleep deprivation, slept participants experienced fewer traumatic intrusions across 7 days, reported lower emotional hyperarousal, and showed more accurate recognition of trauma-related stimuli. Moreover, higher subjective sleep quality was associated with fewer intrusions only in the sleep group, while a reversed pattern emerged in the sleep deprivation group. These results provide novel evidence supporting the therapeutic benefits of sleep in protecting mental well-being from trauma exposure. To the extent that sleep modulates trauma-related symptoms, sleep can be conceived as the potential target for early interventions among trauma victims.

KEYWORDS

emotional memory, experimental trauma, sleep-dependent consolidation, traumatic intrusions

1 | INTRODUCTION

Experiencing heightened arousing, traumatic events can lead to a constellation of detrimental effects, including sleep disturbances (e.g. insomnia; Spoormaker & Montgomery, 2008), recurrent intrusive memories (Iyadurai et al., 2019) and impaired memories of traumatic experiences (e.g. loss of details; Jones et al., 2007). These symptoms constitute core features of post-traumatic stress disorder (PTSD; American Psychiatric Association, 2013). In particular, the co-occurrences of sleep disruption and maladaptive memory/emotion processing raise an intriguing question on whether sleep interventions in the early aftermath of trauma could potentially change the trajectory of post-traumatic symptomatology (Spoormaker & Montgomery, 2008).

Sleep disturbances are common among trauma survivors, with the prevalence rates up to 80%–90% (Koffel et al., 2016). Disrupted sleep could be an adaptive consequence of traumatic experiences that prevents traumatic memories from being consolidated. Indeed, mounting evidences suggest sleep preferentially consolidates emotional memories and makes them long-lasting (Cox et al., 2018; Hu et al., 2006; Wagner et al., 2001). Besides memories, a few studies suggested sleep may also preserve affective tones of emotional

memories, indicated by subjective and physiological responses (Ashton et al., 2019; Baran et al., 2012; Menz et al., 2013; but also see Cox et al., 2018; Cunningham et al., 2014; Van Der Helm et al., 2011 for discrepant findings). Accordingly, one tenable hypothesis is that sleep deprivation in the early aftermath of trauma may alleviate PTSD symptoms, including involuntary intrusions and emotional hyperarousal. Indeed, prior research found that compared with sleep, sleep deprivation following viewing trauma films not only reduced involuntary intrusions across 7 days (Porcheret et al., 2015), but also weakened subjective fear and autonomic physiological responses (Kuriyama et al., 2010).

An alternative theoretical account makes an opposite prediction: compared with sleep deprivation, sleep should alleviate PTSD-like symptoms. This proposition is in accordance with the theoretical argument that involuntary intrusions and impaired voluntary memories among patients with PTSD are due to inadequate integration of traumatic experiences into one's existing autobiographical memory schema (Brewin, 2001; Ehlers & Clark, 2000). From this perspective, sleep provides an optimal opportunity to consolidate newly acquired memories: via repeated memory reactivation implicated during the non-rapid-eye-movement (NREM) sleep, initially hippocampal-dependent memories are consolidated and redistributed to a wider memory representation network (e.g. neocortex; Rasch & Born, 2013). Therefore, sleep in the early aftermath of trauma could stabilize traumatic memories and make them less likely to intrude into conscious awareness as fragmented, image-like flashbacks. Furthermore, while memories are consolidated during sleep, research suggests that sleep attenuates the affective tones of emotional memories (Cox et al., 2018; Cunningham et al., 2014). Supporting this theoretical account, research has found that post-trauma sleep (versus staying awake) led to fewer and less distressful involuntary intrusions (Kleim et al., 2016; Porcheret et al., 2019; Woud et al., 2018).

While most sleep and traumatic memory studies focused on involuntary intrusion given its clinical implications (Iyadurai et al., 2019), voluntary memories of traumatic experiences have received relatively little attention. Having accurate memories of traumatic experience can be valuable: trauma survivors shall accurately discriminate between experienced and unexperienced trauma-related stimuli to avoid overgeneralized fearful memories. Ideally, interventions of PTSD should reduce traumatic intrusions while leaving voluntary memories intact (Holmes et al., 2010). Previous studies suggest that involuntary intrusions and voluntary memories of traumatic experiences are dissociable using visuo-spatial interference tasks (Lau-Zhu et al., 2019). Given the role of sleep in system-level memory consolidation and in emotional processing (Rasch & Born, 2013; Walker & van der Helm, 2009), we hypothesized that post-trauma sleep would play a protective role in processing traumatic memories, and result in fewer involuntary intrusions and higher voluntary recognitions of the same traumatic experience.

2 | MATERIALS AND METHODS

Materials, data and scripts are available at the Data Availability.

2.1 | Participants

Sixty-two non-smoking participants were recruited from the university for monetary compensation. Two participants were excluded: one had seen the film clips before; one had a family member who passed away during the study period, resulting in 60 participants (41 females, mean age = 20.5 years, $SD = 2.05$). Participants were prescreened based on: (a) no chronic medical conditions/current or history of psychiatric/neurological/sleep disorders; (b) having a regular sleep–wake pattern with averaged sleep time > 6 hr per night; (c) not nauseous to blood; (d) no overnight shiftwork/intercontinental travels within 3 weeks including the experiment week. Qualified participants should maintain their sleep schedules, which were verified by paper-based sleep diaries during the study period. Participants provided written consent forms. The study was approved by the Human Research Ethics Committee of the University of Hong Kong.

2.2 | Procedure & Materials

Potential participants completed individual difference questionnaires assessing sleep quality, mood and past traumatic experiences in an online prescreening session (Table 1; Appendix S1).

The study consisted of four lab sessions (Figure 1a). In lab session 1, participants were introduced to the entire experimental procedure. Participants were informed of the aversive traumatic film, but were not aware of any memory tests until the first recognition test.

In lab session 2 (Day 0), participants reported to the lab at about 21:00 and completed questionnaires assessing chronotype/thought control ability/emphatic level (Appendix S1). Any significant baseline group differences would be used as covariates in the regression analyses.

Participants then watched a 14-min trauma film. To measure negative affect induction before and after watching the film, participants rated their affect (anxious, depressed, sad, fearful, hopeless, horrified) on 100-point Visual Analogue Scales (VAS). Following post-film VAS ratings, participants were left alone with their eyes closed for a 5-min resting period. After 5 min, the experimenter entered and asked participants whether they experienced any flashbacks from the films. Verbal responses from participants were noted but not analysed. The experimenter then explained the definition of involuntary intrusions to participants (Porcheret et al., 2015; for verbatim instructions, see Appendix S1). This ensured participants understood the concept of intrusion before the sleep/sleep deprivation manipulation. Participants were then notified of their group assignment.

Participants in the sleep group ($n = 30$) went back home and slept as usual (Kleim et al., 2016; Porcheret et al., 2019), and they reported back to the lab next morning with light breakfasts served. Sleep durations were verified by self-reported sleep diaries and by wrist actigraphy. Participants were instructed to refrain from consuming caffeine/alcohol, playing computer games/watching films/engaging in intense physical or emotionally arousing activities.

Participants in the sleep deprivation group ($n = 30$) stayed in the lab accompanied by two trained experimenters taking shifts

TABLE 1 Individual differences of sleep versus sleep deprivation group ($N = 60$)

	Sleep ($N = 30$)	Sleep deprivation ($N = 30$)	Test statistics and p-values
Age			
Mean ± *SD*	20.57 ± 2.46	20.43 ± 1.59	$W = 414$; $p = .593$
Gender			
Male, *n* (%)	7 (23.33%)	12 (40.00%)	$\chi^2(1) = 1.93$; $p = .165$
Female, *n* (%)	23 (76.67%)	18 (60.00%)	
ISI			
Mean ± *SD*	3.53 ± 1.96	4.43 ± 2.37	$t_{58} = -1.60$; $p = .115$
PSQI			
Mean ± *SD*	3.53 ± 1.46	3.93 ± 1.57	$t_{58} = -1.02$; $p = .311$
(In-lab) BDI-II			
Mean ± *SD*	3.77 ± 3.63	4.30 ± 3.27	$W = 397.5$; $p = .439$
(In-lab) DASS, mean ± *SD*			
Depression	2.20 ± 2.89	2.87 ± 3.00	$W = 377$; $p = .261$
Anxiety	4.20 ± 3.50	4.13 ± 3.56	$W = 441$; $p = .897$
Stress	3.27 ± 3.50	4.47 ± 4.32	$W = 378$; $p = .280$
TEQ			
Mean ± *SD*	0.43 ± 0.68	0.30 ± 0.53	$W = 413$; $p = .501$
TCQ, mean ± *SD*			
Distraction	16.47 ± 2.30	16.33 ± 3.26	$t_{58} = 0.18$; $p = .855$
Social control	14.67 ± 3.71	13.83 ± 3.82	$t_{58} = 0.86$; $p = .394$
Worry	10.53 ± 3.30	10.20 ± 2.37	$t_{58} = 0.45$; $p = .655$
Punishment	9.90 ± 2.66	9.37 ± 1.97	$W = 408.5$; $p = .538$
Reappraisal	16.23 ± 3.14	14.63 ± 3.00	$t_{58} = 2.02$; $p = .048^*$
Total score	67.80 ± 7.76	64.37 ± 8.21	$t_{58} = 1.66$; $p = .101$
MEQ, *n* (%)			
Morningness type, *n* (%)	4 (13.33%)	1 (3.33%)	$\chi^2(2) = 2.02$; $p = .364$
Eveningness type, *n* (%)	7 (23.33%)	7 (23.33%)	
Neither type, *n* (%)	19 (63.33%)	22 (73.33%)	
IRI, mean ± *SD*			
Perspective taking	19.67 ± 4.20	16.67 ± 4.13	$t_{58} = 2.79$; $p = .007^{**}$
Fantasy	16.93 ± 3.96	15.37 ± 5.60	$W = 381.5$; $p = .312$
Empathic concern	19.47 ± 4.09	17.77 ± 4.12	$t_{58} = 1.60$; $p = .114$
Personal distress	12.80 ± 3.98	13.03 ± 3.47	$t_{58} = -0.24$; $p = .810$

Note: To compare between-group differences, for continuous data, independent sample *t*-tests (*t*) were conducted if assumptions were met. Otherwise, Wilcoxon rank-sum tests (*W*) would be performed instead. For count data, chi-square test (χ^2) was conducted.

Abbreviations: BDI-II, Beck Depression Inventory-II; DASS, Depression Anxiety Stress Scales; ISI, Insomnia Severity Index; MEQ, Morningness–Eveningness Questionnaire; PSQI, Pittsburgh Sleep Quality Index; TCQ, Thought Control Questionnaire; TEQ, Trauma Experience Questionnaire.

$^*p < .05$; $^{**}p < .01$.

overnight. During the overnight stay, participants' activities were kept at a minimum level of arousal: they worked on assignments, read books, played board games, etc. Same as the sleep group, they were refrained from watching videos/playing computer games/engaging in intense physically or emotionally arousing activities. Light breakfasts were served the next morning.

All participants started lab session 3 (Day 1) at about 09:00. They completed a 5-min intrusion monitoring task, followed by a recognition-fearful rating task. Participants then received instructions on how to finish the 7-day online intrusion diaries.

In lab session 4 (Day 8), participants completed the second recognition-fearful rating task with a different set of stimuli,

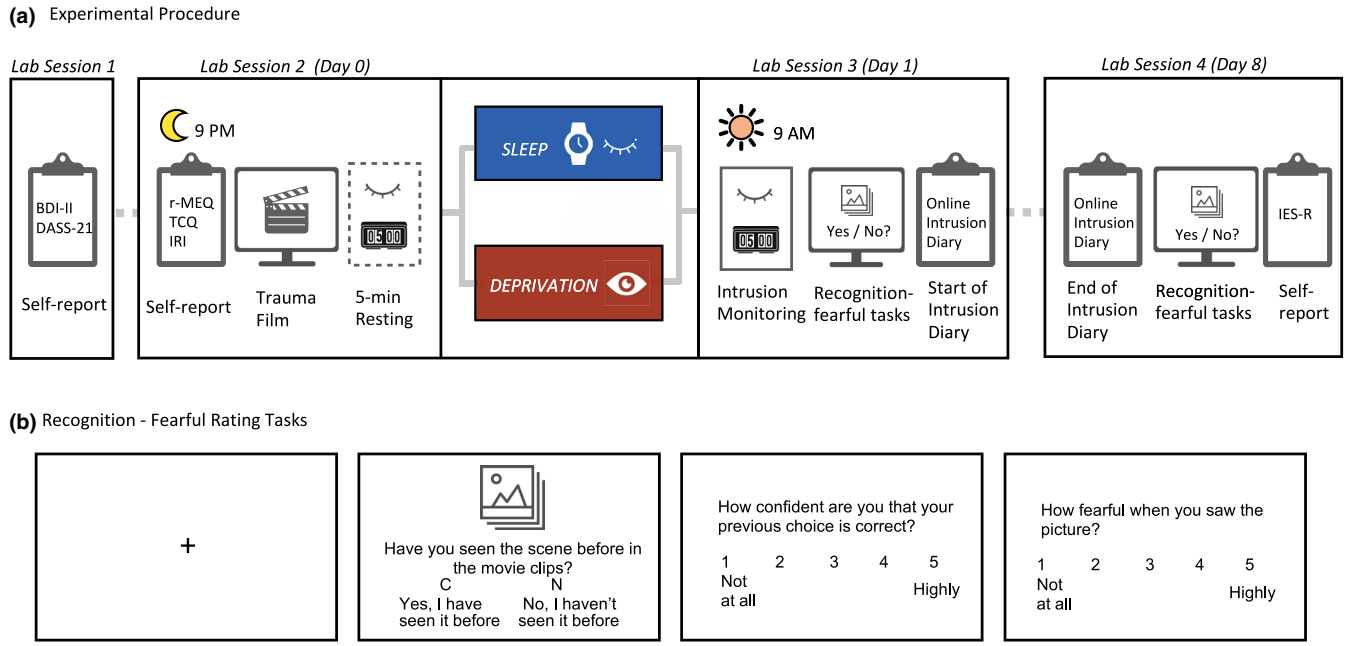

FIGURE 1 (a) Experimental Procedure. Both groups finished Beck Depression Inventory-II (BDI-II) and Depression, Anxiety and Stress Scale - 21 items (DASS-21) in the first lab session. They attended the formal lab session at Day 0 and watched trauma film after finishing in-lab questionnaires (i.e. r-MEQ, Reduced Morningness–Eveningness Questionnaire; TCQ, Thought Control Questionnaire; IRI, Interpersonal Reactivity Index). After a 5-min resting period, the sleep group went home to sleep with actigraphy on to monitor the sleep–wake pattern until the next morning at 09:00 hours. The sleep-deprived group stayed awake, monitored by trained experimenters in the lab until the next morning at 09:00 hours. A 5-min intrusion monitoring task and a recognition-fearful rating task were conducted consecutively in the morning, followed by the explanation and the onset of the 7-day online intrusion diary. On Day 8, both groups returned to finish the last lab session and completed the second recognition-fearful rating task as well as the Impact Event Scale-Revised (IES-R) questionnaire. (b) Recognition-fearful rating tasks. On each trial, participants were firstly presented with the screenshots either from the trauma film clips they watched or from a similar film they had not watched in the lab, and were asked to judge the picture as "old" or "new". Confidence and fearful level were obtained on a scale from 1 (not at all) to 5 (highly).

followed by the Impact of Event Scale-Revised (IES-R; Weiss & Marmar, 1997) to assess PTSD-like symptoms. They also rated accuracies of their intrusion diaries on a 1 (highly inaccurate) to 10 (highly accurate) scale. Participants were then debriefed and compensated.

2.2.1 | Trauma film

Participants sat in a dark room in front of a 22-inch Dell monitor and watched a 14-min film wearing soundproof headphones. Participants watched nine aversive video clips depicting fatal transportation accidents (e.g. car accidents, plane crashes, train wreck, etc. each separated by 5-s blank screen) to induce PTSD-like symptoms such as intrusions and hyperarousal (James et al., 2016). Participants were instructed to watch the films as if they were bystanders on the scene, and they should not look away or close their eyes as verified by a webcam.

2.2.2 | Pictorial stimuli

We selected 60 screenshots from the trauma film as old stimuli, with half of them containing aversive scenes (e.g. dead bodies, etc.), and the remaining half depicting non-aversive neutral scenes (e.g. landscapes, etc.). Sixty new screenshots (30 negative, 30 neutral) were selected from similar, but unwatched traffic accident films. Old and new pictures were similar in content (see Data Availability for materials). These 120 pictures were equally divided into two sets to be used in immediate (Day 1) and delayed (Day 8) recognition tests, with the two sets counterbalanced across participants.

2.3 | Assessments

2.3.1 | Involuntary intrusive memory

Lab-based intrusion monitoring task

On Day 1 morning, participants completed an intrusion monitoring task, during which they closed their eyes for 5 min, and pressed the spacebar whenever they experienced an involuntary intrusion about the trauma film. Distinctions between intentional recall and involuntary intrusion were emphasized, and only involuntary intrusions should be recorded. Participants also responded to nine true/false questions regarding the definition of intrusion and the task requirements. Incorrect responses were re-explained by experimenters to ensure accurate understanding (Appendix S1).

1-week online intrusion diary

From Day 1 to Day 7, participants were instructed to write down every intrusion from the film as soon as it happened, including detailed descriptions and timing. Participants also rated vividness/distress levels for each intrusion on a 0–10 scale (not at all vivid/distressing, extremely vivid/distressing). Participants reported "N/A" on the diary if they did not experience any intrusion on that day. An email reminder was sent to participants at about 20:00 on each of the seven days. Participants also responded to eight true/false questions on Day 1 to make sure they understood the instructions.

2.3.2 | Voluntary recognition

Recognition-fearful rating task

Participants completed the recognition-fearful rating tasks on Day 1 and Day 8. In each trial, participants made an old/new judgement, followed by confidence and fearful ratings on 1 (not confident/fearful at all) to 5 (highly confident/fearful) scales (Figure 1b).

2.3.3 | Impact of Event Scale-Revised

On Day 8, participants finished the 22-item IES-R to measure PTSD-like symptoms with direct references to the trauma film, including three subscales: intrusion, avoidance and hyperarousal. High internal consistencies have been previously reported (Beck et al., 2008).

2.4 | Statistical analysis

All statistical analyses were performed in *R 3.6.0* (see Data Availability for scripts). Statistical model details are reported in Appendix S1.

To measure affect changes, participants' average ratings of the six VAS items were submitted to a 2 (Time: pre- versus post-film) × 2 (Group: sleep versus sleep deprivation) mixed ANOVA.

For the lab-based intrusion task, we employed a Poisson generalized linear mixed model (GLMM) to analyse the total number of intrusions, using group and gender as predictors, and participants as a random intercept, with significant baseline individual differences controlled.

For 1-week intrusion diary, we used a Poisson GLMM to analyse the total number of intrusions during the week. Group, day and gender were entered as predictors. Baseline differences were scaled and entered as covariates, with participants entered as a random intercept. For participants who experienced at least one intrusion during the week, we further calculated averaged distress and vividness ratings by dividing the sum of ratings by the total number of intrusions, followed by multiple linear regressions with group and gender as predictors and baseline individual differences as covariates. The timing of intrusions (i.e. morning/afternoon/evening) was analysed in a chi-square test to examine whether sleep/sleep deprivation may differentially influence the timing of intrusion.

For voluntary recognition, we used a signal detection approach to calculate each participant's memory sensitivity [$d' = Z(\text{Hit}) - Z(\text{False Alarm})$] and response biases [$C = -(Z(\text{Hit}) + Z(\text{False Alarm}))/2$]. Hit refers to the proportion of "old" response to old pictures, and false alarm refers to the proportion of "old" response to new pictures. Higher values of d indicate more sensitive discriminations between old and new stimuli; higher values of C indicate more stringent response criteria in giving "old" responses (i.e. less likely to judge pictures as "old"; Macmillan & Creelman, 2005). Both d' and C were submitted to 2 (Group: sleep versus sleep deprivation) × 2 (Time: 12 hr versus 7 day post-trauma) × 2 (Valence: negative versus neutral) mixed ANOVAs. We next analysed voluntary recognition at item-level through a binomial GLMM, using item-level accuracy data (1 = correct; 0 = incorrect). Group, Time, Valence, Picture status (old versus new) and their interactions were used as predictors. Participants and picture stimuli were entered as random intercepts to control for individual differences and idiosyncratic features of individual pictures. Lastly, we performed mixed-effects ordinal logistic regression analyses on confidence and fearful ratings, with group and gender as predictors, and baseline differences as covariates (Appendix S1).

To directly compare the impact of sleep on involuntary intrusions and voluntary recognitions, we standardized the total number of intrusions from diary and d's from the 12-hr recognition test across all participants within each measurement (Lau-Zhu et al., 2019). These scores were submitted to 2 (Group: sleep versus sleep deprivation) × 2 (Measurement: voluntary versus involuntary memory) mixed ANCOVAs with significant baseline individual differences as covariates.

To examine individual differences, we ran correlations between participants' baseline sleep quality (Pittsburgh Sleep Quality Index [PSQI]; Buysse et al., 1989), prior trauma exposure (Trauma Experience Questionnaire [TEQ]; adapted from Foa, 1995) and diary-based intrusions within sleep and sleep deprivation groups, separately. Differences of correlation coefficients were examined using Fisher's z tests.

3 | RESULTS

Descriptive statistics are reported as mean ± standard deviation unless stated. Demographic and questionnaire scores are presented in Table 1. Correlations between baseline and outcome measures are presented in Appendix S1. No baseline group differences were found, except for the reappraisal subscale from the Thought Control Questionnaire (TCQ; Wells & Davies, 1994) and the perspective taking subscale from the Interpersonal Reactivity Index (IRI; Davis, 1983). These two scores were thus controlled in subsequent analyses. Overall, participants in the sleep group slept for 6.73 ± 0.89 hr (7.45 ± 1.03 hr reported in sleep diary) the night after the experimental trauma (Table 2). Effect sizes, estimated group

differences and their 95% confidence intervals (CIs) are presented in Table 3.

3.1 | Affect changes

The mixed ANOVA on average VAS ratings showed that watching trauma films significantly enhanced negative affect: pre- versus post-film: 24.48 ± 24.70 versus 48.44 ± 26.08; $F_{1,57} = 79.55$, $p < .001$, $\eta_p^2 = 0.58$. Neither group effect nor the interaction was significant ($F < 1.17$, $p > .283$).

3.2 | Lab-based intrusion monitoring task

Two participants from the sleep group reported 27 and 43 intrusions, and were excluded because their data fell 3 *SD*s above the group means (5.18 ± 6.88). We found a marginally significant group difference, such that sleep led to fewer intrusions than sleep deprivation ($\beta = -0.24$, $z = -1.67$, $p = .096$, Cohen's $d = -0.17$; Figure 2a). No other effects were significant ($p > .112$). Results were robust against over-dispersion and zero-inflation ($p = .944$ and $p = .664$). Analyses with the exclusion of 3 median absolute deviations (MAD) similarly showed marginally significant group differences ($p = .084$); but analyses without exclusion showed insignificant group differences ($p = .443$; see Appendix S1).

3.3 | Diary-based involuntary intrusions over 1 week

Self-reported diary accuracy did not differ between groups ($p = .310$). Two independent raters, who were blind to experimental conditions, rated the 96 intrusion records and excluded ones not counted as intrusion or were from the film. Inter-rater reliability is high: Cohen's Kappa = 0.93, $p < .001$. For inconsistent ratings ($n = 2$), a third rater was involved to reconcile the inconsistencies. Of 96 intrusions, 81 (84.38%) were included in the analyses.

Diary- and lab-based involuntary intrusions were highly correlated ($r_s = .52$, $p < .001$). We found post-trauma sleep significantly reduced involuntary intrusions compared with sleep deprivation ($\beta = -0.46$, $z = -2.52$, $p = .012$; Cohen's $d = -0.32$; see model results in Table 4 and Figure 2b), with involuntary intrusions significantly declined over time for both groups ($\beta = -0.46$, $z = -6.46$, $p < .001$; Figure 2c). Female participants reported more intrusions than male participants (1.46 ± 1.64 versus 1.00 ± 1.41; $\beta = 0.38$, $z = 2.03$, $p = .043$). Again, the model was robust against over-dispersion ($p = .232$) and zero-inflation ($p = .640$).

Day-by-day analyses revealed marginally significant group differences from Day 2 to Day 5 ($0.069 \le p \le .094$; Appendix S1), suggesting the benefits of sleep in reducing intrusions were evident days after sleep/sleep deprivation manipulations (Figure 2c).

Regression analyses with self-reported distress and vividness among participant-reported intrusions during the week (sleep: $n = 15$; deprivation: $n = 20$) showed no group differences in either distress or vividness ($p > .518$). Female participants reported higher distress levels than male (3.91 ± 2.00 versus 1.66 ± 1.09; $\beta = 0.96$, $t = 2.66$, $p = .012$), while no gender effect was found in vividness ($p = .387$).

The timing of the intrusions did not differ across two groups ($\chi^2(2) = 0.76$, $p = .685$).

3.4 | Voluntary recognitions

Descriptives are presented in Table 5. Two participants' d' values were excluded because they exceeded mean ± 3 *SD*s.

We found a marginally significant group effect on d' ($F_{1,56} = 3.06$, $p = .086$, $\eta_p^2 = 0.052$): the sleep group exhibited relatively higher sensitivities than sleep deprivation with a moderate effect size (Cohen's $d = 0.48$). We also found a significant time effect ($F_{1,56} = 19.03$, $p < .001$, $\eta_p^2 = 0.25$), such that memory sensitivity declined over time. No other effects were significant ($p > .163$; see Appendix S1 for discussions of the absence of Valence × Group interaction). Note that analyses with 3MAD exclusion and without exclusion yielded no significant group differences ($p = .165$, $p = .178$; Appendix S1).

The same ANOVA on *C* revealed a significant group effect ($F_{1,58} = 4.83$, $p = .032$, $\eta_p^2 = 0.077$): sleep led to more stringent response biases in responding "old" than the sleep deprivation (Cohen's $d = 0.53$). Again, a significant time effect showed that responses became more stringent over time ($F_{1,58} = 23.31$, $p < .001$, $\eta_p^2 = 0.29$). Consistent with previous studies (Dougal & Rotello, 2007), we found a significant valence effect ($F_{1,58} = 57.14$, $p < .001$, $\eta_p^2 = 0.50$), with more stringent response biases (fewer "old" responses) to neutral than to negative pictures. We found a marginally significant Valence × Group interaction ($F_{1,58} = 2.89$, $p = .095$, $\eta_p^2 = 0.047$):

TABLE 2 Data summary obtained from actigraphy in sleep group ($N = 29$)

	Sleep ($N = 29$)[a]
Averaged bed time	00:27
Averaged wake time	07:47
Duration in bed (min)	
Mean ± *SD*	440.69 ± 60.84
Sleep time (min)	
Mean ± *SD*	403.62 ± 53.68
Sleep latency (min)	
Mean ± *SD*	22.66 ± 37.32
Sleep efficiency (%)	
Mean ± *SD*	96.75 ± 3.67
Wake after sleep onset	
Mean ± *SD*	13.76 ± 15.97

[a]One participant failed to follow the instruction of using the actigraphy and thus was excluded from the summary.

TABLE 3 Descriptive values (mean ± *SD*), effect sizes (based on mean and *SD* of sleep and sleep deprivation groups) and the 95% CIs of estimated group differences

	Sleep	Sleep deprivation	Effect size	Estimated group difference [95% CI][a]
Diary-based intrusion	1.07 ± 1.46	1.57 ± 1.68	−0.32	−0.92 [−1.77, −0.15]
Lab-based intrusion[b]	3.82 ± 3.97	4.47 ± 3.69	−0.17	−0.48 [−1.16, 0.13]
$d'^{b,c}$	2.05 ± 0.52	1.82 ± 0.44	0.48	0.24 [−0.023, 0.49]
C^{c}	0.28 ± 0.39	0.09 ± 0.34	0.53	0.24 [0.042, 0.45]
IES-R Hyperarousal subscale	0.14 ± 0.24	0.42 ± 0.47	−0.76	−0.28 [−0.47, −0.10]

Abbreviations: CI, confidence interval; IES-R, Impact of Event Scale-Revised.

[a]Estimated group differences were obtained from models; 95% CI were obtained through bootstrap with 1,000 resamples. For IES-R hyperarousal, group mean difference was calculated with 95% bootstrap CI.

[b]After 3SD exclusion.

[c]Averaged from 12 hr and 7 days recognition tests.

compared with sleep deprivation, sleep group was more stringent in making "old" judgement with neutral pictures ($t_{73.6} = 2.65$, $p = .010$, Cohen's $d = 0.68$), but not with negative pictures ($t_{73.6} = 1.47$, $p = .146$, Cohen's $d = 0.29$). No other effects were significant ($p > .123$).

Item-level analyses without exclusion (Table 6) revealed a significant Group × Time interaction: sleep led to more accurate memory judgements than sleep deprivation in the immediate 12-hr recognition test ($z = 2.45$, $p = .014$), but not in the 7-day delayed test ($z = 0.58$, $p = .563$). We also observed a significant Group × Old/New interaction: sleep led to more accurate correct rejections to new pictures than sleep deprivation ($z = 3.26$, $p = .001$), but no group difference was found in old pictures ($z = -0.25$, $p = .804$). This interaction was quantified by a marginally significant Group × Valence × Old/New interaction ($\beta = -0.07$, $z = -1.95$, $p = .051$; Figure 2d): compared with sleep deprivation, the sleep group showed higher correct rejections to new neutral pictures ($z = 3.76$, $p < .001$), and to new negative pictures with a marginally significant effect ($z = 1.79$, $p = .074$). No group effect was found regarding old neutral ($z = -0.59$, $p = .554$) or old negative pictures ($z = 0.14$, $p = .888$).

3.5 | A direct comparison between involuntary and voluntary memories

The ANCOVA without any exclusion revealed a significant Group × Measurement interaction ($F_{1,56} = 6.61$, $p = .013$, $\eta_p^2 = 0.106$; Figure 2e): while the sleep group outperformed the sleep deprivation group in immediate voluntary recognition ($t_{112} = 1.84$, $p = .068$, Cohen's $d = 0.55$), the sleep group reported fewer involuntary intrusions in diaries ($t_{112} = -1.79$, $p = .076$, Cohen's $d = -0.32$). This interaction remained significant when averaging immediate and delayed d' ($F_{1,56} = 5.38$, $p = .024$, $\eta_p^2 = 0.088$), and when excluding the two potential outliers identified in d' analysis ($F_{1,54} = 5.68$, $p = .021$, $\eta_p^2 = 0.095$).

3.6 | Impact of Event Scale - Revised

Internal consistencies (Cronbach's alpha) for IES-R subscales were high: 0.70–0.79. Participants who slept reported significantly lower hyperarousal than sleep-deprived ones in a Wilcoxon rank-sum test ($W = 286$, $p = .008$, Cohen's $d = -0.76$; Figure 2f). No significant differences were found on other subscales (Table 7; $p > .222$).

3.7 | Individual difference analyses

We found that poorer sleep quality (higher PSQI scores) was associated with more diary-based intrusions in the sleep group ($r_s = 0.40$, $p = .029$), whereas the relationship was reversed in the sleep deprivation group ($r_s = -0.35$, $p = .060$). Fisher's z test revealed that sleep versus sleep deprivation significantly moderated this relationship ($z = 2.88$, $p = .004$; Figure 3a).

Sleep also significantly moderated the relationship between prior traumatic experience (TEQ scores) and diary-based intrusions ($z = 2.58$, $p = .010$; Figure 3b): while more trauma experience was associated with more diary-based intrusions in the sleep group ($r_s = 0.37$, $p = .045$), a reversed pattern was found in the sleep deprivation group ($r_s = -0.31$, $p = .101$). Given that there were no between-group differences in TEQ scores ($W = 413$, $p = .501$), this finding suggested that while prior traumatic experience is a vulnerable factor for subsequent intrusions, participants who were sleep-deprived would be particularly vulnerable to recent traumatic exposure even when they reported fewer prior traumatic experience.

4 | DISCUSSION

Employing the trauma film paradigm, we reported that compared with sleep deprivation, post-trauma sleep: (a) reduced involuntary intrusions; (b) enhanced voluntary recognitions; and (c) lowered emotional hyperarousal associated with traumatic memories. Thus, sleep exerted opposite impacts on involuntary and voluntary expressions of the traumatic memories, and attenuated affective responses to traumatic memories. Collectively, these data suggest that sleep in the early aftermath of trauma serves as an "overnight therapy" in protecting people's mental well-being from traumatic exposure.

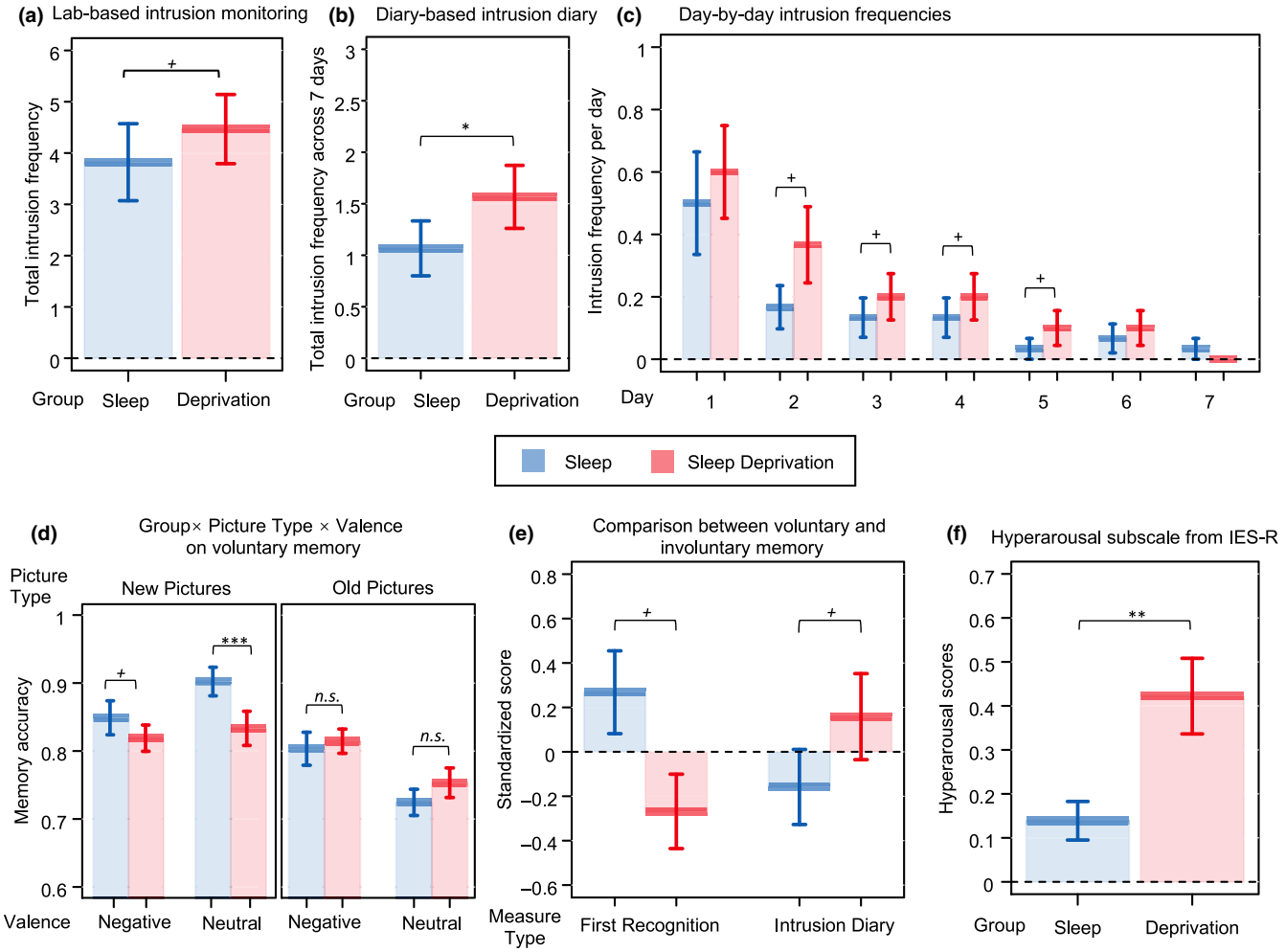

FIGURE 2 (a) Lab-based 5-min intrusion frequency between groups. Total intrusions reported during the intrusion monitoring task were calculated. The sleep group reported marginally lower lab-based intrusions compared with sleep deprivation. (b) Diary-based intrusion frequency during 1 week (Poisson generalized linear mixed model [GLMM] fitted). Intrusions were summed up across 7 days for each participant. The sleep group showed a significantly lower number of total intrusions than the sleep deprivation group. (c) Day-by-day intrusion for both groups. Overall, both groups showed a significant decline overtime. A marginal trend was observed from Day 2 to Day 5, suggesting the sleep group reported less intrusion than the sleep deprivation group (see details in Appendix S1). (d) Group × Picture Type × Valence on voluntary memory accuracy (binomial GLMM fitted). The sleep group showed superior accuracy in judging new pictures than the sleep deprivation group (especially neutral pictures). But no such effect was found in old pictures. (e) Direct comparison between involuntary intrusion (diary-based intrusion) and voluntary recognition (12 hr post-trauma). Standardized scores across both groups were obtained. Compared with sleep deprivation, the sleep group performed marginally better in the recognition task with relatively lower intrusion frequency reported during the following week. (f) The self-reported hyperarousal scores across groups. The sleep group scored significantly lower than the sleep deprivation group. $^{**}p < .01$; $^{*}p < .05$; $^{+}p < .1$; n.s.: non-significant

Among intrusion measures, we found a significant group difference in diary-based intrusion, consistent with most prior studies using trauma films (Kleim et al., 2016; Porcheret et al., 2019; Woud et al., 2018; but see Porcheret et al., 2015 for opposite results). According to the theoretical accounts of PTSD, excessive involuntary intrusions could be due to insufficient integration between highly salient traumatic memories and existing autobiographical memory framework (Brewin, 2001; Ehlers & Clark, 2000). Based on converging findings from ours and from previous studies (Kleim et al., 2016; Porcheret et al., 2019; Sopp et al., 2019a; Woud et al., 2018), we consider sleep provides a critical time window for system-level consolidation and integration to happen, which then reduces involuntary intrusions (Rasch & Born, 2013).

When analysing day-by-day intrusions, we observed marginal group differences on Days 2–5, with the sleep group reporting fewer intrusions than the sleep deprivation group (Appendix S1). This pattern was largely consistent with Kleim et al. (2016), who found benefits of sleep in reducing intrusion observed from Day 3 onwards. Nevertheless, Porcheret et al. (2015) reported that sleep led to more intrusions especially during the first few days. Inconsistencies could be due to procedural differences, such as participants in Porcheret et al. (2015) being kept in lab on the first day of intrusion diaries, whereas participants from Kleim et al. (2016) and ours went back to daily routines after sleep manipulations. Beyond group differences, our individual difference analyses showed that sleep

TABLE 4 The model summary of Poison generalized linear mixed model for diary-based involuntary intrusion

	β	Standard error	*z*-value	*p*-value
(Intercept)	−0.73	0.28	−2.60	.009**
Group (sleep versus sleep deprivation)	−0.46	0.18	−2.52	.012*
Day	−0.46	0.07	−6.46	< .001***
Gender (female versus male)	0.38	0.19	2.03	.043*
Reappraisal subscale	0.43	0.17	2.48	.013*
Perspective taking subscale	0.11	0.17	0.63	.528

Note: To analyse intrusion frequency, Group (sleep versus sleep deprivation), Day (1–7) and Gender (female versus male) were entered as fixed effect, with participant as a random effect.

*$p < .05$; **$p < .01$; ***$p < .001$.

manipulation significantly moderated the relationship between baseline sleep quality/prior trauma exposure and subsequent intrusions: in the sleep group, higher baseline sleep quality/fewer prior trauma exposure was associated with fewer intrusions; while the reverse was found among sleep-deprived participants. Together, these results highlight the protective role of sleep in reducing unwanted intrusions of traumatic memories.

As compared with its effect on involuntary intrusions, how sleep influences voluntary memory of trauma remained unclear. We found that sleep (versus sleep deprivation) led to more accurate memory recognitions. At an item-level, participants who slept were more accurate in rejecting new, unexperienced trauma-related stimuli; whereas sleep-deprived participants were more likely to judge new trauma-related stimuli as old. Signal detection analyses suggested that sleep shifted response criterion to be more stringent in judging stimuli as "old", whilst sleep-deprived participants exhibited a more liberal response bias especially for neutral pictures. These findings suggest that sleep deprivation led to impaired distinction between old and new stimuli (i.e. over-generalization; Menz et al., 2013). It is worth noting that Porcheret et al. (2019) reported that sleep increased accurate recognitions to old neutral but not to new neutral images, which could be due to the fact that Porcheret et al. (2019) only used neutral pictures, while we used both negative and neutral pictures in the recognition tests.

TABLE 5 Voluntary memory performance and ratings from both groups ($N = 60$; mean ± *SE*)

	Sleep ($N = 30$)	Deprivation ($N = 30$)		Sleep ($N = 30$)	Deprivation ($N = 30$)
Hit rate			False alarm		
Lab Session 3			Lab Session 3		
Negative	0.88 ± 0.02	0.87 ± 0.02	Negative	0.15 ± 0.02	0.19 ± 0.02
Neutral	0.80 ± 0.02	0.80 ± 0.03	Neutral	0.10 ± 0.02	0.18 ± 0.03
Lab Session 4			Lab Session 4		
Negative	0.73 ± 0.04	0.76 ± 0.02	Negative	0.15 ± 0.03	0.17 ± 0.03
Neutral	0.65 ± 0.03	0.71 ± 0.03	Neutral	0.10 ± 0.02	0.15 ± 0.03
	Sleep[a] (N = 29)	Deprivation[a] (N = 29)		Sleep (N = 30)	Deprivation (N = 30)
Memory sensitivity (*d'*)[a]			Memory bias (*C*)		
Lab Session 3			Lab Session 3		
Negative	2.60 ± 0.14	2.44 ± 0.17	Negative	−0.05 ± 0.10	−0.25 ± 0.11
Neutral	2.65 ± 0.18	2.08 ± 0.18	Neutral	0.40 ± 0.09	0.07 ± 0.10
Lab Session 4			Lab Session 4		
Negative	2.00 ± 0.14	1.85 ± 0.08	Negative	0.31 ± 0.12	0.17 ± 0.09
Neutral	2.03 ± 0.15	1.95 ± 0.18	Neutral	0.60 ± 0.09	0.32 ± 0.11
	Sleep ($N = 30$)	Deprivation ($N = 30$)		Sleep ($N = 30$)	Deprivation ($N = 30$)
Confidence rating			Fearful rating		
Lab Session 3			Lab Session 3		
Negative	4.07 ± 0.08	4.01 ± 0.09	Negative	2.48 ± 0.15	2.60 ± 0.14
Neutral	3.95 ± 0.08	3.96 ± 0.10	Neutral	1.82 ± 0.10	1.95 ± 0.12
Lab Session 4			Lab Session 4		
Negative	3.79 ± 0.10	3.85 ± 0.10	Negative	2.56 ± 0.16	2.50 ± 0.13
Neutral	3.79 ± 0.10	3.80 ± 0.12	Neutral	1.84 ± 0.11	1.76 ± 0.10

[a]Two participants were excluded as their scores fell beyond ±3 *SD*, resulting 29 in sleep and 29 in sleep deprivation group for memory sensitivity (*d'*).

TABLE 6 Model summary of binomial generalized linear mixed model for voluntary recognition

	β	Standard error	*z*-value	*p*-value
(Intercept)	1.90	0.14	13.21	< .001***
Group (sleep versus sleep deprivation)	0.13	0.08	1.68	.093+
Time (12 hr versus 7 days)	0.23	0.04	6.55	< .001***
Valence (negative versus neutral)	0.11	0.12	0.93	.350
Old/New (new versus old)	0.20	0.12	1.62	.105
Gender (female versus male)	−0.12	0.08	−1.62	.106
Reappraisal subscale	−0.05	0.07	−0.72	.471
Perspective taking subscale	−0.00	0.08	−0.05	.957
Group × Time	0.08	0.03	2.29	.022*
Group × Valence	−0.03	0.03	−0.97	.334
Time × Valence	0.04	0.04	1.12	.264
Group × Old/New	0.15	0.03	4.24	< .001***
Time × Old/New	−0.28	0.04	−7.94	< .001***
Valence × Old/New	−0.19	0.12	−1.54	.124
Group × Time × Valence	0.00	0.03	0.06	.951
Group × Time × Old/New	−0.02	0.03	−0.61	.541
Group × Valence × Old/New	−0.07	0.03	−1.95	.051+
Time × Valence × Old/New	−0.04	0.04	−1.26	.209
Group × Time × Valence × Old/New	0.00	0.03	−0.10	.918

Note: The correctness of the old/new judgement from the 120 trials of each participant was entered as the response variable (1: correct; 0: incorrect). Group (sleep versus sleep deprivation), Time (12 hr versus 7 days), Valence (negative versus neutral), Picture status (new versus old) and their interactions were entered as fixed effects (categorical predictors), with participant and individual pictorial stimuli as random effects. Gender, reappraisal and perspective taking subscale were entered as covariates. The table shows the model summary including coefficient β, standard error, *z*-value and their corresponding *p*-value.

*$p < .05$; ***$p < .001$; +$p < .1$.

TABLE 7 Results summary for IES-R from sleep versus sleep deprivation group ($N = 60$, mean ± *SE*)

	Sleep ($N = 30$)	Sleep deprivation ($N = 30$)	Tests
IES-R subscale			
Avoidance	1.04 ± 0.12	1.10 ± 0.13	$t_{58} = -0.37$, $p = .712$
Intrusion	0.43 ± 0.08	0.54 ± 0.08	$W = 369.5$, $p = .231$
Hyperarousal	0.14 ± 0.04	0.42 ± 0.09	$W = 286$, $p = .008$**
IES-R total mean			
Mean ± *SE*	1.61 ± 0.21	2.06 ± 0.26	$W = 367$, $p = .222$

Abbreviation: IES-R, Impact of Event Scale-Revised.

**$p < .01$.

Among emotional response measures, we found that sleep reduced hyperarousal based on IES-R, even when sleep led to more accurate recognitions of trauma-related stimuli. This finding complements previous results that sleep led to less distressful intrusions (Kleim et al., 2016), and supports the notion that sleep attenuates emotional responses of the memories (Cox et al., 2018; Cunningham et al., 2014; Van Der Helm et al., 2011). Enhanced explicit recognition and attenuated emotional response are largely consistent with the "sleep to forget, sleep to remember" hypothesis (Walker & van der Helm, 2009), which posits that sleep benefits the de-coupling of affective responses (i.e. forget) from emotional memories (i.e. remember).

Limitations and future directions should be noted. First, there were inconsistencies with different outcome measures and exclusion criteria. We observed a significant group difference in diary-based intrusion, but only marginally significant differences in lab-based intrusion, while no significant difference was found in the IES-R intrusion subscale. Furthermore, we found group differences on IES-R hyperarousal but not on fearful/distress ratings. Discrepancies could be due to different sensitivities of measurements in assessing the impacts of sleep manipulations on PTSD-like symptoms. For instance, intrusion diaries happened outside the laboratory across 7 days, which is arguably more ecologically valid than the intrusion monitoring task that happened immediately after sleep/sleep deprivation. At a procedural level, slept participants went back home while sleep-deprived participants stayed in the lab for the whole night, which might also introduce

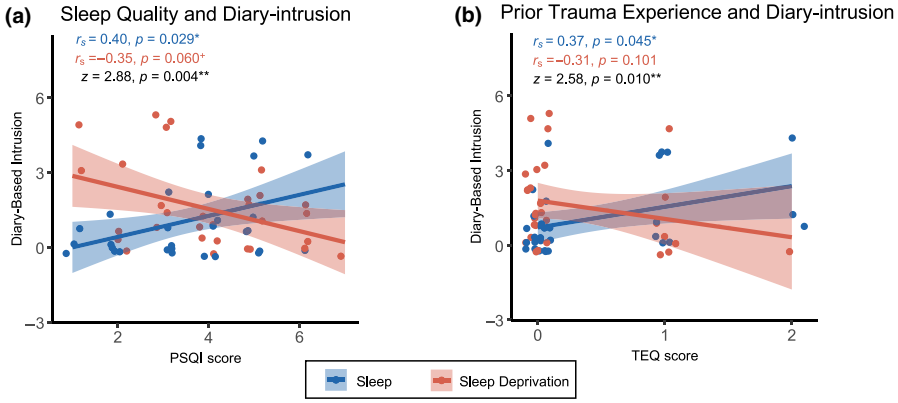

FIGURE 3 Correlations (in Spearman rho) between diary-based intrusion and (a) baseline subjective sleep quality, as measured by Pittsburgh Sleep Quality Index (PSQI) and (b) prior traumatic experience, as measured by Trauma Experience Questionnaire (TEQ). Corresponding Fisher's *z* tests were presented in black. $^{**}p < .01$; $^{*}p < .05$; $^{+}p < .1$

differences in post-trauma interference other than sleep manipulations. That being said, our results were largely consistent with a broader literature suggesting the protective role of sleep in reducing diary-based intrusions regardless of sleep environments (Kleim et al., 2016; Porcheret et al., 2019; Woud et al., 2018).

Second, somehow unexpectedly, the sleep group reported higher scores on the reappraisal subscale from the TCQ and perspective taking subscale from the IRI than the sleep deprivation group. Scores on these measures were positively correlated with intrusions (Appendix S1). However, our results and conclusions are unlikely undermined because: (a) we have controlled these measures in analyses; and (b) the sleep group actually reported fewer intrusions despite their higher scores on these two subscales.

Third, there were limitations with experimental materials and the robustness of the statistical results. To allow enough foil images in the old/new recognition tests, we chose homogeneous trauma films depicting traffic accidents, which could result in fewer diary-based intrusions (mean: 1.32 here) than previous studies using heterogeneous trauma films (e.g. 2.86 from Porcheret et al., 2015; 5.42 from Porcheret et al., 2019). Furthermore, the old/new picture sets were agreed by the two experimenters but were not rated by independent samples. Note that this concern was alleviated as idiosyncratic features of each picture were controlled in linear mixed models. Moreover, interpretation of marginally significant results (i.e. lab-based intrusions and *d′*) requires caution, as these differences became non-significant when statistical outliers were included. Future studies with larger sample sizes and preregistered analytical plans are warranted to replicate these results.

Finally, it remains unclear how exactly sleep benefits the processing of traumatic experiences. If reduced intrusions and enhanced recognition are indeed due to consolidation/integration processes, future studies will benefit from direct assessments/manipulations of sleep-based memory processes (Hu et al., 2020; Lewis & Bendor, 2019). Relatedly, research showed that spindles during NREM (Kleim et al., 2016) and 4–8 Hz theta activities during REM sleep were associated with reduced involuntary intrusions (Sopp et al., 2019b). Further investigations are warranted to explore how sleep-consolidation-related neural activities may modulate involuntary intrusions.

In sum, our results provided further evidence that sleep protects mental well-being from traumatic exposure, as evidenced by reduced involuntary intrusions, more accurate voluntary recognitions and lowered emotional hyperarousal. Importantly, these benefits emerged even when sleep-deprived participants resumed their routine sleep in subsequent nights, highlighting a crucial role of sleep in the early aftermath of trauma in attenuating PTSD-like symptoms. Our study bears both theoretical and clinical implications for understanding the protective role of sleep in processing traumatic memories, and provides novel insights into developing evidence-based interventions of trauma-related disorders.

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CONFLICT OF INTERESTS

The authors declare no conflict of interests.

AUTHOR CONTRIBUTIONS

SZ and XH conceptualized the study and designed the experiment. EYYL and SXL contributed to experimental designs. SZ conducted the study, analysed and interpreted the data under the supervision of XH. SZ and XH wrote the manuscript, with EYYL and SXL providing feedbacks to the manuscript. All authors approved the final manuscript.

DATA AVAILABILITY STATEMENT

Materials, scripts and data are available at: https://osf.io/tr3qb/

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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