Targeted Memory Reactivation for Relaxation and Restful Sleep

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Abstract

Sleep problems and stress are a widespread problem and closely linked, often reinforcing one another and leading to negative outcomes such as reduced cognitive performance and increased risk of psychological issues. Relaxation techniques like diaphragmatic breathing exercises (DBE) have been shown to alleviate stress and more rarely to improve sleep quality. This study investigated whether DBE could be combined with targeted memory reactivation (TMR), an emerging cognitive-enhancement technique applied during sleep, to reduce perceived stress and enhance sleep quality in a home setting. Fifteen participants completed a 12-day sleep diary tracking sleep quality and related qualitative variables. After three days, they began practicing daily DBE. From day four onward, TMR was applied during sleep using audio cues associated with the DBE. Perceived stress was measured before and after the intervention. Results showed a significant reduction in perceived stress following the intervention, while no significant change in sleep quality was observed after TMR began. As the first study to explore the interaction between DBE, TMR, stress, and sleep quality, this research adds to the still growing body of TMR research and finding practical ways to deal with stress and sleep quality issues through relaxation techniques.

Keywords: sleep quality, perceived stress, diaphragmatic breathing exercises (DBE), targeted memory reactivation (TMR), stress reduction

Introduction

The reasons why someone might have trouble falling asleep are so diverse, one could assume that everyone reading these lines could report at least a few that affected them during the last months. From feeling sick, to noisy neighbours, to ruminating about various topics and corresponding stress. And with that, you're certainly not alone. Self-reported sleep disturbances affect up to a fourth of the population (Morin & Benca, 2012) and stress has emerged as a prominent predictor for sleep disturbances (Almojali et. al., 2017).

Sleep disturbances can have various negative effects like mood impairments or a lack of energy (Morin & Benca, 2012), which negatively affects life as a whole and may accelerate problems such as stress and worsening academic performance (Almojali et. al., 2017). Bad sleep also predicts lower energy and higher fatigue levels (Boolani et. al., 2018), which makes the instance of people to skip sleep during stressful situations (Almojali et. al., 2017) or use it for passive gains (such as "Learn Japanese while you're sleeping" type videos that can be found on Youtube) feel like a sad irony.

Interestingly, recent studies have shown that interventions similar to "learn Japanese while sleeping" videos can have a positive effect under certain conditions. This phenomenon is known as Targeted Memory Reactivation (TMR), a process in which memories are reactivated during sleep through various cues in order to strengthen them. Its discovery suggests that, under the right circumstances, passive cognitive progress during sleep may indeed be possible. When considered more broadly, the ability of the brain to reactivate and consolidate memories during sleep could offer an unexpected solution to stress. By using TMR to reactivate memories of relaxation, it may be possible to promote more continuous sleep and enhance the feeling of restfulness upon waking, thus also reducing stress. This intriguing potential of sleep to enhance not only learning but also emotional well-being underscores the essential role of healthy sleep in cognitive functioning and highlights the importance of addressing sleep-related problems and their far-reaching consequences.

Sleep problems and their consequences

Sleep problems can arise from a multitude of causes and affect individuals across all demographics. In some cases, sleep disturbances occur as symptoms secondary to diagnosed medical or psychological conditions. For example, chronic pain and depression are frequently associated with disrupted sleep, with individuals reporting insomnia being approximately five times more likely to experience severe anxiety or depression (Pearson et al., 2006). Many people, however, report subjective sleep difficulties without any identifiable medical or psychological explanation (Morin & Benca, 2012). Everyday stressors are among the most frequent contributors to persistent sleep disturbances, while other causes, such as circadian rhythm disruptions from jet lag, are typically short-lived (Bastien et al., 2004). This paper primarily focuses on sleep quality issues that are not presumed to be caused by diagnosed conditions, although most of the findings presented remain applicable across both categories.

A recent national survey indicated that between forty and fifty percent of Americans experience difficulty falling asleep or maintaining sleep at least three nights per week (National Sleep Foundation, 2025). Approximately twelve to forty eight percent of adults report dissatisfaction with the overall quality of their sleep (Ohayon, 2002), and up to fifteen percent experience daytime impairments related to self-reported insomnia (Morin & Benca, 2012). The consequences of poor sleep frequently include deficits in cognitive functions, such as reduced concentration, impaired memory, and slower information processing (Ratcliff & Van Dongen, 2009). The most common symptoms are nighttime awakenings, with higher estimates putting their appearance rate (at least three nights per week) at thirty five percent for adults, while up to twenty three percent even report waking up every night (Ohayon, 2008). Disturbances in mood regulation, including irritability and increased emotional reactivity, are also commonly reported (Buysse et al., 2007). Over time, chronic sleep difficulties may increase the risk of developing mood disorders such as clinical depression (Morin & Benca, 2012).

Individuals exposed to persistent stressors are frequently among the first to develop maladaptive sleep patterns. This has been demonstrated in studies conducted on medical student populations in both the United States and Saudi Arabia by Ahrberg et al. (2012) and Almojali et al. (2017), respectively. Despite the critical role of sleep, it appears that many students voluntarily reduce their sleep duration to allocate more time to studying. Almojali et al. (2017) highlighted that short and poor-quality sleep had detrimental effects on the academic material students were attempting to learn. Correspondingly, Ahrberg et al. (2012) found that good sleep quality was a significant predictor of improved academic performance. These findings illustrate how poor sleep quality, along with its associated decline in cognitive function, can negatively affect the average adult’s capacity to perform effectively.

To address this issue, some researchers have proposed mindfulness-based stress reduction as a potential method to enhance sleep quality. A systematic review by Winbush et al. (2007) concluded that, although definitive conclusions remain elusive due to a scarcity of well-controlled studies, mindfulness-based stress reduction may positively impact sleep quality by reducing cognitive processes that interfere with sleep, such as stress. The review also noted that mind-body relaxation techniques continue to be an active field of investigation. Although not specifically named in the review, diaphragmatic breathing exercises represent an example of such techniques.

Diaphragmatic Breathing Exercises

According to a literature review by Hopper et. al. from 2019, only a handful of studies in English are available that investigate whether diaphragmatic breathing exercises (DBE) lead to a reduction in stress. However, out of the few studies available and included in their meta-analysis, all supported the claim that conducting DBE led to a reduction in stress, measured by psychological self-reports and physiological markers respectively, in adults.

Similarly, evidence supporting the effectiveness of DBE in improving sleep quality remains limited, particularly within healthy populations. A notable study by Liu et al. (2020) examined the effects of DBE on a sample of nurses working during the early peak of the COVID-19 pandemic in China. These healthcare workers faced stressful and extended shifts, which contributed to a high prevalence of self-reported poor sleep quality. In this study, the nurses were taught DBE while listening to an audio recording consisting of relaxing music and guided instructions for the breathing technique. Participants were instructed to perform the exercise at least once daily while listening to the audio file. After a period of four weeks, the nurses reported significant improvements in their reported sleep quality and less awakenings during the night. Recent findings by Trihandayani (2024) further suggest that relaxation techniques such as deep breathing exercises may help reduce nighttime awakenings by supporting both physiological relaxation and improvements in sleep initiation and continuity in adults with sleep disorders.

The findings reported by Liu et al. (2020) served as a primary source of inspiration for investigating the relationship between DBE and sleep quality in our research. In selecting an appropriate DBE protocol on YouTube, we sought to closely replicate the general instructions outlined in their study. However, a persistent challenge in the research literature, including the one by Liu et al., is the frequent lack of detailed description regarding the specific parameters and instructions of DBE interventions. Many studies either provide vague accounts or omit any details of the breathing exercises employed, a concern previously highlighted by Cahalin et al. (2002). According to our comprehensive literature review for this project, this issue has not substantially improved over the past two decades. This lack of clarity has raised questions about the replicability of DBE research findings. To address this issue, we included the instructions provided to our participants in the appendix of this paper. Despite variations in the precise execution of DBE across studies, the observed beneficial effects of DBE in various scenarios have been largely consistent, suggesting that minor differences in instructions do not critically affect outcomes (Cahalin et al., 2002). This is important, as otherwise a combination with TMR might prove more difficult.

Targeted Memory Reactivation

Targeted memory reactivation (TMR) is a process through which memories are reactivated during sleep, typically resulting in improved memory reconsolidation (Oudiette & Paller, 2013). For TMR to be effective, the sound cue must be sufficiently unique to trigger a specific association, as generic sounds generally fail to produce similar benefits (Donohue & Spencer, 2011). Most research on TMR, primarily focused on knowledge recall, has identified the strongest effects during slow-wave sleep (SWS), also called deep sleep. However, it remains possible that stimuli presented during rapid eye movement sleep could influence other types of memory, such as emotional memory (Oudiette & Paller, 2013). During SWS, TMR has been shown to enhance the consolidation of emotional and visual memory pairs, including negative and neutral sound-picture associations (Cairney et al., 2013), as well as skill-based memories, such as performance in the music and rhythm game Guitar Hero (Antony et al., 2012).

While the majority of TMR studies are conducted in controlled sleep laboratory environments (Göldi & Rasch, 2019), some research has begun to explore its application in home settings. For example, Göldi and Rasch (2019) found that the benefits of TMR could also be observed when administered at home in real-life settings without tight cue timing and volume controls, but effects only became really apparent after three days of repeated use. This delay was attributed to participants needing time to adjust to the TMR setup. In their study, all participants learned the same 120 Dutch-German word pairs over four days, with half of the Dutch words (60) being repeatedly played during sleep over three consecutive nights at home. Results showed that memory for the cued words improved compared to uncued words. In contrast, certain laboratory studies, such as that by Cairney et al. (2013), have demonstrated reasonably high effects following a single TMR session. A study by Whitmore et al. (2022) also found effects comparable to those of laboratory-based TMR studies in a home setting, specifically for spatial memory. However, their study used a specialized smart device that measured participants' movement and heart rate to time the TMR cues during appropriate sleep stages, thereby mimicking the manual cueing process used in laboratory settings. Both Göldi and Rasch as well as Whitmore et al. found that sleep disturbances moderated the effectiveness of TMR in home environments and that TMR audio cues could be the cause of such sleep disturbances.

TMR and the emotion of feeling relaxed

Thinking back to the Liu et al. (2020) paper, an MP3 file containing music and guided instructions for diaphragmatic breathing could be played at set intervals during the night, following protocols commonly used in contemporary TMR research to mimic sound cues that are specifically played during deep sleep in laboratory settings. This approach could add a new dimension to research on DBE, sleep quality, stress, and TMR in real-life environments. By utilizing a relatively novel auditory stimulus, created by combining DBE instructions with relaxing background sounds, the method avoids the potential pitfall of relying on commonplace or generic cues for TMR. The key question is whether re-exposing individuals to relaxation-associated auditory stimuli during sleep can reactivate the associated memories and mental state, thereby aiding overall stress reduction, enhancing sleep quality and mitigating the adverse effects of disturbed sleep. This could also directly influence the common insomnia symptom of nighttime awakenings, as relaxation induced through relaxation techniques including “deep breathing exercises” was shown to aid sleep initiation and maintenance, next to physiological relaxation, in adults with sleep disorders (Trihandayani 2024).

To our knowledge, this combined approach has not yet been empirically tested. Therefore, our theoretical framework is based on two main concepts: the documented beneficial effects of DBE on stress and sleep, which we will partially aim to replicate roughly following the protocol of Liu et al., and the incorporation of TMR, motivated by evidence that TMR can enhance the consolidation of skill learning (Antony et al., 2012) and emotional memories (Cairney et al., 2013). Given the suitability of our experimental setup for integrating these methods, we hypothesize that participants will demonstrate improved sleep quality once the TMR intervention begins to exert its effect, as well as that our participants will report lower stress levels after the intervention.

Methods

Recruitment & Participants

Our sample consisted of 16 participants who responded to the recruitment message posted on social networking sites through one of the researchers. One participant withdrew before their starting date, leading the final sample size to be 15. The final sample included three participants aged 18–24, ten participants aged 25–34, one participant aged 35–44 and one participant aged 65 or older. In terms of gender, five participants identified as male, nine as female, and one as other/non-binary. There were no formal exclusion criteria; anyone who considered themselves capable of completing the project was eligible to participate. However, people with outside influences on sleep quality such as chronic illness or young children in the house were asked to note these facts in the comments of one of the surveys used. Although monetary compensation was mentioned during recruitment, its availability was uncertain at that time and the participants were notified of that fact. At the time of the completion of this paper, no compensation has been handed out to the participants yet.

One participant was excluded from the PSQ analysis due to excessive missing data but remained included for the sleep diary analysis. Participation was voluntary, and participants could withdraw at any point up until 48 hours after completing the study.

Procedure

All instructions and materials were provided in English. Each participant was assigned a number, which was used to identify whether each participant had handed in their surveys and for communication. At the beginning of the project (also referred to as day 0), participants completed the Perceived Stress Questionnaire (PSQ) (Levenstein et al., 1993), which measures current stress and related mood levels across different domains during the last few weeks. Example items include “You are irritable and grouchy” and “You feel you are in a hurry”.

Responses were given on a four-point Likert scale ranging from 1 = almost, 2 = sometimes, 3 = often, and 4 = usually.

Participants were able to freely choose their starting date across a 14 day timeframe, from which the study had to be completed on 13 consecutive days. Starting from the first day of the study and continuing daily throughout the project, participants completed a short online sleep diary, namely the Consensus Sleep Diary (CSD) (Carney et al., 2012), which included questions such as, "When did you go to bed?", "Did you wake up during the night?" and “How would you rate the quality of your sleep?” to assess their sleep quality and patterns. In case of night time awakenings and sleep disturbances, participants were given the chance to write a comment on what they thought caused them to wake up or disturbed them, as well as another open question to note any other unique circumstances. In addition, a few items measured daily mood levels, caffeine intake and physical activity (Appendix X). All surveys were administered through the online platform qualtrics.

On the fourth day of the study, participants were invited to watch a video (Appendix Y) in which they were introduced to a diaphragmatic breathing exercise designed to promote relaxation. The video also informed them about some background information on DBE, as well as potential physiological and psychological health benefits.

After watching the video, participants received a soundcloud link, which contained an MP3 file that combined the DBE instructions from the video that they had watched with relaxing river sounds. From that day onward, participants were asked to perform the breathing exercise at least once per day using the provided audio file. The recommended time for the exercise was 8-10 minutes, although participants were free to extend the duration if they wished. All audio files were hosted on the platform “Soundcloud”, while each participant was notified of the ability to receive an MP3 version of it as an alternative.

From the fifth day onward, participants were additionally asked to play a nighttime version of the breathing exercise audio file when going to bed and to let it continue playing throughout the night until waking in the morning. This nighttime version contained the same instructions and sounds as the daytime version, but these were played sporadically between recordings of wood crackling in a fire. The initial crackling segment lasted 40 minutes to ensure that participants were typically asleep by the time the breathing instructions, which were intended to serve as TMR cues, began. This design choice was based on findings from TMR studies, such as the one by Whitmore et al. (2022), which show that TMR cues should be played during deep sleep phases. Continuous playback throughout the night was intended to increase the likelihood that the relevant sound cues would coincide with deep sleep phases for the same reason. Participants were instructed to use a playback device of their choice, such as a mobile phone, headphones, or laptop, and to ensure that the volume was comfortable while keeping the overall audio and especially the spoken instructions clearly audible.

On the final day of the diary (Day 12), participants again completed the Perceived Stress Questionnaire.

Participants were reminded daily via a WhatsApp group channel to complete all required surveys for that day and informed about the start of each experimental phase (e.g., on which day to begin the breathing exercise). Reminder messages always included links to the necessary materials and were personalized using the participants' numbers. Participants who skipped a diary day were asked to, if possible, fill in the missing entry one day after. Once data collection for a participant was complete and a 48-hour period for participants to possibly withdraw their consent to use their data had passed, participants' names were detached from their numbers and deleted to anonymize their data.

Data analysis

Pre- and post-intervention comparisons of perceived stress levels were conducted using scores from the PSQ through a paired samples t-test to assess whether scores were lower following the intervention. A repeated measures ANCOVA was used to compare sleep quality based on CSD data across three averaged time points in the intervention (Base, DBE, TMR). The covariates included "Awakenings," "Mood positive," "Mood negative," "Exercise in the evening," and "Caffeine in the evening." A linear mixed effects model was used to evaluate the relevance of each independent covariate. Additionally, comments entered in the diary were used for qualitative appraisal, but were not included in the statistical analysis.

Since time stamps for CSD completion were available to the researchers, errors in diary date entries made by participants were corrected manually to ensure proper labeling. All data were initially planned to be analyzed using JASP (Version 0.18.3). After the paired samples t-test was performed in JASP, it became apparent that JASP's structure for conducting repeated measures ANCOVA was incompatible with the formatting of our dataset, and attempts to reformat the data were unsuccessful. Consequently, the repeated measures ANCOVA and the linear mixed effects models were calculated using R (Version 4.5.0).

Preliminary steps

For the PSQ, all scores were averaged per participant. Reverse scored items had been set up as reverse scored in the survey and thus required no recalculation. For the CSD, sleep quality was averaged per participant in accordance with the following three time frames. Base: Day 1-3, DBE: Day 4-7, TMR: Day 8-12. The TMR phase was measured after participants had listened to the TMR audio at night for three days, allowing them to adjust to the setup, in line with the theoretical rationale proposed by Göldi & Rasch (2019). The average number of awakenings was calculated across the previously mentioned three timeframes, as were the average scores for positive and negative mood. The caffeine and exercise responses were recoded to Yes = 1 and No = 0, and then averaged across the same timeframes per participant. One participant had missed the final two sleep diary entries, so only three days were used to calculate their TMR phase scores.

Preliminary analysis

Prior to conducting the t-test for the PSQ score differences before and after the experiment, the assumption of normality for the difference scores was assessed using the Shapiro-Wilk test. The test indicated no significant deviation from normality, $W = 0.94$, $p = .433$.

For testing differences in sleep quality as measured by the sleep diaries across the three conditions: Base, DBE and TMR with a repeated measures ANOVA, the assumption of sphericity was evaluated using Mauchly's test, which did not indicate a significant violation, $W = 0.65$, $p = .063$ (see Table 5). Therefore, no correction was applied to the degrees of freedom in the primary ANOVA.

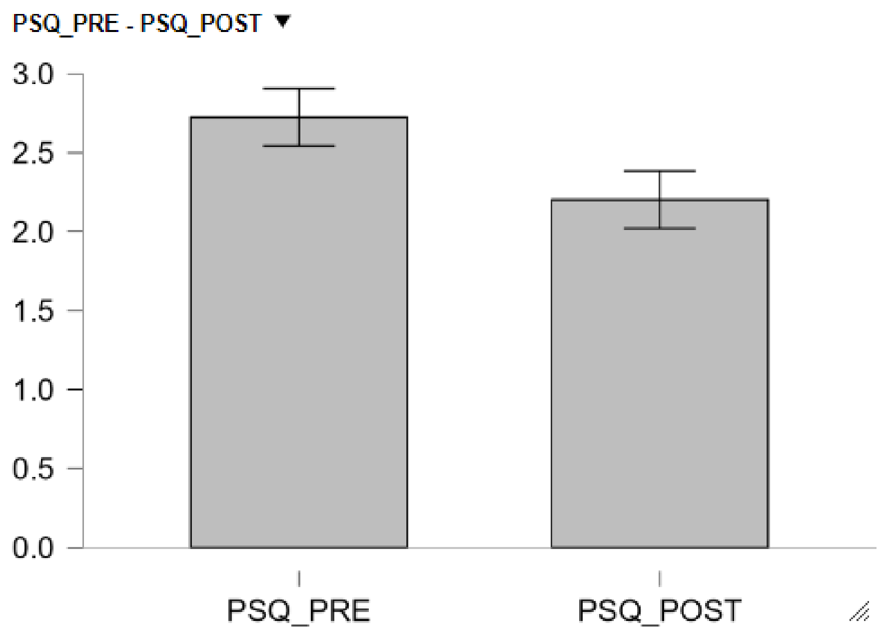
Results

Perceived Stress Questionnaire Analysis

To evaluate the effect of the intervention on perceived stress, a paired samples t-test was conducted comparing PSQ scores before and after the intervention. Consistent with the hypothesis, PSQ scores were significantly lower following the intervention ($M = 2.20$, $SD = 0.49$) than before ($M = 2.72$, $SD = 0.35$), $t(df = 13) = 4.38$, $p < .001$ (see Table 1, Appendix). This indicates a statistically significant reduction in self-perceived stress after the intervention. The magnitude of the difference was large, as reflected in Cohen's $d = 1.17$, 95% CI [0.47, 1.84]. The standard error of Cohen's d was 0.36, suggesting a reasonably precise estimate of the effect size.

Figure 1

Perceived Stress Questionnaire (PSQ) Box Plots



Consensus Sleep Diary Analysis

The hypothesis that sleep quality would differ across conditions, with the highest ratings during TMR (targeted memory reactivation), followed by DBE (deep breathing exercise), and the lowest during the base condition, was tested using a repeated measures ANOVA. The main effect of Condition was not significant, $F(2, 28) = 0.82$, $p = .450$, generalized eta squared (ges) = 0.051 (see Table 3). This suggests that overall sleep quality ratings did not significantly vary between the three conditions. Estimated marginal means indicated that mean sleep quality ratings were slightly higher in the DBE condition ($M = 3.33$, $SE = 0.14$, 95% CI [3.03, 3.63]) and TMR condition ($M = 3.29$, $SE = 0.10$, 95% CI [3.08, 3.51]) compared to the base condition ($M = 3.09$, $SE = 0.19$, 95% CI [2.69, 3.49]) (see Table 5). However, pairwise comparisons using Bonferroni adjustment revealed that none of these differences reached statistical significance (all p values > .79). For example, the comparison between base and DBE yielded an estimated mean difference of -0.24, p = .798, and between base and TMR of -0.20, p = 1.00 (see Tables 7 and 8). The assumption of sphericity was evaluated using Mauchly's test, which did not indicate a significant violation, W = 0.65, p = .063 (see Table 6). Therefore, no correction was applied to the degrees of freedom in the primary ANOVA. Results were similar when applying Greenhouse-Geisser and Huynh-Feldt corrections. Potential covariates, including mood (positive and negative), caffeine consumption, exercise, and number of awakenings, were explored using ANCOVA and linear mixed models. None of these covariates showed a significant effect on sleep quality ratings (all p values > .14) (see Tables see table 4, 9, 10). Specifically, the number of awakenings did not significantly predict sleep quality, F(1, 9) = 0.004, p = .949 in the ANOVA model, and was not a significant predictor in the mixed model either, t(37) = 0.93, p = .36. A post hoc power analysis indicated low statistical power to detect a small to medium effect (power = .285 for f = 0.25), suggesting that the study may have been underpowered to detect subtle differences in sleep quality across conditions (see Table 11). In summary, while descriptive statistics suggested a trend toward improved sleep quality in the DBE and TMR conditions compared to baseline, these differences did not reach statistical significance. Exploratory analyses indicated that factors such as mood, caffeine, exercise, and awakenings did not significantly influence the outcome.

Table 2
CSD Average Scores

Variable	Base	DBE	TMR
Sleep Quality	3.11	3.27	3.23
Mood Negative	2.02	2.12	2.18
Mood Positive	2.72	2.64	2.92
Awakenings	1.02	1.18	1.05
Caffeine	0.24	0.43	0.25

Exercise	0.13	0.18	0.21

Table 3
ANOVA Results

Effect	df	SS	F	p	ges
Intercept	1, 14	467.71	1936.71	< .001	0.92
Condition	2, 28	2.16	0.82	.450	0.05

Table 4
Linear Mixed Model Fixed Effects

Predictor	Estimate	SE	t	p
Intercept	3.06	0.69	4.42	< .001
Condition DBE	0.19	0.23	0.80	.426
Condition TMR	0.21	0.22	0.97	.338
Mood_Neg	0.07	0.18	0.38	.707
Mood_Pos	-0.10	0.20	-0.50	.620
Caffeine	0.31	0.48	0.64	.529
Exercise	-0.10	0.49	-0.21	.832
Awakenings	0.09	0.10	0.93	.357

Qualitative analysis

To put our statistical findings into context, we reviewed the qualitative data for possible explanations regarding the lack of effect of our intervention on sleep quality. In the comment section of the CSD, participants noted various factors they believed disrupted their sleep or influenced its quality. Among these, the following were mentioned on more than one night: any variation of a cold or illness, including chronic medical conditions (reported by 5 out of 15 participants); work-related late nights (2 out of 15); external noises such as loud neighbors, environmental sounds, or weather (9 out of 15); use of sleep aids like melatonin or sleep medication (2 out of 15); engaging social events near bedtime or during the day, including those possibly involving alcohol or drugs (3 out of 15); unexplained restlessness (2 out of 15); and menstruation (1 out of 15).

Only one participant reported no such issues at all, while two others mentioned a single night of disturbance and no other problems. Since these comments were submitted voluntarily, it is unclear whether the number of participants reporting these issues accurately reflects the true frequency of their occurrence. In particular, late-night work led to significant deviations from individuals' typical bedtimes. As expected, we observed substantial within- and between-person differences in the time participants went to bed, the duration they remained awake while in bed, and how long it took them to fall asleep. Comments were usually submitted for nights that showed these irregular patterns, such as prolonged wakefulness following awakening from a bad dream. Based on these patterns, it seems reasonable to infer that the issues participants chose to report did, in fact, negatively impact their sleep quality.

Most nighttime awakenings were attributed to the need to use the bathroom or were caused by noises from various sources, such as birds or a partner. Other recurring reasons included getting up to drink water and feeling uncomfortably warm. Notably, the TMR audio file was not mentioned in the diary entries as a cause of awakening. However, one participant privately informed the researcher that they found the nighttime version of the audio file uncomfortable. They described the fire crackling sound as "sounding like someone typing on a keyboard next to my head" and said it made falling asleep more difficult. Upon request, this participant switched to using the regular TMR audio file during the night, since this was the segment intended to provide the cueing effect in the first place.

Excluding toilet breaks, alarms, and water consumption, a total of 60 out of 178 recorded nights (33.7 percent) were affected by issues that participants believed had a negative impact on their sleep quality and/or caused nighttime awakenings.

Discussion

The aim of the present study was to explore whether a combination of Diaphragmatic Breathing Exercises (DBE) and Targeted Memory Reactivation (TMR) could elicit feelings of relaxation and thus enhance sleep quality and reduce sleep. To the best of our knowledge, this is the first study to examine the potential synergistic effects of these two techniques. We hypothesized that the integrated intervention would yield a measurable reduction in perceived stress and contribute to improved sleep quality consistent with previous findings on DBE, for example Liu et al. (2020), over the duration of the study. While the results did not support our hypothesis regarding sleep quality, as no significant changes were observed across conditions, we did find a significant reduction in perceived stress levels from pre- to post-intervention. This finding lends support to the effectiveness of the combined DBE and TMR protocol in alleviating stress, even if improvements in sleep quality were not statistically evident. However, these findings lead us to think about why only stress was affected by our intervention.

A straightforward explanation could be explored when looking at the comments our participants wrote in the Consensus Sleep Diary (CSD). Many of them provided multiple reasons for sleep disturbances outside of our control, such as noises unrelated to the TMR or illness. It is obvious that our intervention can’t stop someone’s neighbor from throwing a party and therefore disturbing the participants' sleep, even when they feel more relaxed through the means of our intervention. That said, this interpretation relies on the assumption that participants’ sleep quality, and their overall sleep experience, were primarily affected by the issues they noted in the comments. This overlooks other significant potential causes of stress or mental unrest in their lives, such as rumination, which may not have been captured by the diary entries because participants did not perceive them as directly related. Previous studies by Göldi and Rasch (2019) and Whitmore et al. (2022) have both emphasized that any form of sleep disturbance can moderate the effectiveness of TMR in home settings.

Because our study was conducted remotely, we also cannot be certain that all participants consistently followed the instructions each day as intended. This limitation, combined with the relatively small number of observations per condition and the modest sample size, introduces the risk of influential outliers. However, such outliers were not clearly observable in our dataset (see Figure 2).

An alternative explanation for our findings is that the intervention may simply have no effect on sleep quality, while still being effective in reducing perceived stress. This would somewhat stand in contrast to the results reported by Liu et al. (2020), where DBE alone led to improvements in sleep quality. As mentioned earlier, studies involving DBE often present limitations in their methods sections (Cahalin et al., 2002), which can obscure subtle yet important differences in how the breathing exercises are implemented. Such inconsistencies make replication difficult. For instance, variations in the timing of the breathing exercise could play a critical role in determining its impact on sleep quality. Unfortunately, this represents a natural limitation that was beyond our control and reflects broader methodological challenges commonly encountered in this field of research.

It is also possible that the combination of DBE and TMR contributed to participants' relaxation, but that TMR alone may not be sufficient to reactivate emotional states during sleep in a way that produces measurable improvements in sleep quality. So far, research on emotional TMR has mainly focused on linking emotional memories to visual stimuli (Cairney et al., 2013), rather than using the emotional component itself as the primary retrieval cue. In our study, the DBE instructions served as the cue intended to initiate memory reactivation. This may have primarily strengthened participants' memory and recall of the DBE procedure itself, which could explain both the reduction in perceived stress and the positive feedback received regarding the DBE.

A similar and plausible alternative explanation is that the daily practice of DBE was the primary factor behind the observed reduction in stress levels after the intervention, while TMR had no measurable effect on either stress or sleep quality. Unlike TMR, DBE has already been shown to reduce stress in previous research, as demonstrated in the meta-analysis by Hopper et al. (2019). It is therefore possible that our study simply replicated this effect without identifying a new one.

Finally, given the limited duration of our study, we cannot exclude the possibility that TMR may indeed have a relaxing influence, but that this effect takes longer to emerge in real-life settings. This idea is supported by findings from Göldi and Rasch, who reported a delayed onset of TMR effectiveness when compared to laboratory studies on vocabulary learning. These delays can be attributed to less precise cue exposure in the absence of dedicated personnel and equipment, a challenge also noted by Whitmore et al. (2022).

Limitations and strengths

A key limitation of our study arose from the lack of control over several aspects of the intervention due to its administration in a private, home-based context. Although TMR has been shown to be effective when delivered in participants' homes (Göldi & Rasch, 2019), a substantial proportion of previous studies has been conducted in sleep laboratories. Laboratory settings provide researchers with greater control over how TMR stimuli are presented to participants. In contrast, in a private setting such as ours, it is possible that participants did not set the TMR audio at an adequate volume or failed to loop the audio file throughout the night. Despite providing clear instructions through official SoundCloud manuals in the TMR phase start reminder message, which included guidance on how to enable continuous looping, many participants accidentally selected the “share” function instead, as shown by “Your track has been shared” emails sent by SoundCloud and participants apologizing for it later. This suggests that SoundCloud’s interface may have been confusing for some participants. Another limitation concerns the audio material itself. One participant noted during the study, and gave permission to include this comment, that “the audio file sounds like someone typing on a keyboard next to my head.” Although this may reflect a personal preference, in studies with small sample sizes, as is common in TMR research (Hu et. al., 2020), even well-intentioned additions such as relaxing background sounds may have unintended negative effects, as small samples are more suggestive to one outlier strongly influencing the result (Wilcox et al., 2018). With more professional support and greater control over the preparation and delivery of the audio file, the effectiveness of the intervention could differ significantly from the outcomes observed in our study. In contrast to the study by Whitmore et al. (2022), our project lacked the technical equipment and financial resources to monitor participants' sleep patterns and let a machine learning model play the sound cues at optimized volumes during deep sleep phases only. Instead, the audio was played continuously throughout the night at a volume chosen by the participants themselves, which might have been more disturbing to their sleep and less effective overall. Future studies with greater financial and technical resources may be better equipped to optimize cue delivery, potentially enhancing the effectiveness of TMR through more precise and personalized exposure to sound cues.

The duration of our study was relatively short, running for less than two weeks. This limitation was largely due to the time constraints of conducting the project as part of a master’s thesis, as well as practical considerations related to maintaining participant engagement over time with uncertain monetary compensation. The short duration meant that each condition contributed only a small number of observations per participant in the sleep diary dataset. This increases the susceptibility of the data to the influence of outliers or night-to-night variability that may not reflect consistent patterns. Extending the length of future studies could help to address this limitation by providing a larger and more stable dataset for each individual and condition.

In addition to increasing the study duration, future research could consider shifting from a within-subject design to a design that includes a separate control group and fixed starting days for all participants. Such a change could improve the ability to detect condition-specific effects and control for potential confounding variables that may fluctuate over time when the same participants are being measured for both scenarios on different weekdays. However, it is important to acknowledge that both within-subject and between-subject designs have their respective advantages and disadvantages. Our within-subject approach allowed us to increase the number of observations per condition within the practical limitations of a master's thesis, and gave participants the opportunity to experience changes themselves, mirroring a more natural, real-life progression. Nonetheless, incorporating a well-matched control group in future studies could offer additional methodological robustness and provide clearer insight into the effects of the intervention.

An alternative approach could involve a longer study period in which different groups receive the TMR intervention at staggered time points. This type of design could help separate intervention effects from general time-related influences. While our study partially followed this approach by allowing participants to begin within a two-week window, this flexibility in scheduling led to small starting cohorts, typically consisting of only one or two participants.

The diversity of our sample in terms of occupation and geographic location was one of the major strengths of this project. Since the aim was to explore potential interventions for a problem that affects a wide range of individuals (Ohayon, 2002, 2008), including participants from varied life contexts, such as students and workers from different countries, increases the likelihood that the findings may be replicable across different populations.

Another strength of our study was that it appeared to be highly engaging for participants. We received considerable positive feedback, indicating that participants enjoyed learning and practicing the DBE and found the experience fun and relaxing. The daily reminders we sent helped keep the study on participants' minds and likely supported their continued involvement. By allowing participants to integrate the tasks flexibly into their daily routines rather than imposing a strict schedule, the design may have contributed to sustained motivation. This combination of regular reminders and flexible task integration might help explain the exceptional fact that no participants dropped out after starting the project, along with multiple reports of positive experiences and intrinsic motivation. These observations could suggest that the topic and real-life study designs are of interest to a wide range of people.

Future Outlook

Future research could involve collaboration between academia and private industries to explore the integration of smart wearables that prompt users to perform breathing exercises when physiological signs of stress are detected. Similarly, wearables capable of detecting sleep phases could be tested further for accurately timed TMR cues, with the goal of making such technology available to the general public. Repeating the study with tighter control over the intervention, a longer duration, and larger sample sizes could help clarify the effects of the unique DBE and TMR combination on stress and sleep quality. Based on our findings, it may also be valuable to investigate the impact of DBE in more focused contexts, such as among office workers in high-stress situations or students during exam periods, where stress levels are elevated and interventions may be particularly relevant.

Summary

Poor sleep quality and elevated stress affect many individuals and are associated with detrimental consequences for cognitive functioning, health, and mood. Diaphragmatic breathing exercises (DBE) are sometimes employed to mitigate these negative effects. In this study, we investigated whether combining DBE with targeted memory reactivation (TMR) during sleep could enhance sleep quality and reduce overall perceived stress. While no significant effects on sleep quality were observed, the intervention resulted in a significant reduction in perceived stress levels. These findings suggest that future research could further explore the potential of DBE–TMR combinations for stress reduction in longer and potentially more focused studies. Additionally, companies, universities, and other organizations may wish to examine the effectiveness of DBE in reducing stress within their specific contexts.

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Appendix

Appendix X - Daily mood level, caffeine and exercise questions

Yesterday, I felt energetic (not at all, slightly, moderately, quite a bit, very much)

Yesterday, I felt stressed (not at all, slightly, moderately, quite a bit, very much)

Yesterday, I felt anxious (not at all, slightly, moderately, quite a bit, very much)

Yesterday, I felt happy (not at all, slightly, moderately, quite a bit, very much)

Did you drink coffee, caffeinated energy drinks or similar drinks after 15:00? (Yes, No)

Did you exercise in the evening? (Yes, No)

Appendix Y - Diaphragmatic breathing exercise instructions and tutorial

UCLA Health. (2020, March 24). *Diaphragmatic breathing | UCLA Integrative Digestive Health and Wellness Program* [Video]. YouTube. https://www.youtube.com/watch?v=g2wo2Impnfg

Table 1

Paired Samples T-Test

								95% CI for Cohen's d	
Measure 1		Measure 2	t	df	p	Cohen's d	SE Cohen's d	Lower	Upper
PSQ_PRE	-	PSQ_POST	4.375	13	< .001	1.169	0.356	0.469	1.843

Note. Student's t-test.

Table 5

Estimated Marginal Means

Condition	M	SE	95% CI
Base	3.09	0.19	[2.69, 3.49]
DBE	3.33	0.14	[3.03, 3.63]
TMR	3.29	0.10	[3.08, 3.51]

Table 6

Mauchly's Test of Sphericity

Effect	W	p
Condition	0.65	.063

Table 7

Pairwise Comparisons (Bonferroni-adjusted)

Contrast	Estimate	SE	t	p
Base - DBE	-0.24	0.21	-1.16	.798
Base - TMR	-0.20	0.23	-0.90	1.000
DBE - TMR	0.04	0.21	0.19	1.000

Table 8

Pairwise Comparison 95% CIs

Contrast	Estimate	95% CI
Base - DBE	-0.24	[-0.82, 0.33]
Base - TMR	-0.20	[-0.83, 0.42]
DBE - TMR	0.04	[-0.54, 0.62]

Table 9

Covariate Effects (Participant Level)

Predictor	F	p
Mood_Neg	1.48	.254
Mood_Pos	1.30	.283
Caffeine	2.62	.140
Exercise	1.31	.283
Awakenings	0.00	.949

Table 10

Covariate Effects (Condition Level)

Predictor	F	p
Condition	0.62	.545
Mood_Neg	0.01	.912
Mood_Pos	0.02	.882
Caffeine	0.00	.979
Exercise	0.28	.604
Awakenings	0.70	.411

Table 11

Approximate Power

k	n	f	α	Power
3	15	0.25	0.05	0.29

Figure 2

Average Sleep Quality scores across per participant the different phases