Received: 14 November 2019 | Revised: 4 January 2020 | Accepted: 11 February 2020
DOI: 10.1111/jsr.13022

REGULAR RESEARCH PAPER

Journal of Sleep Research ESRS

The impact of five nights of sleep restriction on emotional reactivity

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Abstract

An inadequate amount of sleep can negatively affect emotional processing, causing behavioural and neurofunctional changes. However, unlike the condition of total sleep deprivation, which has been extensively studied, the effects of prolonged sleep restriction have received less attention. In this study, we evaluated, for the first time, the effects of five nights of sleep restriction (5 hr a night) on emotional reactivity in healthy subjects.

Forty-two subjects were selected to participate, over two consecutive weeks, in two experimental conditions in counterbalanced order. The subjects were tested the morning after five nights of regular sleep and after five consecutive nights of sleep restriction. During the test, participants evaluated valence and arousal of 90 images selected from the International Affective Picture System.

The subjects perceived pleasant and neutral pictures in a more negative way in the sleep-restriction condition compared to the sleep condition. This effect survived after removing the contribution of mood changes. In contrast, there was no significant difference between conditions for ratings of unpleasant pictures.

These results provide the first evidence that an inadequate amount of sleep for five consecutive nights determines an alteration of the evaluation of pleasant and neutral stimuli, imposing a negative emotional bias. Considering the pervasiveness of insufficient sleep in modern society, our results have potential implications for daily life, as well as in clinical settings.

KEYWORDS
affective valence, emotion, emotional reactivity, sleep curtailment, sleep loss

1 | INTRODUCTION

An increasing body of evidence has demonstrated that an inadequate amount of sleep can negatively affect emotional processing (e.g., Tempesta, Socci, De Gennaro, & Ferrara, 2018). The specific role of sleep in the modulation of emotional processing has been explained by two different hypotheses. The first one, put forward by Walker and van der Helm (2009) and currently dominating the field, suggests that when emotional memories are consolidated over sleep, the negative emotional reactivity is simultaneously attenuated. On the other hand, Wagner speculates that, as sleep enhances consolidation of the emotional memory, its emotional valence will also be maintained (Wagner, Hallschmid, Rasch, & Born, 2006).

In general, with "emotional reactivity" we refer to the quality and intensity of response to affective stimuli (Wheeler, Davidson, & Tomarken, 1993). The most common way to test emotional reactivity is to evaluate the emotional response to affective pictures along two dimensions: arousal (ranging from calm to excitement) and valence (ranging from positive to negative, with neutral often considered an intermediate value) (Labar & Cabeza, 2006; Lang, Greenwald, Bradley, & Hamm, 1993).

Over the last years, an increasing body of evidence has demonstrated a link between sleep and emotional reactivity, showing behavioural and neurofunctional alterations imposed by sleep loss (Tempesta et al., 2010; Yoo, Gujar, Hu, Jolesz, & Walker, 2007; Zohar, Tzischinsky, Epstein, & Lavie, 2005). For example, Baran, Pace-Schott, Ericson, and Spencer (2012) showed an attenuation of negative ratings after 12 hr of daytime wakefulness, whereas a period of 12 hr including sleep was associated with a relative maintenance of the initial negative ratings. Likewise, Groch, Wilhelm, Diekelmann, and Born (2013) suggested that sleep does not modify the emotional reactivity associated with emotional stimuli. In fact, they observed that valence and arousal ratings of emotional pictures were not affected by rapid eye movement (REM)-rich or slow-wave sleep (SWS)-rich sleep.

On the other hand, other studies suggest that sleep may protect or even potentiate emotional reactivity. Indeed, Wagner, Fischer, and Born (2002) suggested that sleep increases emotional reactivity, showing that subjective ratings of the negative valence following late sleep were more negative for pictures viewed before sleep compared to new, unfamiliar pictures. Similarly, Lara-Carrasco, Nielsen, Solomonova, Levrier, and Popova (2009) showed that REM sleep deprivation alters emotional evaluation, in particular reducing reactivity to the negative valence of stimuli.

Other studies turned their attention to the effects of sleep loss on our responses to emotional stimuli and demonstrated that inadequate sleep amplifies negative emotional consequences of disruptive daytime events (Zohar et al., 2005). This role of sleep loss as a potentiating factor of emotional reactivity has been repeatedly confirmed. Tempesta et al. (2010) observed that sleep-deprived subjects evaluate the neutral pictures in a more negative way compared to normally sleeping subjects, indicating that sleep affects emotional evaluations. In addition, more recently we reported a similar emotional bias not only in sleep-deprived individuals but also in poor sleepers, who showed a more negative evaluation of neutral stimuli compared to good sleepers (Tempesta, De Gennaro, Natale, & Ferrara, 2015). Moreover, we observed that sleep-deprived subjects rated positive and neutral pictures more negatively than the good sleepers, confirming the enhancement of negative affective tone after sleep loss, whereas a night of good sleep left emotional ratings unchanged. Additionally, Pilcher, Callan, and Posey (2015) showed that both total and partial sleep deprivation affects reactivity to emotional pictures, and the negative effect was greater for positive stimuli, whereas negative picture ratings proved to be more resistant to sleep loss conditions. An inadequate amount of sleep is linked to a negative bias also in the processing of facial expressions of emotions. Following sleep deprivation individuals evaluated facial expressions as more threatening (Goldstein-Piekarski, Greer, Saletin, & Walker, 2015). Altogether, these studies indicate that a period of sleep deprivation is associated with an alteration in emotional reactivity. However, it should be noted that most of the studies aimed at investigating the behavioural effects of sleep loss have used acute total sleep deprivation as the experimental manipulation. On the other hand, the effects of partial and prolonged sleep deprivation have received scarce scientific attention, even though sleep restriction is more prevalent in the general population as a result of social activities, medical conditions and sleep disorders.

Even less attention has been dedicated to the potential effects of sleep restriction on emotional processing. Specifically, a functional brain imaging study showed that 5 days of sleep restriction alters the functional connectivity between the amygdala and the ventral anterior cingulate cortex in response to the facial expression of fear (Motomura et al., 2013). On the other hand, a behavioural study in a sample of adolescents showed no alterations in emotional reactivity after only one night of sleep restriction (Reddy, Palmer, Jackson, Farris, & Alfano, 2017).

For this reason, the aim of this study is to evaluate the effects of five consecutive days of sleep restriction on emotional reactivity in healthy young adults. We hypothesized that a limitation of 5 hr of sleep per night for five consecutive nights could be sufficient to induce alterations in emotional reactivity, reflected by increased negativity in the evaluation of the emotional stimuli.

2 | MATERIALS AND METHODS

2.1 | Subjects

Forty-five subjects were selected to participate in the experiment (mean age ± *SD*, 24.17 ± 4.09 years; 21 males). Each participant filled out the Beck Depression Inventory (BDI-II: Ghisi, Flebus, Montano, Sanavio, & Sica, 2006), the State-Trait Anxiety Inventory (STAI-T: Moroni et al., 2006), the Pittsburgh Sleep Quality Index (PSQI: Buysse, Reynolds, Monk, Berman, & Kupfer, 1989; Curcio et al., 2013) and the Insomnia Severity Index (ISI; Bastien, Vallières, & Morin, 2001; Castronovo et al., 2016) to control for the presence of mood or anxiety disorders, sleep disorders and insomnia. Furthermore, each participant filled out a self-reported questionnaire on daily habits of consumption of coffee, alcohol, cigarettes, activating drinks (e.g., coke or energy drinks), chocolate and medications.

All subjects declared that they had habitual sleep duration of 7–8 hr per night and did not take naps during the day.

Participants were requested not to increase their habitual caffeine, alcohol, medication and cigarette consumption throughout the experimental protocol, and all the subjects were also asked not to smoke or eat for at least 30 min before each assessment.

Three subjects, who did not comply with the sleep-restriction protocol, were excluded from all the analyses. Therefore, the final group of participants comprised 42 subjects (mean age ± *SD*, 24.09 ± 4.2 years; 20 males).

The whole investigation was approved by the local Institutional Review Board and was conducted according to the principles established by the Declaration of Helsinki. Written informed consent was obtained from all participants before the investigation.

2.2 | Stimuli

One hundred and eighty colour pictures were selected from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2008), corresponding to those already used in a previous study (Tempesta et al., 2010). The pictures depicted 60 pleasant events (mean valence, 7.0; mean arousal, 5.1), 60 neutral events (mean valence, 4.5; mean arousal, 3.1) and 60 unpleasant events (mean valence, 1.6; mean arousal, 6.1). The stimuli were divided into two samples of equal size and composition (30 pleasant, 30 neutral and 30 unpleasant stimuli) to be presented in a counterbalanced order in the two experimental conditions. Stimuli presentation and recording of responses were managed by means of the Superlab 5.0.5 software (Cedrus, San Pedro, California, USA), on iMac computers with a display of 21.5 inches.

2.3 | Procedure

The experimental protocol consisted of a crossover design that involved two conditions, which were applied during two consecutive weeks in a counterbalanced order (Figure 1). In one condition, the subjects were required to sleep for five consecutive nights (from Sunday to Thursday) according to their normal sleep habits (Sleep Condition [SC]). In the other condition, a maximum of 5 hr of sleep per night for five consecutive nights (from Sunday to Thursday) was imposed (Sleep-Restriction Condition [SRC]). In the SRC participants were instructed to go to bed approximately at 02:00 hours and to wake up at about 07:00 hours. According to the procedure, there were two washout nights between the two experimental conditions. The testing phase was scheduled on the Friday morning of both weeks. It was held at the Laboratory of Sleep Psychophysiology and Cognitive Neurosciences, Department of Biotechnological and Applied Clinical Sciences of the University of L'Aquila (start time ranging from 09:00 to 10:00 hours).

At the beginning of each testing phase, subjective sleepiness and mood were measured, respectively, by using computerized versions of the Karolinska Sleepiness Scale (KSS; Akerstedt & Gillberg, 1990) and a visual analogue scale (VAS; Stern, Arruda, Hooper, Wolfner, & Morey, 1997). The KSS required indication of subjective sleepiness, on a scale ranging from 1 (very alert) to 9 (very sleepy). The VAS required the subjects to self-evaluate their current status concerning eight dimensions: happiness, sadness, tension, calmness, irritability, tiredness, energy and concentration. Each subject was asked to evaluate "How do you feel right now?" by pressing the left mouse button on a 200-mm line, presented in the centre of the computer screen, between the extremes of "not at all" and "very much". Values representing the positions of the typed pixel are transformed into a scale of values from 0 to 10. Scores for the items sad, tense, irritable, happy and calm (reverse scored) were summed together to obtain the Negative Mood Index (NMI); higher NMI values indicate a more negative mood (range, 0–50). Scores for the items energetic, concentrated and tired (reverse scored) were summed to obtain an alertness index (AI; range, 0–30).

Subjects then underwent a task already used in a previous study (Tempesta et al., 2010). They were instructed that a series of 90 trials would be presented; for each trial, they were prompted to estimate the affective valence and arousal of one picture.

Trials consisted of a full-screen presentation (for 2,000 ms) of a picture selected from one of the two samples (see "Stimuli" paragraph), depending on the condition (i.e., SC or SRC). The order of presentation of the pictures (pleasant, neutral, unpleasant) was randomized for each subject and condition. Then, after a 1,000-ms black screen, the subjects were presented with a screen containing a smaller version of the same image with an underlying Self-Assessment Manikin valence scale (SAM; Bradley & Lang, 1994; Lang, 1980). The SAM valence scale consists of cartoon-type figures representing nine human emotional expressions, ranging from smiling and happy to frowning and unhappy. This screen was presented until the participant responded or for 3,000 ms; after that, a SAM arousal scale took the place of the SAM valence scale. The SAM arousal scale is another nine-item scale of cartoon-type figures, depicting expressions ranging from calm and relaxed to excited and wide-eyed. Likewise, this screen was presented until a participant responded or for 3,000 ms. Both valence and arousal evaluations

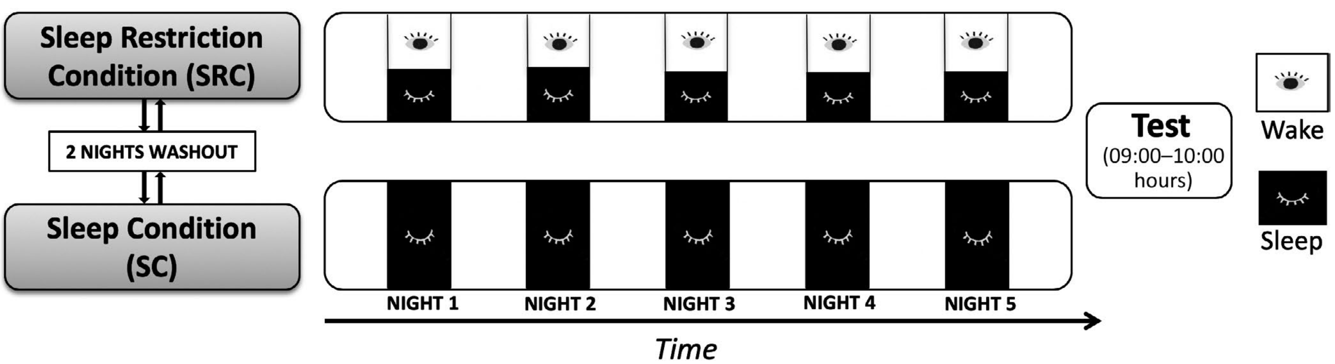

FIGURE 1 Experimental protocol. Schematic representation of the experimental protocol that included sleep-restriction (SRC) and sleep conditions (SC) in counterbalanced order, separated by two washout nights. The test session was carried out after five nights of regular sleep in the sleep conditions and after five nights of sleep curtailment in the sleep-restriction condition

were made on a nine-point scale, pressing the numbers on the keyboard from 1 to 9.

2.4 | Sleep measures

To obtain a subjective sleep assessment of the two consecutive experimental weeks, each morning all the participants completed a sleep diary to report their subjective sleep duration and sleep quality.

To obtain an objective assessment of sleep and to control participants' compliance with the experimental protocol, all participants wore a Geneactiv accelerometer (ActivIn-sights Ltd). Participants wore the accelerometer on their non-dominant wrist from Sunday morning and for the entire duration of both the experimental conditions. The Geneactiv accelerometer has been proven to be reliable in examining sleep in adults (Te Lindert & Van Someren, 2013). Devices were initialized by Geneactiv PC software (version 3.2, ActivIn-sights Ltd) with measurement frequency set to 50 Hz. Geneactiv data were uploaded to the computer using the same Geneactiv PC software.

Calculation of the sleep parameters was performed offline using a custom-written MATLAB program with a graphical user interface (version 2018a, The Mathworks Inc.), using the default medium threshold setting. The program was obtained directly from the authors (Te Lindert & Van Someren, 2013) and represents a validated method to transform accelerometry data into the traditional actigraphic movement counts.

Four variables, total sleep time (TST), sleep efficiency (SE%), sleep onset latency (SOL) and wake after sleep onset (WASO), were obtained by the Geneactiv data for the five nights of each experimental condition, with the support of sleep diaries.

Furthermore, constant telephone monitoring was carried out by means of calls, text messages and photographs, so as to ensure compliance with the timetable established in the sleep-restriction condition. The subjects also had to warn the experimenter when they went to bed, when they woke up and when they got out of bed. The participants were asked to keep their telephone near the bed with the ringtone activated during the night, to allow the experimenter to wake up them at the pre-established time, if she or he did not receive the text message the participant had to send upon awakening. Because daytime napping was not allowed throughout either of the experimental conditions, all actograms were checked for unintended naps by an expert, who also checked the accuracy of falling asleep and awakening times declared by subjects by means of the sleep diaries and text messages.

Mean scores of the actigraphic measures and sleep diary data obtained in the two conditions are reported in Table 1.

2.5 | Data analysis

To evaluate the effects of sleep restriction on subjective measures, sleepiness (KSS), alertness (AI) and negative mood (NMI) scores have been separately submitted to a paired samples Student's *t* test, comparing the two conditions (SRC and SC).

To investigate the relationship between sleep restriction and emotional reactivity and to control for the potential mediator effect of mood on emotional reactivity, average valence and arousal

TABLE 1 Actigraphic and sleep diary parameters

	SRC	SC			
	Mean ± *SE*	Mean ± *SE*	t_{41}	*p*	Cohen's d
Objective sleep variables (actigraphy)					
TST	265.60 ± 2.13	419.54 ± 4.56	−37.56	.00000001	−5.80
SE%	90.61 ± 0.46	89.39 ± 0.64	2.25	.03	0.35
SOL	4.48 ± 0.68	11.37 ± 2.04	−3.30	.001	−0.51
WASO	14.88 ± 0.93	29.54 ± 1.86	−11.27	.0000001	−1.74
Subjective sleep variables (diary)					
S-TST	294.10 ± 1.66	469.28 ± 4.95	−34.30	.00000001	−5.30
S-SOL	9.07 ± 1.43	11.31 ± 1.31	−2.56	.01	−0.40
S-WASO	2.02 ± 0.56	4.10 ± 1.10	−2.59	.01	−0.41
SA	0.48 ± 0.12	0.89 ± 0.16	−4.54	.00001	−0.70
Lights off time	01:54 ± 0:05	00:16 ± 0:09			
Wake up time	06:48 ± 0:05	08:05 ± 0:12			

Note: Means (and standard errors) of actigraphic and sleep diary parameters in the two conditions (SRC, sleep-restriction condition; SC sleep condition). The paired samples *t* test results (t, *p* and Cohen's d) are also shown.

Abbreviations: SA, subjective number of awakenings; SE%, sleep efficiency; SOL, sleep onset latency (min); S-SOL, subjective sleep onset latency (min); S-TST, subjective total sleep time (min); S-WASO, subjective wake after sleep onset (min); TST, total sleep time (min); WASO, wake after sleep onset (min); lights off time and wake up time: hour:min ± min.

ratings of the IAPS pictures were separately submitted to a mixed model analysis of covariance (ANCOVA) with condition (SC or SRC) and affective valence (pleasant, neutral or unpleasant) as within factors and delta of NMI scores as a covariate. The delta of NMI scores was calculated as the mood evaluation in the sleep condition minus the mood evaluation in the sleep-restriction condition.

For all the analyses, in the case of significant effects Bonferroni post hoc tests were carried out; the level of significance was always set at $p < .05$. The Greenhouse–Geisser correction for degrees of freedom was applied when appropriate.

Effect size estimates were given by partial eta-square for the ANOVAs and by Cohen's d for Student's *t* tests (Cumming, 2012).

3 | RESULTS

3.1 | Subjective sleepiness, mood and alertness measures

A paired samples *t* test on sleepiness scores (KSS) revealed a significant difference between the two conditions ($t_{41} = 5.67$; $p = .000001$, Cohen's d = 0.87), indicating greater sleepiness perceived in the condition of sleep restriction (mean ± standard error [*SE*], 5.55 ± 0.35) compared to the regular sleep condition (mean ± *SE*, 3.43 ± 0.32).

Analysis of the Negative Mood Index (NMI) scores also showed a significant difference between conditions ($t_{41} = 4.38$; $p = .00007$; Cohen's d = 0.68), indicating a more negative mood in the sleep-restriction condition (mean ± *SE*, 18.55 ± 1.32) than in the sleep condition (mean ± *SE*, 12.79 ± 1.23).

Similarly, Alertness Index (AI) scores showed a significant difference between conditions ($t_{41} = -6.98$; $p = .0000001$; Cohen's d = −1.08), showing that after the five nights of sleep restriction subjects felt less activated (mean ± *SE*, 12.89 ± 0.80) than after the five nights of regular sleep at home (mean ± *SE*, 20.40 ± 0.86).

3.2 | Picture valence ratings

ANCOVA on picture valence ratings did not show a significant effect of the covariate ($p = .83$). The ANCOVA showed a significant main effect for Condition ($F_{2,80} = 5.83$; $p = .02$; $\eta^2_p = 0.13$) and Affective Valence ($F_{1.7,74.4} = 377.17$; $p = .00000001$; $\eta^2_p = 0.90$); moreover, the interaction Condition × Affective Valence ($F_{2,80} = 3.63$; $p = .03$; $\eta^2_p = 0.08$) was also significant. Post hoc

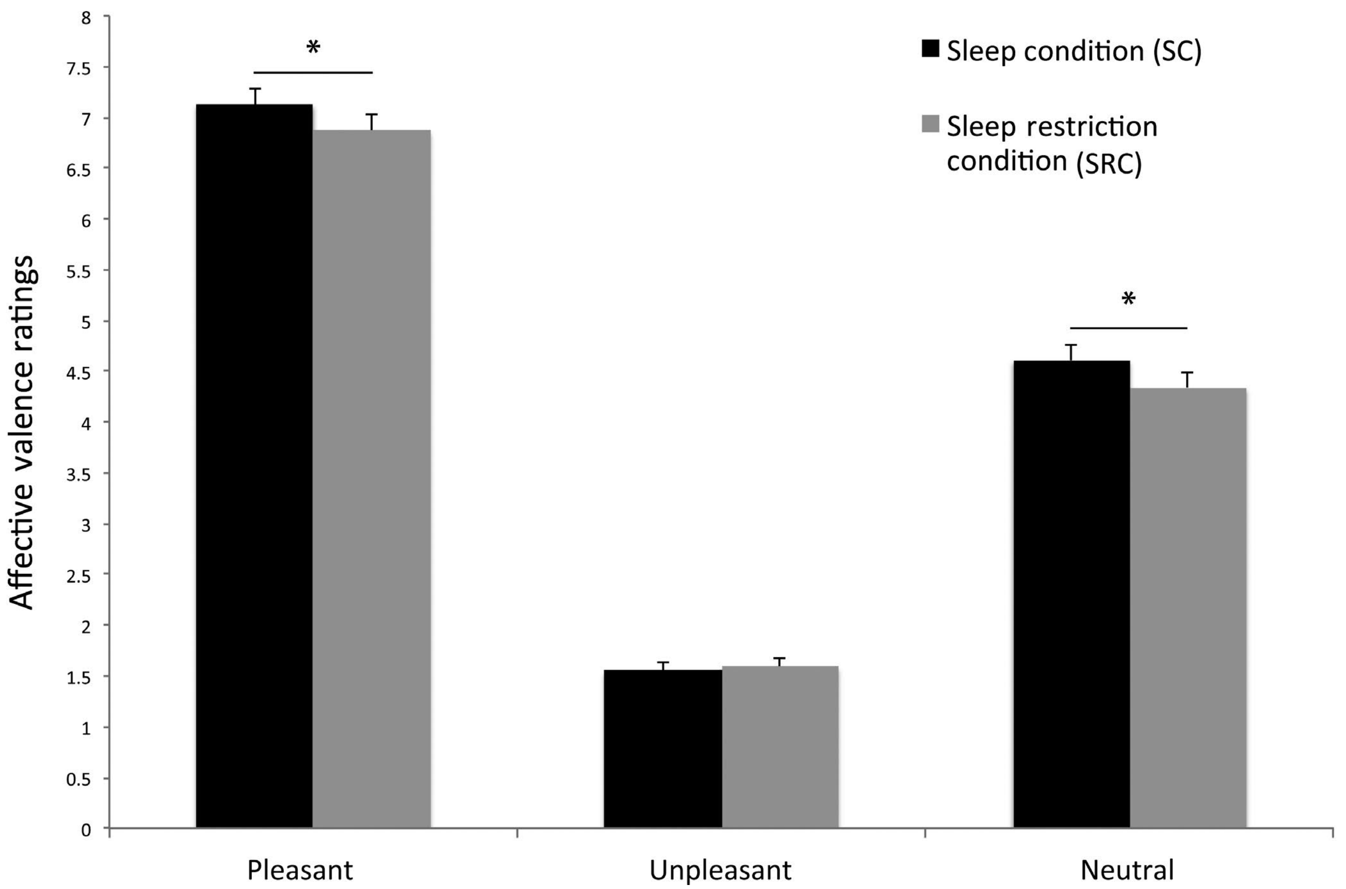

FIGURE 2 Mean valence ratings (and standard error [*SE*]) as a function of condition (sleep vs. sleep restriction) and of picture affective valence (pleasant vs. neutral vs. unpleasant). The asterisks indicate that in the sleep-restriction condition, the subjects rated positive and neutral pictures more negatively compared to the sleep condition (*$p = .04$)

comparisons revealed that subjects rated pleasant pictures less positively in the sleep-restriction condition than in the sleep condition (p = .04). In contrast, as far as the rating of unpleasant pictures is concerned, post hoc analysis did not show any significant difference between conditions (p = 1). Finally, post hoc comparisons for mean valence ratings of emotionally neutral pictures revealed that, in the sleep-restriction condition, the subjects evaluated those stimuli more negatively than in the sleep condition (p = .04) (Figure 2).

3.3 | Picture arousal ratings

ANCOVA on picture arousal ratings did not show a significant effect of the covariate (p = .25). In addition, ANCOVA showed no significant main effect for Condition ($F_{2,80} = 1.50$; $p = .22$; $\eta^2_p = 0.03$). Instead, the analysis revealed a significant main effect of Affective Valence ($F_{1.4,54.7} = 39.80$; $p = .00000001$; $\eta^2_p = 0.50$), indicating that the different emotional content of the pictures determines a different evaluation of the elicited arousal. The Condition × Affective Valence interaction was not significant ($F_{1.4,54.7} = 0.66$; $p = .47$; $\eta^2_p = 0.02$).

4 | DISCUSSION

In the present work, we aimed to evaluate the effect of 5 days of sleep restriction on emotional reactivity. Our results confirm a direct role of sleep on the affective evaluation of emotional stimuli. The few available studies investigating the cognitive effects of sleep restriction revealed a significant negative effect on executive functioning, sustained attention and long-term memory (see Lowe, Safati, & Hall, 2017), whereas insufficient evidence has been accumulated regarding other cognitive dimensions (e.g., multitask performance that involves working memory, mental arithmetic and signal-discrimination, decision-making or problem-solving abilities). In this context, the present study represents the first investigation evaluating the effects of five consecutive nights of sleep restriction on emotional reactivity in healthy young adults.

Results obtained were consistent with our hypothesis that an inadequate amount of sleep for five consecutive nights impacted on emotional reactivity, leading to a decrease in the valence rating of IAPS pictures. In particular, our results showed that sleep restriction specifically affects the evaluation of pleasant and neutral emotional stimuli, which are appraised in a more negative way. On the other hand, sleep restriction does not alter the assessment of the affective valence of unpleasant pictures. The latter result is consistent with our previous studies showing no significant effect of either acute total sleep deprivation (Tempesta et al., 2010, 2015) or poor sleep (Tempesta et al., 2015) on the evaluation of explicitly unpleasant stimuli. Of note, Pilcher et al. (2015) found the same pattern of results following one night of total sleep deprivation. It can be hypothesized that the lack of any effect on the rating of the negative stimuli may be due to the intrinsic strength and significance of these stimuli, which could presumably maintain their emotional value, irrespective of the experimental manipulation, due to their salience and goal relevance. Accordingly, our results support the interpretation of Pilcher et al. (2015), who proposed that negative pictures are more engaging than positive ones, determining stable subjective ratings in sleep-deprived subjects. In this view, the effect of sleep loss on emotional reactivity could involve automated attentional and self-regulatory processes.

Sleep restriction produced significant increases in negative mood compared to the sleep condition, together with a decreased subjective alertness. However, it is worth noting that the effect of sleep restriction on the evaluation of neutral and positive stimuli survived after removing mood changes. This suggests that the negative bias in emotional valence evaluation was not directly linked to mood changes when the participants were subjected to prolonged sleep restriction.

Regarding the arousal measure, our results, in strict accordance with previous studies (Tempesta et al., 2010, 2015), reported no significant effects of sleep restriction on subjective ratings of arousal for all types of pictures. However, they are in disagreement with studies using physiological measures (Baglioni et al., 2010; Franzen, Buysse, Dahl, Thompson, & Siegle, 2009). Franzen et al. (2009), for example, showed that negative stimuli elicit a larger pupillary reactivity in sleep-deprived individuals. Probably, physiological measures have a greater sensitivity and are more appropriate for the arousal assessment.

Our data seem to support the Walker and van der Helm hypothesis (Walker & Van der Helm, 2009), according to which sleep attenuates negative emotional reactivity. Indeed, we found that five nights of sleep restriction increases the negative emotional reactivity for neutral and positive stimuli, as suggested by the above-mentioned model. This aspect could have interesting clinical implications because chronic sleep restriction is frequently experienced due to medical conditions, sleep disorders, work demands and lifestyle (Banks & Dinges, 2007). In this regard, there is growing evidence that sleep disturbances may develop and/or maintain several clinical symptoms expressed in mood disorders (Baglioni et al., 2011; Buysse, 2004) or in post-traumatic stress disorder (PTSD; Germain, Buysse, & Nofzinger, 2008). Because the architecture and amount of sleep are disrupted in these clinical populations, sleep-dependent emotional reactivity could be altered, leading to more negative reactions to life events, at the expense of positive emotional experiences.

In the present study, objective measures of sleep duration confirmed that the protocol was successful in restricting sleep by altering participants' sleep length. Indeed, actigraphic data showed that following chronic sleep restriction the time spent asleep (TST) decreased, as well as WASO and SOL, whereas sleep efficiency increased, pointing to an increased homeostatic sleep drive. However, a potential limitation of our study is linked to the nature of the prolonged sleep restriction protocol, which is typically characterized by the lack of a laboratory setting. This aspect may have limited the experimental control over environmental factors. In addition, this study focused on effects of sleep restriction on emotional reactivity across 5 days, which did not allow the assessment of day-to-day changes. Moreover, whether the effect of sleep restriction is cumulative cannot be answered by our study: indeed, after chronic sleep restriction, long-term behavioural adaptation could take place, bringing emotional reactivity back to basal levels. Finally, the exclusive use of subjective rating scales for evaluating emotional reactivity is a potential limitation. For example, regarding the evaluation of arousal, it would have been useful to include an objective measure of psychophysiological activation. Future studies on the effects of sleep restriction should add objective measures of emotional reactivity and physiological measures of the brain, including sleep parameters, to investigate the mechanisms by which prolonged sleep loss alters emotional processing.

In conclusion, the present study indicates, for the first time, that five consecutive nights of sleep restriction causes significant alterations in emotional reactivity, giving way to a more negative evaluation of both neutral and positive stimuli. These effects are particularly interesting because chronic sleep restriction is a common and underestimated health problem in the general population. Therefore, our results further indicate that an adequate amount of sleep is essential for appropriate emotional reactivity.

AUTHOR CONTRIBUTIONS

The authors discussed the contents of this article together. DT and MF conceived the study, and elaborated the theoretical framework and the research hypotheses. DT and FS collected and analysed the data. LDG provided a significant contribution to the discussion. The final version of the manuscript was written by DT and MF.

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REFERENCES

Akerstedt, T., & Gillberg, M. (1990). Subjective and objective sleepiness in the active individual. *International Journal of Neuroscience*, *52*, 29–37. https://doi.org/10.3109/00207459008994241

Baglioni, C., Battagliese, G., Feige, B., Spiegelhalder, K., Nissen, C., Voderholzer, U., … Riemann, D. (2011). Insomnia as a predictor of depression: A meta-analytic evaluation of longitudinal epidemiological studies. *Journal of Affective Disorders*, *135*, 10–19. https://doi.org/10.1016/j.jad.2011.01.011

Baglioni, C., Lombardo, C., Bux, E., Hansen, S., Salveta, C., Biello, S., … Espie, C. A. (2010). Psychophysiological reactivity to sleep-related emotional stimuli in primary insomnia. *Behaviour Research and Therapy*, *48*, 467–475. https://doi.org/10.1016/j.brat.2010.01.008

Banks, S., & Dinges, D. F. (2007). Behavioral and physiological consequences of sleep restriction. *Journal Clinical Sleep Medicine*, *15*, 519–528.

Baran, B., Pace-Schott, E. F., Ericson, C., & Spencer, R. M. (2012). Processing of emotional reactivity and emotional memory over sleep. *Journal of Neuroscience*, *32*, 1035–1042. https://doi.org/10.1523/JNEUROSCI.2532-11.2012

Bastien, C. H., Vallières, A., & Morin, C. M. (2001). Validation of the Insomnia Severity Index as an outcome measure for insomnia research. *Sleep Medicine*, *2*, 297–307. https://doi.org/10.1016/s1389-9457(00)00065-4

Bradley, M. M., & Lang, P. J. (1994). Measuring emotion: The self-assessment manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry*, *25*, 49–59. https://doi.org/10.1016/0005-7916(94)90063-9

Buysse, D. J. (2004). Insomnia, depression and aging. Assessing sleep and mood interactions in older adults. *Geriatrics*, *59*, 47–51.

Buysse, D. J., Reynolds, C. F., Monk, T. H., Berman, S. R., & Kupfer, D. J. (1989). The Pittsburgh Sleep Quality Index: A new instrument for psychiatric practice and research. *Psychiatry Research*, *28*, 193–213. https://doi.org/10.1016/0165-1781(89)90047-4

Castronovo, V., Galbiati, A., Marelli, S., Brombin, C., Cugnata, F., Giarolli, L., … Ferini-Strambi, L. (2016). Validation study of the Italian version of the Insomnia Severity Index (ISI). *Neurological Sciences*, *37*, 1517–1524. https://doi.org/10.1007/s10072-016-2620-z

Cumming, G. (2012). *Understanding the new statistics: Effect sizes, confidence intervals, and meta-analysis*. New York, NY: Routledge.

Curcio, G., Tempesta, D., Scarlata, S., Marzano, C., Moroni, F., Rossini, P. M., … De Gennaro, L. (2013). Validity of the Italian version of the Pittsburgh Sleep Quality Index (PSQI). *Neurological Sciences*, *34*, 511–519. https://doi.org/10.1007/s10072-012-1085-y

Franzen, P. L., Buysse, D. J., Dahl, R. E., Thompson, W., & Siegle, G. J. (2009). Sleep deprivation alters pupillary reactivity to emotional stimuli in healthy young adults. *Biological Psychology*, *80*, 300–305. https://doi.org/10.1016/j.biopsycho.2008.10.010

Germain, A., Buysse, D. J., & Nofzinger, E. (2008). Sleep-specific mechanisms underlying posttraumatic stress disorder: Integrative review and neurobiological hypotheses. *Sleep Medicine Review*, *12*, 185–195. https://doi.org/10.1016/j.smrv.2007.09.003

Ghisi, M., Flebus, G., Montano, A., Sanavio, E., & Sica, C. (2006). *Beck Depression Inventory-II: Edizione Italiana*. Firenze, Italy: Giunti Editore.

Goldstein-Piekarski, A. N., Greer, S. M., Saletin, J. M., & Walker, M. P. (2015). Sleep deprivation impairs the human central and peripheral nervous system discrimination of social threat. *Journal of Neuroscience*, *35*, 10135–10145. https://doi.org/10.1523/JNEUROSCI.5254-14.2015

Groch, S., Wilhelm, I., Diekelmann, S., & Born, J. (2013). The role of REM sleep in the processing of emotional memories: Evidence from behavior and event-related potentials. *Neurobiology of Learning and Memory*, *99*, 1–9. https://doi.org/10.1016/j.nlm.2012.10.006

LaBar, K. S., & Cabeza, R. (2006). Cognitive neuroscience of emotional memory. *Nature Reviews Neuroscience*, *7*, 54–64. https://doi.org/10.1038/nrn1825

Lang, P. J. (1980). Behavioral treatment and bio-behavioral assessment: Computer applications. In J. B. Sidowski, J. H. Johnson, & T. A. Williams (Eds.), *Technology in mental health care delivery systems* (pp. 119–137). Norwood, NJ: Ablex.

Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (2008). *International affective picture system (IAPS): Affective ratings of pictures and instruction manual. Technical Report A-8*. Gainesville, FL: University of Florida.

Lang, P. J., Greenwald, M. K., Bradley, M. M., & Hamm, A. O. (1993). Looking at pictures: Affective, facial, visceral, and behavioral reactions. *Psychophysiology*, *30*, 261–273. https://doi.org/10.1111/j.1469-8986.1993.tb03352.x

Lara-Carrasco, J., Nielsen, T. A., Solomonova, E., Levrier, K., & Popova, A. (2009). Overnight emotional adaptation to negative stimuli is altered by REM sleep deprivation and is correlated with intervening dream emotions. *Journal of Sleep Research*, *18*, 178–187. https://doi.org/10.1111/j.1365-2869.2008.00709.x

Lowe, C. J., Safati, A., & Hall, P. A. (2017). The neurocognitive consequences of sleep restriction: A meta-analytic review. *Neuroscience & Biobehavioral Reviews*, *80*, 586–604. https://doi.org/10.1016/j.neubiorev.2017.07.010

Moroni, L., Bettinardi, O., Vidotto, G., Balestroni, G., Bruletti, G., Giorgi, I., & Bertolotti, G. (2006). Anxiety and depression short scale: Norms for its use in rehabilitation. *Monaldi Archives for Chest Disease*, *66*, 255–263. https://doi.org/10.4081/monaldi.2006.516

Motomura, Y., Kitamura, S., Oba, K., Terasawa, Y., Enomoto, M., Katayose, Y., … Mishima, K. (2013). Sleep debt elicits negative emotional reaction through diminished amygdala-anterior cingulate functional connectivity. *PLoS ONE*, *8*(2), e56578. https://doi.org/10.1371/journal.pone.0056578

Pilcher, J. J., Callan, C., & Posey, J. L. (2015). Sleep deprivation affects reactivity to positive but not negative stimuli. *Journal of Psychosomatic Research*, *79*, 657–662. https://doi.org/10.1016/j.jpsychores.2015.05.003

Reddy, R., Palmer, C. A., Jackson, C., Farris, S. G., & Alfano, C. A. (2017). Impact of sleep restriction versus idealized sleep on emotional experience, reactivity and regulation in healthy adolescents. *Journal of Sleep Research*, *26*, 516–525. https://doi.org/10.1111/jsr.12484

Stern, R. A., Arruda, J. E., Hooper, C. R., Wolfner, G. D., & Morey, C. E. (1997). Visual analogue mood scales to measure internal mood state in neurologically impaired patients: Description and initial validity evidence. *Aphasiology*, *11*, 59–71. https://doi.org/10.1080/02687039708248455

Te Lindert, B. H. W., & Van Someren, E. J. W. (2013). Sleep estimates using microelectromechanical systems (MEMS). *Sleep*, *36*, 781–789. https://doi.org/10.5665/sleep.2648

Tempesta, D., Couyoumdjian, A., Curcio, G., Moroni, F., Marzano, C., De Gennaro, L., & Ferrara, M. (2010). Lack of sleep affects the evaluation of emotional stimuli. *Brain Research Bulletin*, *82*, 104–108. https://doi.org/10.1016/j.brainresbull.2010.01.014

Tempesta, D., De Gennaro, L., Natale, V., & Ferrara, M. (2015). Emotional memory processing is influenced by sleep quality. *Sleep Medicine*, *16*, 862–870. https://doi.org/10.1016/j.sleep.2015.01.024

Tempesta, D., Socci, V., De Gennaro, L., & Ferrara, M. (2018). Sleep and emotional processing. *Sleep Medicine Reviews*, *40*, 183–195. https://doi.org/10.1016/j.smrv.2017.12.005

Wagner, U., Fischer, S., & Born, J. (2002). Changes in emotional responses to aversive pictures across periods rich in slow-wave sleep versus rapid eye movement sleep. *Psychosomatic Medicine*, *64*, 627–634. https://doi.org/10.1097/01.psy.0000021940.35402.51

Wagner, U., Hallschmid, M., Rasch, B., & Born, J. (2006). Brief sleep after learning keeps emotional memories alive for years. *Biological Psychiatry*, *60*(7), 788–790, https://doi.org/10.1016/j.biopsych.2006.03.061

Walker, M. P., & Van der Helm, E. (2009). Overnight therapy? The role of sleep in emotional brain processing. *Psychological Bulletin*, *135*, 731–748. https://doi.org/10.1037/a0016570

Wheeler, R. E., Davidson, R. J., & Tomarken, A. J. (1993). Frontal brain asymmetry and emotional reactivity: A biological substrate of affective style. *Psychophysiology*, *30*, 82–89. https://doi.org/10.1111/j.1469-8986.1993.tb03207.x

Yoo, S. S., Gujar, N., Hu, P., Jolesz, F. A., & Walker, M. P. (2007). The human emotional brain without sleep – a prefrontal amygdala disconnect. *Current Biology*, *17*, 877–878. https://doi.org/10.1016/j.cub.2007.08.007

Zohar, D., Tzischinsky, D. O., Epstein, R., & Lavie, P. (2005). The effects of sleep loss on medical residents' emotional reactions to work events: A cognitive-energy model. *Sleep*, *28*, 47–54. https://doi.org/10.1093/sleep/28.1.47

How to cite this article: Tempesta D, Salfi F, De Gennaro L, Ferrara M. The impact of five nights of sleep restriction on emotional reactivity. *J Sleep Res*. 2020;29:e13022. https://doi.org/10.1111/jsr.13022