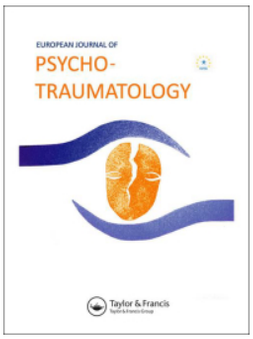

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Sleep and day-to-day PTSD symptom variability: an ecological momentary assessment and actigraphy monitored study in trauma-exposed young adults

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ABSTRACT

Background: Disrupted sleep and post-traumatic stress disorder (PTSD) are bi-directionally linked and have been found to mutually reinforce each other on a day-to-day basis. However, most of the previous research has focused on subjective measures of sleep only.

Objective: Here, we investigated the temporal relationship between sleep and PTSD symptoms using both subjective (sleep diary) and objective measures of sleep (actigraphy).

Methods: Forty-one non-treatment seeking, trauma exposed young adults (age $M = 24.68$, $SD = 8.15$) with a range of PTSD symptom severities (PTSS, 0–53 on PCL-5) were recruited. Participants completed two surveys per day over four weeks to measure day-time PTSD symptoms (i.e. PTSS and number of intrusions) and night-time sleep subjectively, while wearing an actigraphy watch to measure sleep objectively.

Results: Linear mixed models revealed that subjectively reported sleep disruptions were associated with elevated next-day PTSS and increasing number of intrusive memories both within and between participants. Similar results were found for daytime PTSD symptoms on night-time sleep. However, these associations were not found using objective sleep data. Exploratory moderator analyses including sex (male vs. female) found that these associations differed in strength between sexes but were generally in the same direction.

Discussion: These results were in line with our hypothesis with regards to the sleep diary (subjective sleep), but not actigraphy (objective sleep). Several factors which have implications on both PTSD and sleep, such as the COVID-19 pandemic and/ or sleep-state misperception, may be potential reasons behind those discrepancies. However, this study had limited power and needs to be replicated in larger samples. Nonetheless, these results add to the current literature about the bi-directional relationship between sleep and PTSD and have clinical implications for treatment strategies.

Sueño y variabilidad diaria de los síntomas del TEPT: Evaluación ecológica momentánea y estudio monitorizado por actigrafía en adultos jóvenes expuestos a trauma

Antecedentes: Las perturbaciones del sueño y el trastorno de estrés postraumático (TEPT) se encuentran bidireccionalmente asociados y se ha encontrado que se refuerzan mutuamente de forma diaria. Sin embargo, la mayoría de las investigaciones previas se enfocaron únicamente en medidas subjetivas del sueño.

Objetivo: Se investigó la relación temporal entre el sueño y los síntomas del TEPT empleando tanto medidas subjetivas (diario de sueño) como medidas objetivas (actigrafía).

Métodos: Se reclutó a 41 adultos jóvenes expuestos a trauma (edad $M = 24.68$, $SD = 8.15$) con diferente severidad de síntomas del TEPT (STEPT, 0–53 en el PCL-5) que no buscaban atención. Los participantes completaron dos encuestas al día durante cuatro semanas para evaluar la variabilidad diaria de los síntomas del TEPT (por ejemplo, STEPT y número de intrusiones) además del sueño nocturno de forma subjetiva, mientas que empleaban un reloj de actigrafía para evaluar el sueño de forma objetiva.

Resultados: Los modelos mixtos lineales mostraron que las perturbaciones del sueño reportadas subjetivamente estuvieron asociadas a una elevación de los STSS al día siguiente y a un incremento en el número de memorias intrusivas comparada tanto en los participantes con relación a su propia variabilidad de síntomas como en los participantes

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STEPT; intrusiones; trauma; EMA; actigrafía; diario de sueño; sexo

关键词
PTSS; 闯入; 创伤; EMA; 体动记录仪; 睡眠日记; 性

HIGHLIGHTS

- Elevated day-time PTSD symptom severity (PTSS) and more frequent intrusive memories were generally associated with subjectively reported disruptions in sleep and vice versa, but not with objective measures of sleep.
- While longer subjective sleep duration predicted reductions in PTSS and shorter sleep onset latency predicted reduced numbers of intrusions the next day, reduced daytime PTSS was only associated with reductions in distress associated with nightmares during the following night.
- Exploratory analyses showed that sex (men vs. women) moderated the bi-directional relationships between night-time sleep and day-time PTSD symptoms with longer sleep onset latency and lower sleep efficiency being related to worse PTSD symptoms the next day in women, but was not associated with men.

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entre ellos. Se encontraron resultados similares en relación con los síntomas del TEPT diurnos y el sueño nocturno. Sin embargo, estas asociaciones no se encontraron empleando datos objetivos de sueño. Los análisis exploratorios de moderación, incluyendo al sexo (masculino vs femenino), encontraron que estas asociaciones diferían entre sexos, pero generalmente presentaban la misma dirección de asociación.
Discusión: Estos resultados son acordes a nuestra hipótesis relacionada al diario de sueño (sueño subjetivo), pero no a la actigrafía (sueño objetivo). Existen diversos factores que tienen repercusión tanto sobre el TEPT como sobre el sueño, tales como la pandemia por la COVID-19 y una percepción alterada del estado de sueño, que podrían ser potencialmente la razón tras esta discrepancia. Sin embargo, el estudio tiene poder limitado y necesita ser replicado en muestras más grandes. No obstante, estos resultados se añaden a la literatura existente sobre la relación bidireccional entre el sueño y el TEPT, además de tener implicancias clínicas para las estrategias de tratamiento.

睡眠和日常 PTSD 症状变异性：一项针对创伤暴露年轻人的生态瞬时评估和活动记录监测研究

背景：睡眠障碍和创伤后应激障碍 (PTSD) 是双向关联的，并且被发现在日常生活中相互增强。然而，大部分前人研究只关注睡眠的主观测量。
目的：在这里，我们使用主观（睡眠日记）和客观睡眠测量（活动记录仪）考查了睡眠与 PTSD 症状之间的时间关系。
方法：招募了 41 名具有不同 PTSD 症状严重程度（PTSS，PCL-5 为 0-53）的非寻求治疗的创伤暴露年轻人（年龄 $M = 24.68$，$SD = 8.15$）。 参与者在四个星期内每天完成两项调查，以主观测量白天的 PTSD 症状（即 PTSS 和 闯入次数）和夜间睡眠，同时佩戴活动记录仪客观测量睡眠。
结果：线性混合模型显示，主观报告的睡眠中断与第二天 PTSS 升高以及参与者个体内和个体间的侵入性记忆数量增加有关。白天PTSD 症状对于夜间睡眠也发现了类似的结果。 然而，使用客观睡眠数据并未发现这些关联纳入性别（男性与女性）在内的探索性调节因素分析发现，这些关联在性别之间的强度不同，但通常方向相同。
讨论：这些结果符合我们关于睡眠日记（主观睡眠）的假设，但不符合活动记录（客观睡眠）。对 PTSD 和睡眠都有影响的几个因素，例如 COVID-19疫情和/或对睡眠状态的误解，可能是这些差异背后的潜在原因。 然而，本研究效应有限，需要在更大的样本中进行重复。尽管如此，这些结果增加了睡眠和 PTSD 之间双向关系的现有文献，对治疗策略具有临床意义。

1. Background

Post-traumatic stress symptoms commonly develop in response to the experience of a traumatic event and symptoms include intrusions (i.e. recurring involuntary, distressing memories of the traumatic event including flashbacks and nightmares), avoidance of trauma-related reminders, alterations in cognition and mood, and hyperarousal including restlessness or sleeplessness (American Psychiatric Association, 2013). A formal diagnosis for post-traumatic stress disorder (PTSD) can be made if PTSD symptoms persist over at least one month and are associated with clinically significant impairment and distress. However, rather than being steady, PTSD symptom severity (PTSS) may fluctuate systematically on a daily basis in individuals with PTSD (Biggs et al., 2019; Schuler et al., 2021). Understanding the causes of these fluctuations may be important in understanding the maintenance and progression of the disorder.

Prior studies investigating the daily dynamic variations of PTSS have shown greater daily fluctuations in negative affect in individuals with PTSD as compared to healthy controls (Dornbach-Bender et al., 2020) as well as circadian patterns in the occurrence of intrusive memories (Rosi-Andersen et al., 2022). Heightened PTSS are associated with a variety of negative health outcomes including increased substance use (Buckner et al., 2018; Possemato et al., 2015), affective symptoms (Dornbach-Bender et al., 2020; Greene, 2021; Van Voorhees et al., 2018), and disrupted sleep (Slavish et al., 2022).

Sleep disturbances and PTSD have high levels of comorbidity. Up to 90% of individuals with PTSD have difficulties initiating and/or maintaining sleep and experience nightmares related to the trauma (Cox & Olatunji, 2020; Harvey et al., 2003; Ohayon & Shapiro, 2000). Sleep disturbances not only contribute to the development and maintenance of PTSD, but also impact the recovery from trauma (Germain et al., 2008; Koffel et al., 2016). Now, disturbed sleep is recognised as a core symptom of PTSD and the two are found to mutually reinforce each other (Germain, 2013; Spoormaker & Montgomery, 2008). Prior studies have found that increasing PTSS are immediately associated with shorter sleep duration (Dietch et al., 2019), worse sleep quality (Dietch et al., 2019; Short et al., 2018) and nightmares (Short et al., 2018) during the subsequent night's sleep, with some inconsistencies in the literature (DeViva et al., 2020; Hruska & Barduhn, 2021). Further, sleep disruptions during the night, including shorter sleep duration

(Biggs et al., 2020; DeViva et al., 2020; Dietch et al., 2019), greater numbers of nocturnal awakenings (Biggs et al., 2020), lower sleep efficiency (Short et al., 2017) and worse sleep quality (Biggs et al., 2020; Short et al., 2017), predicted increasing PTSS during the following day. All the above-mentioned studies used questionnaire-based, subjective measures of PTSS and sleep including sleep diaries. Interestingly, objective evidence of disrupted sleep in PTSD using wrist-worn actigraphy or polysomnography (PSG) is seldom congruent with subjectively reported sleep issues (Lewis et al., 2020; Rezaie et al., 2018). However, whether the abovementioned associations between subjective sleep and PTSD can also be found in objective measures of sleep is yet to be investigated. A recent study in a large, non-clinical sample of young adults looking at the bi-directional relationship between sleep and stress found that greater daytime stress was associated with both sleep diary- and actigraphy-measured shorter sleep duration. Similarly, lower sleep efficiency and shorter sleep duration derived from both subjective and objective sleep measures, in turn, predicted higher next-day stress levels (Yap et al., 2020). These findings are yet to be translated onto PTSD symptoms in trauma-exposed individuals.

One of the core features of PTSD are intrusions. Individuals with previous trauma-exposure may experience multiple intrusions per day (Kleim et al., 2013), but the specific impact of sleep on the occurrence of intrusions is not well established. Experimental studies using analogue trauma (i.e. distressing video clips with traumatic content such as interpersonal violence) found that sleep compared to wakefulness after viewing the trauma film reduced the overall number of intrusions (Davidson & Marcusson-Clavertz, 2023). Wakefulness, on the other hand, may reduce the occurrence of intrusions immediately after the experiment, but increase the number of intrusions over time (Azza et al., 2020). Emerging evidence suggests that intrusions are associated with reduced sleep quality the following night and shorter sleep duration in turn is related to distress associated with intrusions (Dietch et al., 2019). However, the cumulative effect of increasing numbers of intrusions on sleep and their relationship on a day-to-day basis is yet to be studied.

Over the recent years, biological sex has been found to be an important factor influencing both PTSD and sleep, as well as their relationship (e.g. Kobayashi et al., 2007; Richards et al., 2022; Schenker et al., 2021; Schenker et al., 2022; Zhang et al., 2019). Women are at greater risk of developing PTSD after trauma exposure (Blanco et al., 2018; Felmingham et al., 2010), and are also more likely to report subjective sleep disturbances (Suh et al., 2018), despite lacking objective evidence of disrupted sleep (Mong & Cusmano, 2016). In PTSD using objective measures of sleep recording, sleep duration was found to be shorter in male patients (Kobayashi et al., 2007), while wake after sleep onset (WASO) was longer in female patients compared to controls (Zhang et al., 2019). Using subjective sleep measures, sex differences in the sleep-PTSD relationship are less studied. Some of the few publications found greater subjective sleep disturbances in general and lower sleep quality to be related with higher PTSS in men, while sleep disturbances specifically due to nightmares were associated with higher PTSD severity in women (Gibson et al., 2017; Kobayashi & Delahanty, 2013). Despite some studies including sex as a covariate to account for sex differences (e.g. Dietch et al., 2019; Yap et al., 2020), the role of sex on the sleep-PTSD relationship has not yet been explored and is still not well understood, especially on a day-to-day basis.

Taken together, there is currently a lack of studies investigating the day-to-day associations between sleep and PTSS using both subjective and objective measures of sleep within trauma-exposed individuals. In addition, no study to our knowledge has investigated the moderating role of sex on bi-directional daily relationships between PTSS and subjective or objective sleep.

1.1. Aim and hypotheses

This study investigated the relationship between day-to-day PTSS variability and sleep in non-treatment seeking, trauma-exposed young adults with a range of PTSS using both subjective and objective measures. We hypothesised that based on the previous literature (1) greater subjective sleep disruptions including shorter total sleep time (TST), longer sleep onset latency (SOL), greater number of awakenings after sleep onset, lower sleep efficiency, and/or lower sleep quality to predict more next-day PTSD symptoms (i.e. higher daily PTSS and/or greater number of intrusions), and (2) more PTSD symptoms (i.e. higher daily PTSS and/or number of intrusions) would predict greater sleep disruptions including TST, sleep quality and/or nightmares during the following night. Further, we hypothesised that (3) the same associations can be found using objectively measured actigraphy sleep data. Lastly (4), exploratory analyses investigated whether these associations were uniquely moderated by sex (men vs. women).

2. Methods

2.1. Participants

Participants were recruited through student portals and flyers at the University of Melbourne, Australia and were provided with a link to an anonymous online screening survey. Eligible participants (between 18 and 50 years of age and previously trauma-exposed)

were offered the opportunity to participate in the EMA part of the study and were screened for further exclusion criteria. Overall, 764 completed the baseline survey and 478 met the initial inclusion criteria. 193 participants accepted the offer to take part in the EMA study, but 66 of those met one or more exclusion criteria. Reasons for exclusion were current shift work and/or experiencing recent jetlag, consumption of illicit drugs and/or prescription drugs that interact with sleep (e.g. benzodiazepines, selective serotonin reuptake inhibitors), neurological deficits (e.g. epilepsy), psychotic, suicidal, or bipolar disorders, living outside of Victoria (Australia), not owning a smartphone and/or not willing to download the EMA app, no regular internet access to upload the EMA data and currently in treatment and/or treatment-seeking. 127 participants were eligible and contacted about the EMA part and 41 participants completed the study. The study was approved by the University of Melbourne Human Ethics Committee (ID 14544) and participants were provided with a plain language statement as well as informed consent prior to completing the screening survey.

2.2. Measures

Participants completed validated questionnaires during the baseline assessment as well as during the EMA part of the study.

2.2.1. Trauma Exposure Questionnaire (TEQ)

The TEQ (Vrana & Lauterbach, 1994) is a short checklist recording whether participants have ever experienced a trauma from a list of common criterion A events according to the DSM (e.g. actual or threatened death, serious injury, sexual violence; APA, 2013). Participants indicated if they have experienced these traumas ('yes' or 'no').

2.2.2. PTSD Checklist for DSM-V (PCL-5)

The PCL-5 is a screening tool for probable PTSD assessing the presence and severity of 20 symptoms over the past month which map onto DSM criteria (APA, 2013; Weathers et al., 2013). Participants indicated how bothered they were by each symptom on a scale between 0 ('not at all') and 4 ('extremely'). PTSD diagnosis is probable if the total score is ≥33 (Weathers et al., 2013). For the EMA part, participants completed an adaptation of the PCL-5 with instructions changed from 'in the past month' to 'today'. The daily PTSS score was calculated as the sum of the PCL-5 items excluding the two sleep-related questions (based on previous research: Biggs et al., 2020; Dietch et al., 2019; Gibson et al., 2017; Short et al., 2017). The distress rating due to nightmares (PCL-5 item number 2) was included to test the bi-directional relationship between nightmares and daytime PTSD symptoms.

2.2.3. Pittsburgh Sleep Quality Index (PSQI)

The PSQI is a 19-item questionnaire assessing self-reported sleep over the past month (Buysse et al., 1989). The item scores form seven components indicating difficulties in different aspects of sleep and their sum creates the global score, ranging from 0 ('no difficulties') to 21 ('severe difficulty in all areas'). Global scores above the cut-off of 5 indicate poor sleep (Grandner et al., 2006).

2.2.4. Insomnia Severity Index (ISI)

The ISI is a 7-item questionnaire assessing the self-reported severity of insomnia symptoms during the past two weeks. Each item is scored on a scale from 0 to 4 and the sum score of 15 or higher indicates clinically significant insomnia symptoms (Bastien et al., 2001).

2.2.5. Depression Anxiety and Stress Scale (DASS-21)

The DASS-21 is a 21-item, self-report questionnaire measuring different symptoms associated with depression, anxiety and stress. On a scale from 0 ('not at all') to 3 ('very much or most of the time'), participants rate how often or how strongly they experienced symptoms associated with these domains (i.e. depression, anxiety, or stress) over the past week. The sum score within each domain gives an indication on the current symptom load and range between 'normal' and 'extremely severe' (Henry & Crawford, 2005).

2.2.6. Alcohol Use Disorder Identification Test (AUDIT)

The AUDIT is a 10-item self-reported screening tool assessing alcohol consumption and alcohol-related problems including harmful drinking and potential alcohol use disorder. The questions are scored between 0 and 4 with a maximum sum score of 40. Zero indicates abstinence from drinking. Scores above 8 or 15 indicate hazardous drinking and potential alcohol dependence, respectively (Saunders et al., 1993).

2.2.7. Sleep diary

Participants completed a short version of the consensus sleep diary every morning for the duration of the EMA part of the study (Carney et al., 2012) and item number 2 of the PCL-5 (Weathers et al., 2013). From the diary entries, total time in bed (TIB, time between bedtime and get up time), TST (time between sleep time and wakeup time minus any time awake afterwards), SOL, number of awakenings, WASO, sleep efficiency (calculated as TST/ TIB * 100%), subjective sleep quality (5-point Likert scale ranging from 0 = 'very poor' to 4 = 'very good') and distress due to nightmares (5-point Likert scale ranging from 0 = 'not at all' to 4 = 'extremely') were exported.

Generally, sleep efficiency ≥ 85% is considered as good sleep (Baglioni et al., 2014; Kryger et al., 2022). To compare sleep efficiency with the algorithm used to analyse the watch data (see below), a second sleep efficiency was calculated here using the 'sleep period time' or time between sleep time and wake-up time as the denominator (van Hees et al., 2019). Here, TST, SOL, sleep efficiency, sleep quality, number of awakenings and nightmare distress were included into the models based on the hypotheses. Supplementary Table S.1 includes all sleep diary items and response options.

2.2.8. Daytime diary

Participants completed the adapted PCL-5 daily and the PTSS score was calculated as described above. To assess the number of intrusions, participants additionally reported on a scale of 0 ('None') to 11 ('More than 10'), how many intrusions of previous traumatic events they experienced during the day. Participants were instructed that 'intrusions are sudden, unwanted memories or flashbacks' of a previous traumatic experience (supplementary Table S.2)

2.2.9. Actigraphy

Actigraphy data were collected using GENEActive Original wearables (Activeinsights Ltd, 2019) and configured using GENEActive PC Software (version 3.3, ActiveInsights Ltd, 2019). The measurement frequency was set to 20 Hz, and the measurement period was 30 days. Upon completion of the study, raw data was extracted using GENEActive PC Software (version 3.3, ActiveInsights Ltd, 2019). The data was then analysed using the GGIR algorithm in R (van Hees et al., 2019, see below). The algorithm has been found to have high accuracy compared to PSG (84%) and high sensitivity to detect sleep (93%), but lower specificity to detect wakefulness (20%; Plekhanova et al., 2022).

2.3. Design

The screening survey was conducted using Qualtrics and included the TEQ, PCL-5, DASS-21, PSQI, ISI, AUDIT and demographic variables including age and sex. After enrolment into the EMA part of the study, participants downloaded the Smartphone Ecological Momentary Assessment version 3 (SEMA3) app (Koval et al., 2019) and were posted a GENEActive watch (Activeinsights Ltd, Kimbolton, UK). Participants were instructed about the nature of the study, including the completion of two daily surveys, and wearing the actigraphy watch as much as possible during both day and night starting from the first day of data collection. The first EMA survey (sleep diary) was randomly scheduled to prompt participants between 6 and 7 am and they had the opportunity to complete the survey for the following 360 minutes (i.e. if they were prompted at 6 am, the survey was available to them until 12 am). The second EMA survey (daytime diary) was randomly scheduled to prompt them between 7 and 9 pm with a 180-minute expiry window. While adherence to the EMA surveys was constantly monitored, the watch data was extracted once returned upon completion of the study. Participants received $100 AUD in supermarket gift vouchers as remuneration if survey completion rate was above 50%. Watch compliance was not considered because of some issues with recording. Due to high compliance, all data were included in the present analysis.

2.4. Statistical analysis

Baseline demographic data and sample characteristics were analysed using Welch *t*-test (or Wilcoxon rank sum test where assumptions were not met). The hypotheses were tested using linear mixed models (LMM) or generalised linear mixed models (GLMM), depending on the model fitted (Tabachnick & Fidell, 2007). Separate models were run for each sleep and PTSD variable. Predictors (fixed effects) were included as person mean-centered values to account for the within-person variability and included as grand mean-centered person means to account for between person variability. Participants were included as random effects with random intercept (Brown, 2021; Kleiman, 2017). Models were built using first-order autoregressive covariance structure with maximum likelihood estimation. For models testing the number of intrusions or number of awakenings as the outcome variable, GLMM were fitted using negative binomial distribution or Poisson distribution when dispersion parameters were large (Brooks et al., 2017). Skewed outcome variables were log-transformed (e.g. SOL). The models were run excluding outliers and compared to the full model. No meaningful difference was found; thus, the full models are presented here. Non-linear relationships were considered based on previous research (Porcheret et al., 2020), but visual check of model assumptions did not suggest non-linearity.

GENEActive data were analysed using the GGIR package (van Hees et al., 2019). The *Heuristic algorithm looking at Distribution of Change in Z-Angle* (HDCZA) was used to analyse the watch data as it has been validated to estimate sleep independently of a sleep diary (van Hees et al., 2018). Here, the HDCZA algorithm was used to compare whether the associations between sleep and daytime PTSD symptoms were in the same direction in the objective and subjective sleep (van Hees et al., 2018).

Sex was stepwise included into the model and its interaction with the within- and between-person factors were inspected to investigate their moderating

Table 1. Baseline demographics.

	Total ($n = 41$)				Male ($n = 10$)		Female ($n = 31$)		
	M	*SD*	Min	Max	*M*	*SD*	*M*	*SD*	p^a
Age	24.683	8.151	18	50	22.600	3.471	25.355	9.112	.842[b]
PCL-5	32.951	17.702	2	62	28.600	19.800	34.355	17.083	.423
PSQI	9.2195	4.096	2	16	8.700	4.138	9.387	4.137	.654
ISI	11.854	6.183	2	24	10.800	5.371	12.194	6.467	.507
DASS-D	6.049	4.074	0	15	4.300	3.529	6.613	4.129	.102
DASS-A	5.780	3.831	0	15	5.400	3.307	5.903	4.028	.697
DASS-S	7.976	3.678	0	17	7.100	3.695	8.258	3.688	.402
AUDIT	3.585	4.387	0	16	2.800	2.616	3.839	4.831	.988

Note: Mean (*M*), standard deviation (*SD*) and range. PCL-5: PTSD Checklist for DSM-5 PSQI: Pittsburgh Sleep Quality Index global score, ISI: Insomnia Severity Index, DASS: Depression (D), Anxiety (A) and Stress (S) Scale, AUDIT: Alcohol Use Disorder Identification Test.
[a]Welch *t*-test or [b]Wilcoxon rank sum to test differences between sexes.

effects. *Post-hoc* tests included estimating the slope for each factor of the moderators (male vs. female). All analyses were conducted in R (R Core Team, 2021) using the glmmTBM (Brooks et al., 2017) and emmeans (Lenth, 2021) packages.

3. Results

41 trauma-exposed individuals were included for the current study with baseline PCL-5 scores ranging from 2 to 62. Sleep quality based on the PSQI global score ranged from 3 to 17. 31 participants (aged 18–50) were biologically female (aged 18–50), and 10 participants (aged 18–27) were biologically male (none of the participants indicated their sex as 'other'). Baseline demographics and differences between male and female participants can be found in Table 1. Overall, female participants generally had higher mean scores on most measures, but the differences were not statistically significant compared to male participants. Together, participants were prompted 2296 times and completed 80.18% of the surveys during the study. Compliance rate for the sleep diary was 80.97% and 79.38% for the daytime diary. Participant's daily PCL-5 scores ranged between 0 and 53 and they experienced between 0 and 8 intrusions per day. See Table 2 for EMA descriptive statistics, as well as differences between male and female participants. Figure 1 visualises the average sleep duration form the sleep diary and watch. Plots including the PTSD symptoms and the remaining sleep variables can be found in supplementary Figures S.1–S.3.

3.1. Subjective sleep

3.1.1. Sleep predicting PTSD symptoms

Table 3 includes the results of the LMM with within- and between-person effect of TST, SOL, number of awakenings, sleep efficiency, and sleep quality derived from the sleep diary on daytime PTSS and number of intrusions. A significant within-person effect for TST showed that an increase of one hour of sleep during the night compared to the person's average TST, predicted a 0.421-point reduction (95% CI [−0.758, −0.084], $p = .014$) in PTSS (adapted PCL-5 score) the next day. A similar effects were found for SOL predicting intrusions. The expected log count for the number of intrusions the next day increased by 0.004 (95% CI [0.012, 0.797], $p = .032$) for every minute longer sleep onset latency. This means that there was a 3.63% increase in intrusions for every 10-minute increase in SOL, compared to the person's mean SOL. No other within-person sleep effect was significant.

Table 2. EMA variables.

		Total					Male		Female		
		M	*SD*	Min	Max	ICC	*M*	*SD*	*M*	*SD*	p^a
PTSD symptoms	PTSS (PCL-5)	12.800	13.486	0	53	.695	15.430	14.408	11.929	13.062	**<.001****
	No. intrusions	0.703	1.122	0	8	.542	0.691	1.200	0.707	1.096	.479
Sleep diary	TST (h)	7.149	1.966	0	13.917	.367	6.743	1.723	7.287	2.024	**<.001****
	SOL (mins)	20.594	32.660	1	360	.412	18.057	25.179	21.236	34.323	.230
	WASO (mins)	11.429	32.767	0	360	.349	10.327	39.798	11.799	30.067	**.046***
	NAwk	1.300	1.442	0	11	.414	1.041	1.043	1.387	1.544	**.024***
	SE (%)	92.705	12.078	0	99.867	.404	93.683	8.278	92.386	13.116	.149
	NMd	0.537	0.905	0	4	.431	0.441	0.869	0.570	0.915	**.011***
	SQ	1.615	1.030	0	4	.373	2.457	0.947	2.360	1.056	.272
Actigraphy	TST (h)	6.892	1.893	0.676	22.43	.284	6.581	2.227	6.999	1.753	**<.001****
	WASO (mins)	77.741	43.478	0	289.920	.263	80.382	37.140	76.477	45.423	**.020***
	NAwk	2.853	2.479	0	12	.275	3.203	2.447	2.739	2.480	**.009***
	SE (%)	84.533	7.145	48.872	100	.360	82.956	6.624	85.072	7.240	**<.001****

Note: Mean (*M*), standard deviations (*SD*) and range, TST: total sleep time, SOL: sleep onset latency, WASO: wake after sleep onset, NAwk: number of awakenings, SE: sleep efficiency, NMd: distress from nightmares (PCL item #2), SQ: sleep quality, ICC: intraclass correlation of unconditional model.
[a]Wilcoxon rank sum to test difference between male and female participants.
* $p < .05$, ** $p < .001$.

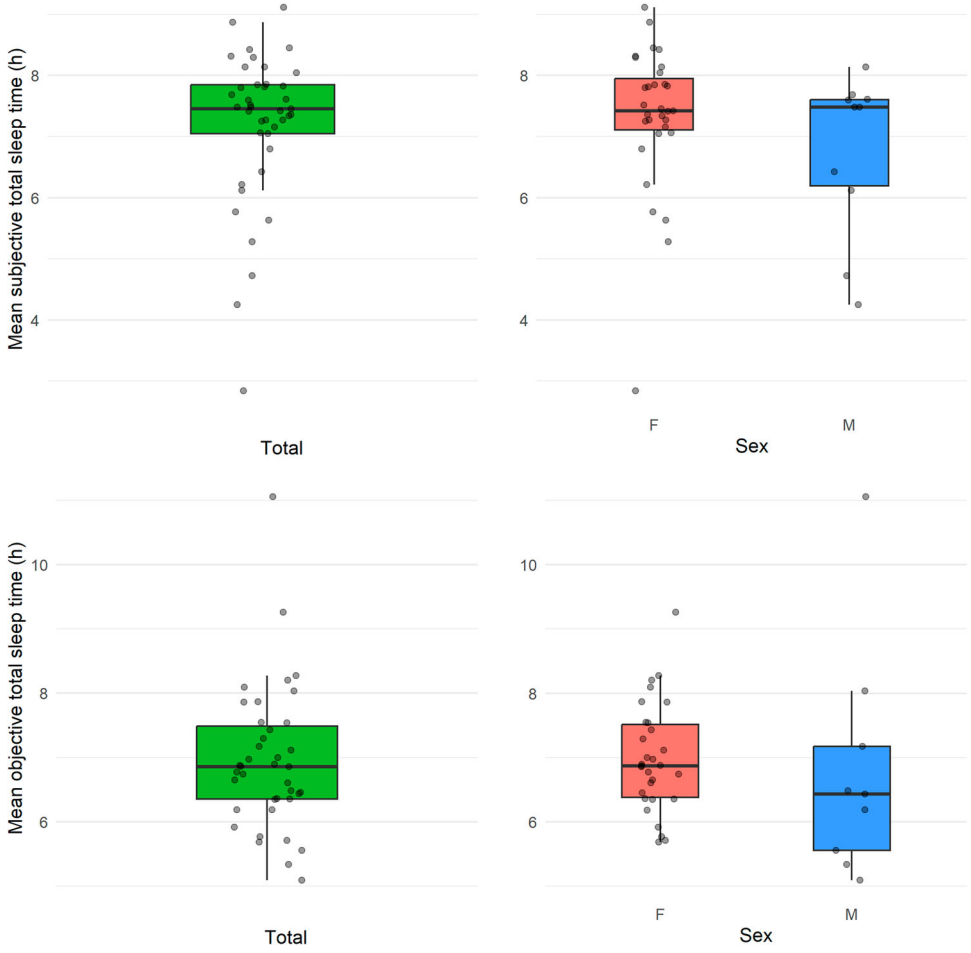

Figure 1. Boxplot of subjective (top) and objective (bottom) TST.

On the between-person level, fewer sleep disruptions (i.e. longer TST, shorter SOL and less nocturnal awakenings) and greater sleep quality (i.e. greater sleep efficiency and higher rated sleep quality) were significantly associated with reduced PTSS. For example, a 1-hour higher average TST compared to the grand mean was associated with significantly reduced PTSS by 5.801 points (95% CI [−7.785, −3.826], $p < .001$). Further, there was also a significant between-person effect for SOL, number of awakenings, sleep efficiency, and sleep quality. Similarly, generally better sleep on the between-person level (i.e. more TST, less awakenings, greater sleep efficiency and higher rated sleep quality than on average), was also associated with less intrusions.

3.1.2. PTSD symptoms predicting sleep

The only significant within-person effect was for PTSS to predict greater distress associated with nightmares during the following night (b = 0.011, 95% CI [0.004, 0.018], $p = .002$). No within-person effect was found for number of intrusions to predict changes in sleep. On the between-person level, however, increasing PTSS was found to predict shorter TST, greater distress from nightmares and lower sleep quality ratings. Similarly, a between-person effect of increasing number of intrusions was found to disrupt sleep including nightmares and sleep quality. LMM summaries can be found in Table 4.

Exploratory results including the remaining sleep variables are reported in the supplement (Tables S.3 and S.4). Across all models (sleep predicting PTSD symptoms and PTSD symptoms predicting sleep), there was high temporal autocorrelation in the residuals between days ($r > .90$).

3.2. Objective sleep

Actigraphy data of 39 participants were available. One participant's data was missing due to a malfunctioning device and another participant's data missing due to a technical issue. Some of the watches stopped recording earlier due to battery issues. Overall, 900 nights of valid actigraphy data were collected with 23.08 nights on average ($SD = 6.04$) per participant. Correlation matrices of the within- and between-person sleep variables (subjective and objective) can be found in the supplementary Figures S.4 and S.5.

3.2.1. Sleep predicting PTSD symptoms

No significant within-person effect was found for objectively measured sleep on either PTSS or number

Table 3. Subjective sleep variables (sleep diary) predicting PTSD symptoms.

	TST (h)	SOL (mins)	NAwk	SE (%)	SQ
PTSS					
within	**−0.421*** [−0.758, −0.084] $p = .014$	0.019 [−0.005, 0.044]	0.008 [−0.440, 0.455]	−0.052 [−0.108, 0.004]	−0.146 [−0.756, 0.464]
between	**−5.806**** [−7.785, -3.826] $p < .001$	**0.281**** [0.133, 0.428] $p < .001$	**5.097**** [2.000, 8.194] $p < .001$	**−0.824**** [−1.154, −0.493] $p < .001$	**−11.373**** [−15.022, −7.724] $p < .001$
Intrusion†					
within	−0.015 [−0.075, 0.046]	**0.004*** [0.000, 0.007] $p = .032$	0.017 [−0.058, 0.093]	−0.002 [−0.011, 0.006]	−0.005 [−0.116, 0.105]
between	**−0.423*** [−0.708, −0.138] $p = .004$	0.017 [−0.003, 0.037]	**0.404*** [0.012, 0.797] $p = .044$	**−0.057*** [−0.102, −0.012] $p = .013$	**−0.975**** [−1.530, −0.419] $p < .001$

Notes: Results are unstandardised regression coefficients [95% confidence interval]. PTSS: PTSD symptom severity (PCL-5), TST: total sleep time (hours), SOL: sleep onset latency (mins), NAwk: number of awakenings, SE: sleep efficiency (%), NMd: distress from nightmares (PCL item #2), SQ: sleep quality.
†Poisson or negative binomial distribution.
* $p<.05$, ** $p<.001$.

of intrusions the following day ($p > .05$). There was, however, a between-person effect for number of awakenings and sleep efficiency. Generally, less objectively measured awakenings were associated with both greater PTSS (b = −4.09 95% CI [−6.119, −2.062], $p < .001$) and number of intrusions (b = −0.023, 95% CI [−0.035, −0.009], $p < .001$). In addition, the between-person effect for sleep efficiency was only significant for predicting PTSS (b = 0.966, [0.325, 1.609], $p = .003$), not intrusions ($p = .077$). See Table 5 for LMM summaries. The associations between objective sleep and daytime PTSD symptoms were in the opposite direction compared to the subjective sleep.

3.2.2. PTSD symptoms predicting sleep

Neither PTSS, nor number of intrusions predicted changes in objectively measured TST on the within- and between-person level (see Table 6). Since the subjective perception of sleep (i.e. sleep quality) cannot be measured with the watch, sleep efficiency was included instead as the objective counterpart to sleep quality. Both between-person increase in PTSS, and higher numbers of intrusions predicted greater sleep efficiency ($p < .05$). Again, these results were not in the same direction compared to the subjective sleep measure.

Table 4. PTSD symptoms predicting subjective sleep variables (sleep diary)

		PTSS	Intrusions
TST (h)	within	0.003 [−0.017, 0.015]	0.097 [−0.014, 0.208]
	between	**−0.070**** [−0.10, -0.045] $p < .001$	−0.519 [−1.081, 0.043]
NMd	within	**0.011*** [0.004, 0.018] $p = .002$	0.040 [−0.012, 0.092]
	between	**0.034**** [0.021, 0.046] $p < .001$	**0.592**** [0.379, 0.805] $p < .001$
SQ	within	−0.000 [−0.008, 0.0085]	0.013 [−0.048, 0.076]
	between	**−0.039**** [−0.052, -0.026] $p < .001$	**−0.357*** [−0.642, -0.072] $p = .014$

Notes: Results are unstandardised regression coefficients [95% confidence interval]. PTSS: PTSD symptom severity (PCL-5), TST: total sleep time (hours), NMd: distress from nightmares (PCL item #2), SQ: sleep quality.
* $p<.05$, ** $p<.001$.

Similar to the subjective measure, residuals were highly autocorrelated. Exploratory results including additional sleep variables are reported in supplementary Tables S.5 and S.6. *Post-hoc* exploratory analyses investigated whether the different effects between the subjective and objective sleep measurements were due to diagnostic status (probable PTSD vs. no PTSD) at baseline and/or alcohol consumption during the measurement period. Neither explained these differences. Results can be found in supplementary Tables S.11–S.14.

3.3. Exploratory moderation analyses

3.3.1. Sex (male vs. female)

At baseline, there was no significant difference between male and female participants (Table 1). However, during the EMA part of the study, participants averaged PTSS and sleep differed between sexes (Table 2). Here, men had higher PTSS ($W = 92{,}801$, $p < .001$) and generally better sleep subjectively. Objectively, women slept better in general. Exploratory moderation analyses revealed that sex was a significant moderator in several models including subjective sleep on the within- and/or between-person level.

Table 5. Objective sleep variables (actigraphy) predicting PTSD symptoms.

		TST (h)	NAwk	SE (%)
PTSS	within	−0.237 [−0.551, 0.077]	−0.084 [−0.159, 0.328]	−0.056 [−0.145, 0.032]
	between	0.193 [−2.832, 3.217]	**−4.091**** [−6.119, −2.062] $p < .001$	**0.966*** [0.324, 1.608] $p = .003$
Intrusion†	within	−0.051 [−0.111, 0.008]	−0.002 [−0.053, 0.049]	−0.005 [−0.023, 0.012]
	between	−0.029 [−0.395, 0.338]	**−0.023**** [−0.677, −0.109] $p < .001$	−0.078 [−0.008, 0.164]

Notes: Results are unstandardised regression coefficients [95% confidence interval]. PTSS: PTSD symptom severity (PCL-5), TST: total sleep time (hours), NAwk: number of awakenings, SE: sleep efficiency (%).
†Poisson or negative binomial distribution.
* $p<.05$, ** $p<.001$.

Table 6. PTSD symptoms predicting objective sleep variables (actigraphy).

		PTSS	Intrusions
TST (h)	within	−0.003 [−0.013, 0.020]	0.116 [−0.013, 0.246]
	between	−0.000 [−0.042, 0.041]	−0.097 [−0.590, 0.396]
SE (%)	within	−0.023 [−0.083, 0.037]	−0.100 [−0.672, 0.472]
	between	**0.144*** [0.020, 0.269]	**1.236*** [0.134, 2.337]
		p = .023	p = .029

Notes: Results are unstandardised regression coefficients [95% confidence interval]. PTSS: PTSD symptom severity (PCL-5), TST: total sleep time, SE: sleep efficiency (%).
* p<.05.

Due to the small number of male participants, only the within-person effects are reported here. Looking at subjective sleep predicting next day PTSS, sex significantly moderated the association with SOL (b = 0.099, 95% CI [0.015, 0.183], p = .020), sleep efficiency (b = −0.195, 95% CI [−0.347, −0.043], p = .012) and sleep quality (b = −1.529, 95% CI [−3.049, −0.013], p = .048). *Post-hoc* tests revealed that in females, longer SOL and lower sleep efficiency than their averages were associated with higher PTSS the next day (SOL: b = 0.029 [0.002, 0.055], p = .028; sleep efficiency: b = −0.083, 95% CI [−0.143, −0.022], p = .007), while no association was found in males (p > .05). There was a significant interaction for sleep quality, but *post-hoc* tests did not find any significant effects within males or females (p > .05). SOL, sleep efficiency and sleep quality interactions are displayed in Figure 2.

Looking at how sex moderated the effect of PTSD symptoms on sleep, no significant interaction was found on the within-person level. Using the objective measure of sleep, none of the interactions reached significance. All moderation model summaries for sex can be found in the supplement including both the within- and between-person effects. Results of moderator analyses including the all sleep variables are reported in the supplement (Tables S.7a–S.10).

4. Discussion

The aim of this project was to investigate the influence of changes in day-to-day sleep on next-day PTSD symptoms and vice versa. As hypothesised, we found disrupted subjective sleep including shorter TST and longer SOL to be associated with increased PTSS (i.e. higher score on the PCL-5) and more intrusions during the next day, respectively. Additionally, those who slept worse overall experienced higher PTSD symptoms. This is in line with previous studies (Biggs et al., 2020; DeViva et al., 2020; Dietch et al., 2019; Short et al., 2017). However, unlike Hruska and Barduhn (2021), we did find that sleep efficiency predicted PTSD symptoms. Elevated day-time PTSS in turn predicted greater distress due to nightmares during the following night. Both higher PTSS and more intrusions were associated with disruptions in subjectively reported sleep in general, confirming our second hypothesis. Using actigraphy as an objective measure of sleep, results were either non-significant, or opposite to the subjective measures. None of the within-person associations reached significance. However, fewer objectively measured nocturnal awakenings and higher sleep efficiency (both aspects of less disrupted sleep) were associated with higher

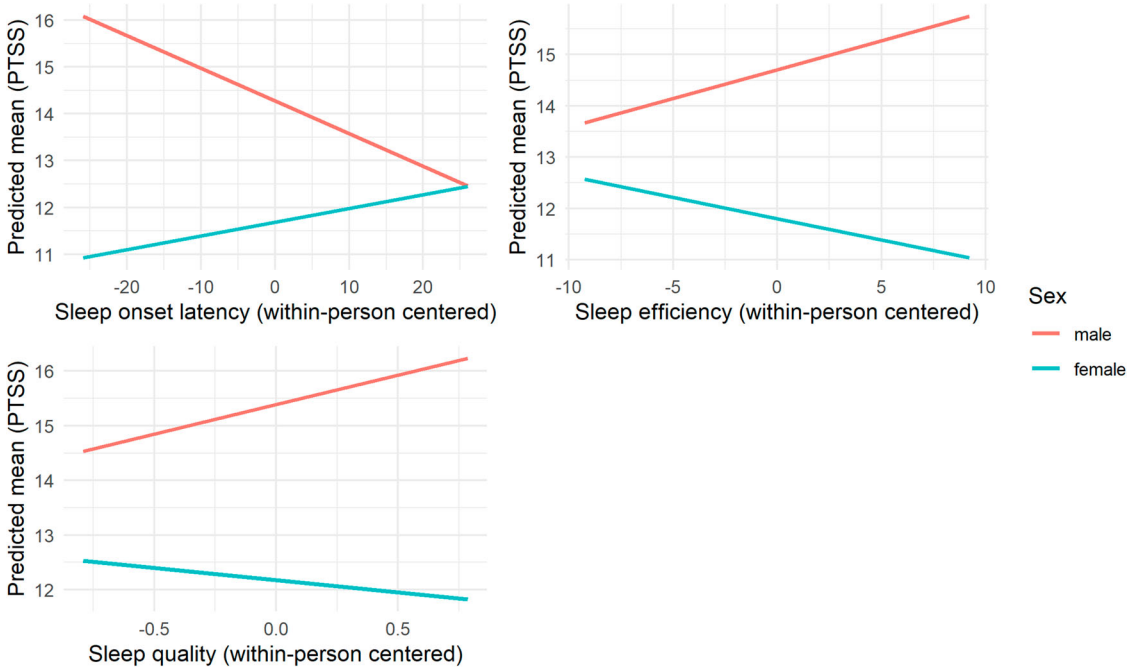

Figure 2. Estimated marginal means (slope) for significant interaction between subjective sleep and sex predicting PTSD symptom severity (PTSS).

PTSS and greater number of intrusions in general. Similarly, greater PTSS and more intrusions were associated with higher sleep efficiency. Neither diagnostic status at baseline nor alcohol consumption during the study sufficiently explained these incongruent findings. If these findings are true despite limited power, there are several potential reasons for these differences.

One factor that may have influenced the unexpected objective sleep results is the COVID-19 pandemic. During the data collection period between March and September 2021, participants were subject to several lockdowns as well as varying levels of pandemic-related restrictions including learning or working from home orders in Victoria, Australia. Studies investigating changes in objective sleep patterns have found that lockdowns were associated with longer sleep duration (Rezaei & Grandner, 2021; Sañudo et al., 2020). At the same time, the pandemic was commonly associated with decreased subjective sleep quality (Neculicioiu et al., 2022; O'Regan et al., 2021) as well as increased PTSD symptoms (e.g. Cao et al., 2022; Kalaitzaki et al., 2022; Rossi et al., 2020). However, there is some evidence which suggested that in those diagnosed with PTSD, PTSS reduced during periods of lockdown (Letica-Crepulja et al., 2022). Together, the pandemic-related restrictions during our data collection may be one explanation for the unexpected results that we found with regards to the objective measures.

Another factor potentially responsible for the divergent findings between objective and subjective sleep may be sleep state misperception (i.e. paradoxical insomnia, American Academy of Sleep Medicine, 2005), which is commonly observed in PTSD (Lewis et al., 2020; Rezaie et al., 2018). A recent study has found that increased sleep state misperception in a PTSD sample was associated with increased re-experiencing symptoms such as trauma-related nightmares (Arditte Hall et al., 2023). These findings could be translated to our study and provide an explanation for the unexpected association with the objective data. Increasing sleep state misperception may have aggravated daytime PTSD symptoms despite seemingly less disrupted sleep based on actigraphy. Future studies could investigate the role of sleep state misperception to further investigate the influence of sleep on PTSD symptoms as well as and differences in subjective and objective sleep using an EMA approach.

Overall, most of our results were significant on the between-person level and only a few significant effects were found with regards to within-person changes. In this sample of non-treatment seeking, trauma-exposed individuals with varying levels of PTSS, variability in sleep may only have a small effect on next-day PTSD symptoms or vice versa and may have been detected because of the long duration of this study. On the between-person level, those who generally slept worse subjectively experienced greater PTSS and more intrusions. While greater PTSD symptoms were also related to subjective sleep disruptions in general, sleep was less impacted by the number of intrusions. This is in line with previous research showing that the bidirectional relationship between sleep and PTSD is asymmetrical. Studies have found that targeted sleep interventions can reduce PTSD severity in clinical populations (e.g. Carlson et al., 2022; Talbot et al., 2014). Sleep on the other hand may be less affected by changes in PTSD symptoms (Gutner et al., 2013; Kartal et al., 2021; Walters et al., 2020). Therefore, the findings from our study is in line with the existing literature which suggests that treating sleep disturbance should be part of PTSD treatment or even treated initially before targeting PTSD symptoms specifically (Walters et al., 2020). However, our sample size was rather small and it has to be acknowledged that our findings have to be interpreted with caution, particularly for the between-person associations.

Exploratory moderator analyses found significant differences in the association between sleep and daytime PTSD symptoms between men and women, suggesting potential differences in those associations between sexes. This is consistent with our previous work which found sex differences in sleep to be related with extinction memories (Schenker et al., 2021; Schenker et al., 2022) and other studies investigating sex differences in PTSD (Gibson et al., 2017; Kobayashi & Delahanty, 2013; Richards et al., 2022; Zhang et al., 2019). Here, greater disruptions in sleep were directly related to worse PTSD symptoms the next day in women only, but no effect was found in men. Again, limited power particularly due to the small number of male participants demand a cautious interpretation of these findings. Nonetheless, these results highlight the importance of accounting for sex when studying sleep-related mechanisms in PTSD and necessitate more research in larger samples.

4.1. Limitations

There are several limitations to this study. First and foremost, this study had limited power due to the rather small sample size. This has implications on the results, meaning that the results have to be interpreted by caution due to an increased risk of type-II errors (Banerjee et al., 2009). Despite the skewed distribution of PTSD between men and women in the general population, this study included only a small number of male participants ($n = 10$). Even though the range in PTSS (men: 0–53, women: 0–52) and intrusions (men: 0–8, women: 0–7) were similar, this has implications on the interpretability of the findings.

Non-significant *post-hoc* findings in men do not necessarily indicate that there was no significant association, but that there might not be enough power to detect the absence of an effect. Future studies should include larger samples of male participants to replicate our findings. Similarly, this study only investigated whether there were differences between men and women and thus results cannot be generalised to any other gender. Sex hormones are known to be important in PTSD (Felmingham et al., 2010; Hsu et al., 2021; Li & Graham, 2017) and fluctuations in sex hormones (including external influence on those fluctuations, e.g. through hormonal contraception) is likely the underlying cause for the sex differences found in the sleep-PTSD relationship (Graham, 2022). In the present study, 18 women reported to have a regular menstrual cycle and 8 women indicated that they used hormonal contraception. While hormonal fluctuations were indirectly measured by tracking the women's menstrual cycle and collecting data across an average menstrual cycle (28 days), we could not account for it due to being underpowered. To investigate the day-to-day influences of sex hormones on the sleep-PTSD relationship, a sufficiently large sample should be included, and choice of hormonal birth control should be controlled for.

Next, this study only investigated the immediate effect of changes in sleep on PTSD symptoms or vice versa. For example, if an individual has fairly regular sleep, sporadic disruptions may have a less clinically significant impact on next-day PTSD symptoms compared to ongoing sleep disruptions. Disrupted sleep over multiple nights, however, may have a greater impact on daytime PTSD symptom changes (Van Dongen et al., 2003). Chronically disrupted sleep is commonly observed in PTSD and may therefore reinforce elevated daytime symptoms and perpetuate the disorder (Mascaro et al., 2021), rather than disruption in an isolated night. While there was some evidence here (i.e. lack of within-person effects but overall between-person effects), future studies could investigate the cumulative effect of disrupted sleep on PTSD symptoms to provide empirical support for this theory.

On a similar note, the present study assumed a linear relationship between changes in sleep and PTSD symptoms and vice versa. Previous research has found a non-linear relationship between sleep duration and the occurrence of intrusive memories (Porcheret et al., 2020). Very little and a lot of sleep were both related to a higher frequency of intrusions. There was no evidence for a non-linear relationship in our sample and limited power prevented exploratory analyses. Nonetheless, we cannot preclude non-linearity in a different (e.g. clinical sample with diagnosed PTSD) and/ or larger sample. Therefore, future research could consider such non-linear associations when including a sufficiently large number of participants.

Lastly, this study used actigraphy to measure sleep objectively. While accelerometers are a non-invasive and convenient way to estimate sleep, there are some limitations. Firstly, the algorithm used here cannot detect SOL without the use of a sleep diary (van Hees et al., 2019). Thus, not all subjective sleep variables could be assessed objectively. Further, the watch generally underestimated sleep efficiency and overestimated nocturnal awakenings compared to the sleep diary, which is in line with previous studies (Jenkins et al., 2022; Yap et al., 2020). While the algorithm used here has been found to provide equivalent sleep estimates to PSG, specificity to detect wakefulness in the sleep window is low as previously reported (Plekhanova et al., 2022). This means that sleep indices that include wakefulness, such as sleep efficiency, number of awakenings, or WASO have to be discussed cautiously. Therefore, other measures of objective sleep could provide a clearer indication of how sleep and particularly periods of wakefulness after initial sleep onset, is related to daytime PTSD symptoms. Several headbands are now available which allow the measurement of sleep using encephalography (EEG) in the home environment without significantly disrupting sleep. To our knowledge, no study has yet been conducted in PTSD samples using such headbands. However, a recent publication used a similar device to test temporal relationships between EEG measured sleep and daytime stress over two weeks in a non-clinical sample. They found that several sleep markers predicted next-day stress level (Yap et al., 2022) indicating feasibility of such methods.

4.2. Conclusion

This study investigated the relationship between both subjectively and objectively measured sleep and daytime PTSD symptoms in a young, non-treatment seeking adult sample with a range of PTSS. From night-to-night, shorter sleep duration predicted higher PTSS, and longer SOL predicted the occurrence of more intrusions (within-person level). Overall, more disrupted subjective sleep (between-person level) was associated with greater PTSS as well as more intrusions. Within-person increase in PTSS was in turn associated with greater distress from nightmares during the following night. Elevated daytime PTSD symptoms, particularly PTSS, were associated with generally more sleep disruptions (between-person). These results were not found when using actigraphy as an objective measure of sleep, which may be explained by pandemic-related lockdowns or sleep state misperception. Sex (men vs. women) was found to moderate these associations in exploratory analyses

and should be accounted for in future research. Despite some limitations, including reduced power, this study provides support for the bi-directional relationship between PTSD and sleep, which adds to the existing literature including objective measures of sleep and exploring potential differences between sexes.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data that support the findings of this study are available on request from the corresponding author (MTS). The data are not publicly available due to containing information that could compromise the privacy of research participants.

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