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Using emotion regulation strategies after sleep deprivation: ERP and behavioral findings

Jinxiao Zhang [1,2] · Esther Yuet Ying Lau [3,4] · Janet Hui-wen Hsiao [1]

Abstract
Sleep deprivation is suggested to impact emotion regulation, but few studies have directly examined it. This study investigated the influence of sleep deprivation on three commonly used emotion regulation strategies (distraction, reappraisal, suppression) in Gross's (1998) process model of emotion regulation. Young healthy adults were randomly assigned to a sleep deprivation group (SD; $n = 26$, 13 males, age = 20.0 ± 1.7) or a sleep control group (SC; $n = 25$, 13 males, age = 20.2 ± 1.7). Following 24-h sleep deprivation or normal nighttime sleep, participants completed an emotion regulation task, in which they naturally viewed or applied a given emotion regulation strategy towards negative pictures, with electroencephalographic (EEG) recordings. A reduction in the centroparietal late positive potential (LPP) amplitudes towards negative pictures from the naturally viewing condition to a regulated condition was calculated as an index of regulatory effects. Comparisons between the two groups indicated that sleep deprivation significantly impaired the regulatory effects of distraction and reappraisal on LPP amplitudes. Suppression did not reduce LPP amplitudes in either group. In addition, habitual sleep quality moderated the effect of sleep deprivation on subjective perception of emotional stimuli, such that sleep deprivation only made good sleepers perceive negative pictures as more unpleasant and more arousing, but it had no significant effect on poor sleepers' perception of negative pictures. Altogether, this study provides the first evidence that sleep deprivation may impair the effectiveness of applying adaptive emotion regulation strategies (distraction and reappraisal), creating potentially undesirable consequences to emotional well-being.

Keywords Sleep deprivation · Emotion regulation · Late positive potential · Reappraisal · Distraction · Suppression

Introduction

Sleep has a close relationship with emotional functioning and emotional health. Sleep loss has been found to impact various emotional functioning at subjective or behavioral levels (for reviews, see Beattie et al., 2015 and Watling et al., 2016), including mood states (Short & Louca, 2015), perception of emotional stimuli, such as pictures of emotional scenes (Daniela et al., 2010; Cote et al., 2015) and human facial emotions (van der Helm et al., 2010; Cote et al., 2014), emotional impulsivity (Anderson & Platten, 2011), emotional expressiveness (Minkel et al., 2011), and emotional intelligence (Killgore et al., 2008). In addition, at the neural level, an increasing number of studies consistently observed decreased functional connectivity within the brain network of prefrontal cortex (PFC)/anterior cingulate cortex (ACC) and subcortical limbic structures in response to emotional stimuli after sleep deprivation (Yoo et al., 2007; Gujar et al., 2011; Chuah et al., 2010; Simon et al., 2015), suggesting global deficits of monitoring and regulatory control of emotional functioning without sleep (Palmer & Alfano, 2017). Moreover, sleep loss or disrupted sleep is a common risk factor for a range of emotional disorders, such as depression and anxiety (Harvey, 2011; Wulff et al., 2010). Recently, there is a growing body of theoretical models and empirical evidence suggesting that emotion regulation is one important mechanism explaining the relationship between sleep and emotional functioning/disorders (O'Leary et al., 2016; Walting et al., 2016). Nevertheless, only a paucity of studies directly examined the impact of sleep loss on emotion regulation.

✉ Jinxiao Zhang
jinx.zhang@stanford.edu

1 Department of Psychology, The University of Hong Kong, Hong Kong, China

2 Department of Psychology, Stanford University, Stanford, CA, USA

3 Department of Psychology, The Education University of Hong Kong, Hong Kong, China

4 Centre for Psychosocial Health, The Education University of Hong Kong, Hong Kong, China

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Emotion regulation is a process that enables us to adjust the intensity, the timing, and the way we experience emotions and express them (Gross, 1998). The ability to regulate maladaptive emotions (e.g., too intense or contextually inappropriate) is vital to mental well-being (Gross & Muñoz, 1995). In the process model of emotion regulation (Gross, 1998), emotion regulation comprises situation selection/modification, attentional deployment, cognitive change, and response modulation at different points during the dynamic process of emotion generation. At each emotion regulation point, there are certain strategies to voluntarily modulate emotions (Gross, 1998; Palmer & Alfano, 2017). There are three commonly used emotion regulation strategies: distraction, reappraisal, and suppression. Distraction refers to a deployment of attention away from emotionally salient stimuli/content and happens at a relatively early stage of emotion regulation. Reappraisal involves reevaluation of the meaning of an emotionally salient stimulus or event and thus happens at a later stage than distraction. Both distraction and reappraisal belong to the antecedent-focused division of emotion regulation (Gross, 1998) and have been shown to effectively attenuate negative emotions (Urry, 2010; Seminowicz & Davis, 2007; Jackson et al., 2000; Phan et al., 2005; Goldin et al., 2008). In contrast, suppression is at the final stage of emotion regulation and belongs to the response-focused division (Gross, 1998). Evidence for the effectiveness of suppression in regulating emotions is mixed (effective: Dunn et al., 2009; Hayes et al., 2010; ineffective: Dan-Glauser & Gross, 2011; Roberts et al., 2008).

Some studies have provided clues to the relationship between sleep and emotion regulation. For example, Mauss and colleagues (2013) had 156 adult participants apply cognitive reappraisal to regulate sad feelings induced by video clips. They found that participants with poorer past week's sleep quality were less capable to implement cognitive reappraisal effectively. Similarly, higher usage of sleep medication as indicated in the Pittsburgh Sleep Quality Index (PSQI) was associated with weaker PFC activations during reappraisal emotion regulation in adults (Minkel et al., 2012). However, these two studies were both cross-sectional in nature, rendering it difficult to conclude any causal relationship between sleep loss and emotion regulation. On the other hand, studies have reported reduced self- or teacher-reported emotion regulation after experimental sleep restriction (1 hour less than the habitual baseline) for 4 or 5 days among children (7-12 years old; Gruber et al., 2012; Vriend et al., 2013). Similar effects of sleep restriction on emotion regulation were found among adolescents and college students based on self- or parent-reported data (Baum et al. 2014). Unfortunately, these experimental or longitudinal studies all depended on subjective reports to measure emotion regulation and have not involved explicit application of strategies to regulate emotional responses. Taken together, the influence of sleep loss on the use of emotion regulation strategies remains unknown to date (Watling et al., 2016; Palmer & Alfano, 2017). However, existing studies have suggested a potential impact of sleep deprivation on these emotion regulation strategies. Poor sleep quality has been associated with poor behavioral performance and weaker PFC activations in applying reappraisal (Mauss, Troy, & LeBourgeois, 2013; Minkel et al., 2012), suggesting that reappraisal may be less effective after sleep loss. Sleep loss also was found to affect attention control (Goel et al., 2009; Chuah et al., 2010), suggesting that attentional distraction may be impaired by sleep deprivation. Sleep deprivation was reported to affect behavioral inhibition (Anderson & Plattern, 2011) and emotional expressiveness (Minkel et al., 2011; Schewarz et al., 2013), suggesting a potential impact of sleep deprivation on suppression of emotional responses. The objective of the current study was to investigate the influence of 24-h sleep deprivation on the use of the three common emotion regulation strategies: distraction; reappraisal; and suppression.

In addition to behavioral measurements in emotion regulation tasks, the late positive potential (LPP) component of the event-related potential (ERP) may serve as a useful index of emotion regulation at the neural level (for a review, see Hajcak, MacNamara, & Olvet, 2010). The LPP is an established sensitive and reliable measure of processing of emotionally charged stimuli (Olofsson & Polich, 2007; Hajcak et al., 2010), beginning approximately 300 ms following stimulus onset and lasting for as long as 5 s during the stimulus presentation with maximal magnitude typically at the central-parietal region (Thiruchselvam et al., 2011; Paul et al., 2013; Parvaz et al., 2012). A large body of studies has found that the LPP magnitude is reliably enhanced for emotional visual stimuli compared with neutral stimuli (Keil et al., 2002; Hajcak & Olvet, 2008; Schupp et al., 2004). Desirably, it seems that the LPP is not sensitive to low-level perceptual features, such as image size (De Cesarei & Codispoti, 2006) and picture complexity (Bradley et al., 2007) or repetitive habituation (Codispoti et al., 2006), making it a robust neural index of emotional processing (Hajcak et al., 2010).

More importantly, LPP amplitudes to stimuli are highly sensitive to the manipulation of emotion regulation strategies. Specifically, reductions in LPP towards negative pictures were observed when participants were instructed to use the emotion regulation strategy of distraction (Dunning & Hajcak, 2009; Thiruchselvam et al., 2011). In addition, the LPP amplitude is reduced if negative stimuli are reappraised in a neutral way (Forti & Hajcak, 2008) or inversely heightened if neutral stimuli are reappraised in an aversive way (MacNamara et al., 2009). Recent evidence also has shown reduced LPP after applying the emotion regulation strategy of suppression to emotional stimuli (Korb et al., 2012; Paul et al., 2013). Taken together, LPP seems to be able to index sensitively the regulatory effect of emotion regulation strategies (e.g., distraction, reappraisal, and suppression).

In addition, recent studies have also found a modulation effect of sleep deprivation on the 300-800 ms LPP but with mixed results (Alfarra et al., 2015; Cote et al., 2015). One study reported that LPP towards nonemotional stimuli increased after sleep deprivation but not towards emotional stimuli (Alfarra et al., 2015). In contrast, another study found enhanced LPP towards emotional stimuli in sleep deprived participants as compared with those with normal sleep (Cote et al., 2015).

The present study

To investigate the impact of sleep deprivation on applying emotion regulation strategies, we measured the LPP and behavioral ratings in an emotion regulation task in individuals who were randomly assigned to either undergo 24-h sleep deprivation or have normal nighttime sleep. On the emotion regulation task (adapted from Thiruchеselvam et al., 2011 and Parvez et al., 2012), the difference between regulated and unregulated conditions was used to index the effectiveness of applying an emotion regulation strategy (see *Methods* for details). It was hypothesized that sleep deprivation would impair the effectiveness of emotion regulation strategies as measured by behavioral and neural measures. To examine the potential moderating effects of individual differences (Van Dongen et al., 2004; Beattie et al., 2015), we also measured participants' habitual sleep quality. It was predicted that habitually good sleepers would be more susceptible to the impact of sleep deprivation, whereas habitually poor sleepers would be less affected, because the latter were more accustomed to the effects of sleep loss or sleep disturbance in their daily life.

Methods

Participants

Fifty-seven healthy participants were initially recruited and randomly assigned to the Sleep Deprivation (SD) or the Sleep Control (SC) group. The final sample consisted of 51 participants, with 3 dropouts in the middle of the study period, 1 excluded due to taking cold medication, and 2 excluded due to actigraphy-verified short sleep duration (<6 hours) on Day 1 and Day 2, respectively. The two groups (SC: $n = 25$; SD: $n = 26$) were similar in their age, gender, scores in Pittsburgh Sleep Quality Index (PSQI), and Emotion Regulation Questionnaire (ERQ), all $ps > 0.05$ (Table 1). All participants were: aged between 18 and 30 years, right-handed, with normal or corrected to normal vision, with no history of sleep disorders, head trauma, or psychiatric conditions, free of current medication and tobacco use, and with no recent shift work. To avoid extraneous effects of transportation, we also limited participants to those living within 20-min walking distance to the laboratory.

Study protocol

The 3-day study protocol was approved by the Human Research Ethics Committee at The University of Hong Kong, and participants' informed consents were obtained before the study commencement. On Day 1, all participants completed a battery of electronic questionnaires (including PSQI, ERQ, and others[1]) and maintained a normal sleep schedule.[2] We made random group assignments on Day 2 afternoon and informed the participants of their group assignments. The SC group continued to maintain normal sleep on Day 2 night. The SD group remained awake and was monitored by trained experimenters at the laboratory throughout the night. Participants' activity during the sleep deprivation was limited to Internet, reading, playing cards, conversations, and short walks. Overarousing activities, such as watching videos of strong emotional valence, intense physical exercise, and playing computer games, were prohibited. They were offered snacks at 01:00, 03:00, and 05:00 (approximately 100 kcal for each time) and had breakfast at 08:00 (no caffeine). Between 10:00 and 13:00 on Day 3, after assessments of sleepiness and vigilance, participants completed the emotion regulation task. Throughout the 3-day study period, participants were asked to abstain from caffeine, alcohol, and daytime naps, and their sleep-wake behaviors were monitored by an actigraphy watch (Micro Sleep Watch, Ambulatory Monitoring, Inc.). They were compensated and debriefed on the end of the experimental day.

Questionnaires

The Chinese Version of PSQI (Buysee, 1989; Tsai et al., 2005) was used to assess habitual sleep quality in the previous month. Poor sleepers were identified by a cutoff score of no less than 5. A Chinese version of the Emotion Regulation Questionnaire (ERQ; Gross & John, 2003) was adopted to measure the tendency to regulate emotion in the facet of reappraisal (6 items) and suppression (4 items). A Chinese version of the Stanford Sleepiness Scale (SSS) assessed participants' self-reported state sleepiness level, ranging from 1 (wide awake) to 7 (entering sleep) (Hoddes et al., 1973).

Psychomotor vigilance task

A computer-based Psychomotor Vigilance Task (PVT) (E-prime 2.0, Psychology Software Tools, Pittsburgh, PA) was conducted to assess participants' vigilance. On each trial, a 1,000-ms target

[1] Other questionnaires included Composite Scale of Morningess, International Personality Item Pool Big-Five Domain Scale, and Depression Anxiety Stress Scale. They were not of interest for the current study and thus are not reported.
[2] Normal sleep schedule in this study: time in bed at least 7 hours and getting up no later than 10:00 at participants' residence.

Table 1 Demographic and sleep information of the SC and the SD groups

	SC group (n = 25)	SD group (n = 26)
Age (yr)	20.20 ± 1.73	20.04 ± 1.70
Gender	13 males, 12 females	13 males, 13 females
ERQ reappraisal	27.56 ± 4.51	28.58 ± 7.23
ERQ suppression	13.96 ± 3.63	14.46 ± 4.80
PSQI	5.72 ± 2.21	4.81 ± 1.92
Sleep duration-Day 1 night (min)	469.5 ± 47.2	457.4 ± 40.8
Sleep duration-Day 2 night (min)	457.3 ± 60.0	-
SSS*	2.44 ± 0.58	4.31 ± 1.35
PVT lapses*	0.24 ± 0.66	7.65 ±13.56
PVT response time (ms)*	344.1 ± 39.0	406.0 ± 69.3

ERQ: Emotion Regulation Questionnaire; PSQI: Pittsburgh Sleep Quality Index; ERQ: Emotion Regulation Questionnaire; SSS: Stanford Sleepiness Scale; PVT: Psychomotor Vigilance Task.

*Significant difference between the SC and the SD groups, $p < 0.01$.

(a red circle) appeared at the center of the screen, and participants were asked to respond as quickly as possible by pressing a button. The inter-trial intervals ranged from 3000 to 10,000 ms. There were 80 trials in the task (about 10 minutes). Response time (in ms) was recorded for each trial, and no response or response time longer than 1,000 ms was counted as a lapse.

Emotion regulation task

Participants were instructed in using three emotion regulation strategies (i.e., distraction, reappraisal, and suppression) on Day 1. In the "maintain" condition (as a baseline), participants were asked to maintain their attention to a picture and react in a natural way. In the "distract" condition, they were asked to think of unrelated thoughts or neutral scenes to feel emotionally neutral while looking at a picture, such as generating mental presentations of a supermarket or geometric patterns. In the "reappraise" condition, participants were instructed to reinterpret the content of a picture to feel emotionally neutral, such as by imagining the scene to be actually in a movie or by thinking that the situation is getting better. In the "suppress" condition, participants were required to inhibit their inner feelings and potential facial or bodily responses not to show their feelings to others. Manipulation check was conducted as follows: in the "distract" and "reappraise" conditions, participants were asked to report the exact way of implementing distraction and reappraisal strategies, and the experimenter would provide feedback in case of inaccurate use of the strategies. In the "suppress" condition, the experimenter checked whether the participants showed emotional expressions to negative pictures. On Day 3, each participant had a brief guided review of the strategies before the emotion regulation task.

At the beginning of the task, participants had a practice of 9 trials (3 "maintain"; 2 "distract"; 2 "reappraise"; and 2 "suppress"). Afterwards, they had 6 blocks of 28 trials (168 trials in total) consisting of 2 "distraction" blocks, 2 "reappraisal" blocks, and 2 "suppression" blocks. In each block, there were 7 trials of neutral pictures to "maintain," 7 trials of negative pictures to "maintain," and 14 trials of negative pictures to "regulate" (using one specified emotion regulation strategy). For example, in a "distraction" block, there were 7 neutral-maintain trials, 7 negative-maintain trials, and 14 negative-distract trials. The order of the 28 trials was randomized in each block, and the 6 blocks were counterbalanced across participants. The blocking design was adopted to avoid participants' potential difficulties switching between distinct strategies or combined use of multiple strategies (Thiruchеselvam et al., 2011). Pictures in the emotion regulation task were standardized pictures from the International Affective Picture System (IAPS; Lang et al., 2008).[3] The negative pictures were randomly distributed for the four "negative" conditions, and the valence and arousal ratings were not different among the conditions. Each trial began with a fixation cross for 500 ms or 1,000 ms (randomly determined to avoid any

[3] Valence: $M = 5.09$, $SD = 0.52$ for neutral pictures, and $M = 2.76$, $SD = 0.83$ for negative; arousal: $M = 3.22$, $SD = 0.69$ for neutral, and $M = 5.66$, $SD = 0.79$ for negative pictures. IAPS No. of neutral pictures used in the task: 1333, 1670, 2039, 2221, 2273, 2372, 2383, 2396, 2446, 2514, 2597, 2840, 5130, 5395, 5471, 5533, 5781, 7000, 7002, 7004, 7009, 7012, 7016, 7020, 7025, 7033, 7036, 7040, 7045, 7052, 7059, 7062, 7090, 7150, 7170, 7185, 7187, 7217, 7237, 7490, 7504, 7560, 7632, 7705; IAPS No. of negative pictures used in the task: 1033, 1052, 1111, 1113, 1205, 1220, 1271, 1274, 1280, 1300, 1304, 1525, 1932, 2115, 2120, 2345.1, 2703, 2716, 2750, 2900, 3001, 3010, 3015, 3016, 3019, 3022, 3059, 3060, 3062, 3063, 3064, 3069, 3101, 3102, 3131, 3150, 3160, 3170, 3181, 3225, 3261, 3400, 3500, 3550.1, 4664.2, 5961, 5970, 5973, 6021, 6022, 6213, 6242, 6300, 6312, 6314, 6370, 6520, 6555, 6560, 6561, 6570.2, 6834, 6910, 6930, 7013, 7046, 7079, 7136, 7361, 7380, 8485, 9000, 9006, 9007, 9040, 9041, 9043, 9045, 9050, 9101, 9102, 9120, 9140, 9150, 9163, 9171, 9181, 9187, 9230, 9253, 9254, 9265, 9280, 9291, 9295, 9301, 9321, 9322, 9326, 9331, 9340, 9373, 9402, 9404, 9405, 9412, 9419, 9421, 9423, 9425, 9427, 9433, 9440, 9470, 9490, 9500, 9520, 9530, 9570, 9571, 9594, 9610, 9622, 9635.1, 9800, 9810, 9832, 9902, 9905, 9910, 9921, 9926, 9940.

time-locking effects on the ERPs), followed by a neutral or negative picture presented for 7,000 ms with 80% size of the entire screen (Fig. 1). At 1,000 ms after the picture onset, an auditory instruction ("maintain," "reappraise," "distract," or "suppress") was played for approximately 900 ms (1,000-1,900 ms). Auditory instructions in the middle rather than precedent cue words were used to avoid the advanced implementation of strategies before stimuli onsets, and auditory instructions were found not to interrupt post-instruction LPP (Parvez et al., 2012; Thiruchselvam et al., 2011). The word "BLINK" was presented for 800 ms after the picture presentation. Afterwards, participants rated their valence (happy 1–9 unhappy) and arousal (calm 1–9 excited) levels on a 1-9 scale during the picture presentation, with no time limit. Participants were asked to refrain from eye blinks during the picture presentation.

EEG recording and data processing

EEG signals were recorded using ANT EEG system (ASA4 software) with 64 standard Ag/AgCl electrodes on a WaveGuard cap (ANT BV, Enschede, Netherlands), based on the international 10-20 system. We adopted an AFz ground and a sampling rate at 512 Hz. During the EEG set-up, we kept the channel impedance levels below 20 kΩ.

With EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) toolboxes, EEG data was re-referenced to the average of two mastoid channels. EEG epochs in the emotion regulation task were extracted from pre-picture 200 ms to 5,000 ms after the picture onset with baseline correction from −200 to 0 ms. Epoched EEG data were filtered with a high pass at 0.05 Hz and a low pass at 30 Hz (24 dB/oct). Artifacts were corrected according to established procedures (Jung et al., 2000), and epochs with voltage changes greater than 100 μV within a 200-ms window (moving 100 ms every time) or absolute voltage greater than 75 μV in the centro-parietal region (CPz, Cz, Pz, CP1, and CP2) were rejected. On average, 8.0% of the epochs were rejected, and the rejection rate did not differ across conditions, $p > 0.05$. Uncontaminated epochs were averaged to generate the average ERPs for each condition in the emotion regulation task (i.e., neutral-maintain, negative-maintain, negative-distract, negative-reappraise, and negative-suppress). Following findings in previous studies that LPP is typically most pronounced at the centro-parietal area (Hajcak et al., 2010; Thiruchselvam et al., 2011), we calculated the preinstruction LPP (mean amplitude of 300-800 ms; Cote et al., 2015; Alfarra et al., 2015) and the postinstruction LPP (mean amplitude of 1900-5000 ms) at CPz. Two participants' left mastoid channel was malfunctioning, and therefore their data were not included in further analysis.

Data analysis

To test the influence of experimental sleep deprivation and habitual sleep quality on the effectiveness of emotion regulation strategies, we first performed 2 (group: SC vs. SD) × 2 (PSQI type: good sleeper vs. poor sleeper) × 5 (condition: neutral-maintain, negative-maintain, negative-distract, negative-reappraise, negative-suppress) repeated-measures ANOVA on the behavioral ratings and the post-instruction LPP amplitudes. If there was a significant group × PSQI type × condition 3-way interaction or a significant group × PSQI type 2-way interaction, 2 (group) × 5 (condition) repeated-measures ANOVA would be conducted separately in habitual good sleepers and habitual poor sleepers. If the 2 × 2 × 5 ANOVA only revealed a significant group × condition 2-way interaction, PSQI type would be excluded from the between-subject factors in subsequent analyses. A significant 2 (group) × 5 (condition) interaction would be followed by a 2 (group) × 2 (condition: neutral-maintain vs. negative-maintain) repeated-measures ANOVA to test the validity of LPP and a 2 (group) × 4 (condition: negative-maintain, negative-distract, negative-reappraise, negative-suppress) repeated-measures ANOVA to test the group effect on emotion regulation strategies. If there was a significant 2 (group) × 4 (condition) interaction, planned paired *t*-tests would be performed in pairs of negative-maintain vs. negative-distract, negative-maintain vs. negative-reappraise, and negative-maintain vs. negative-suppress in the SC group and the SD group separately. A 2 (group) × 2 (picture: neutral vs. negative) repeated-measures ANOVA also was conducted to test the validity of the preinstruction LPP.

Results

Sleep manipulation check

As shown in the actigraphy data, the SC group and the SD group slept for similar amount of time on Day 1 night, $t(49) = 0.982$, $p = 0.331$, Cohen's $d = 0.28$ (Table 1). On Day 2 night, participants in the SC group slept an average of 457.3 min, similar to their sleep duration on Day 1, $t(24) = 0.895$, $p = 0.380$.

The SSS and PVT data revealed the effects of our sleep manipulation. On Day 3 morning, the SD group reported significantly higher sleepiness level on SSS than the SC group, $t(34.3) = 6.457$, $p < 0.001$, Cohen's $d = 2.21$ (Table 1). On the PVT (Table 1), the SD group missed significantly more targets than the SC group, $t(25.1) = 2.784$, $p = 0.010$, Cohen's $d = 1.11$. In addition, the SD group responded slower than the SC group in nonlapsed PVT trials, $t(39.7) = 3.955$, $p < 0.001$, Cohen's $d = 1.26$.

Fig. 1 The emotion regulation task. A trial begins with a fixation (500 or 1,000 ms) and followed by the picture presentation. At 1,000 ms of the picture onset, there is an auditory instruction ("maintain," "reappraise," "distract," or "suppress"). A trial ends with valence and arousal ratings on a 1-9 scale. There are 6 blocks (2 blocks for each emotion regulation strategy) in the task with 28 trials in each block.

Behavioral valence and arousal ratings

To test the potential effects of individual differences in habitual sleep quality on valence and arousal ratings, PSQI type (good sleepers, poor sleepers) was included as a between-subject factor in addition to group (SC group, SD group), and condition (neutral-maintain, negative-maintain, negative-reappraise, negative-distract, negative-suppress) served as a within-subject factor. In all repeated-measures ANOVA, the Greenhouse-Geisser adjustment was adopted if sphericity was not assumed and all pairwise comparisons were performed with the Sidak correction.

Regarding valence ratings, the 2 × 2 × 5 repeated-measures ANOVA revealed a significant main effect of condition, $F(4, 188) = 100.683$, $p < 0.001$, $\eta^2 = 0.682$, and importantly a significant group by PSQI type interaction, $F(1, 47) = 10.516$, $p = 0.002$, $\eta^2 = 0.183$. However, there was no significant three-way interaction or a group by condition interaction, $ps > 0.05$. Pairwise comparisons showed that the valence rating in the neutral-maintain condition ($M = 3.863$, $SE = 0.145$) were less negative than all four negative conditions, all $ps < 0.001$. The valence rating in the negative-maintain condition ($M = 6.202$, $SE = 0.143$) was higher than the negative-reappraise ($M = 5.337$, $SE = 0.170$) and the negative-distract conditions ($M = 5.583$, $SE = 0.175$), $ps < 0.001$, but not the negative-suppress condition ($M = 6.107$, $SE = 0.159$), $p = 0.922$. The significant group × PSQI type interaction was followed by 2 (group) × 5 (condition) repeated-measures ANOVA among good sleepers and poor sleepers separately (Fig. 2a). Among the good sleepers ($n = 32$; 13 in SC group and 19 in SD group), the analysis indicated a significant main effect of condition, $F(4, 120) = 75.332$, $p < 0.001$, $\eta^2 = 0.715$ and a main effect of group, $F(1, 30) = 7.574$, $p = 0.010$, $\eta^2 = 0.202$, with higher valence ratings in the SD group ($M = 5.682$, $SE = 0.227$) than the SC group ($M = 4.702$, $SE = 0.274$). Post-hoc t-tests in good sleepers also showed that the SD group gave higher valence ratings in all five conditions than the SC group, $ps < 0.05$. The pattern of valence ratings among the poor sleepers ($n = 19$; 12 in SC group and 7 in SD group) was different. The analysis showed a significant main effect of condition, $F(4, 68) = 35.429$, $p < 0.001$, $\eta^2 = 0.676$, and a significant main effect of group, $F(1, 17) = 4.902$, $p = 0.041$, $\eta^2 = 0.224$, with lower valence ratings in the SD group ($M = 5.260$, $SE = 0.276$) than the SC group ($M = 6.029$, $SE = 0.211$). However, post-hoc t-tests in poor sleepers revealed lower valence ratings in the SD group than the SC group only in the negative-distract condition, $t(17) = -2.164$, $p = 0.045$, but not in other conditions, $ps > 0.05$ (Fig. 2b).

As for arousal ratings, the 2 × 2 × 5 repeated-measures ANOVA indicated a significant main effect of condition, $F(4, 188) = 111.980$, $p < 0.001$, $\eta^2 = 0.704$. Pairwise comparisons of arousal ratings showed the same pattern as valence ratings across the five conditions: neutral-maintain ($M = 2.025$, $SE = 0.119$) < negative-reappraise ($M = 3.839$, $SE = 0.219$) and negative-distract ($M = 3.914$, $SE = 0.238$) < negative-suppress ($M = 4.404$, $SE = 0.233$) and negative-maintain ($M = 4.587$, $SE = 0.228$), all $ps < 0.001$. There was no significant three-way interaction, $p > 0.05$, but a significant group by PSQI type interaction was found, $F(1, 47) = 6.246$, $p = 0.016$, $\eta^2 = 0.117$. To delineate the interaction, we performed 2 (group) × 5 (condition) repeated-measures ANOVA in good sleepers and poor sleepers separately (Fig. 2c, d). Among good sleepers, there was a significant main effect of condition, $F(4, 120) = 93.323$, $p < 0.001$, $\eta^2 = 0.757$, a main effect of group, $F(1, 30) = 7.570$, $p = 0.010$, $\eta^2 = 0.201$, and a significant condition by group interaction, $F(4, 120) = 3.237$, $p = 0.036$, $\eta^2 = 0.097$. Post-hoc t-tests in good sleepers found that the SD group gave higher arousal ratings in all four negative conditions, $ps < 0.05$, but not in the neutral-maintain condition, $p = 0.092$, compared with the SC group (Fig. 2c). Among the poor sleepers, only a main effect of condition was significant (neutral-maintain < negative-reappraise and negative-distract < negative-suppress and negative-maintain), $F(4, 68) = 34.342$, $p < 0.001$, $\eta^2 = 0.669$, and the SD group and the SC group gave similar arousal ratings, $ps > 0.05$ (Fig. 2d). The nonsignificant group by condition interaction indicated that emotion regulation did not differ in efficacy between the SC and the SD groups as reflected by the behavioral ratings.

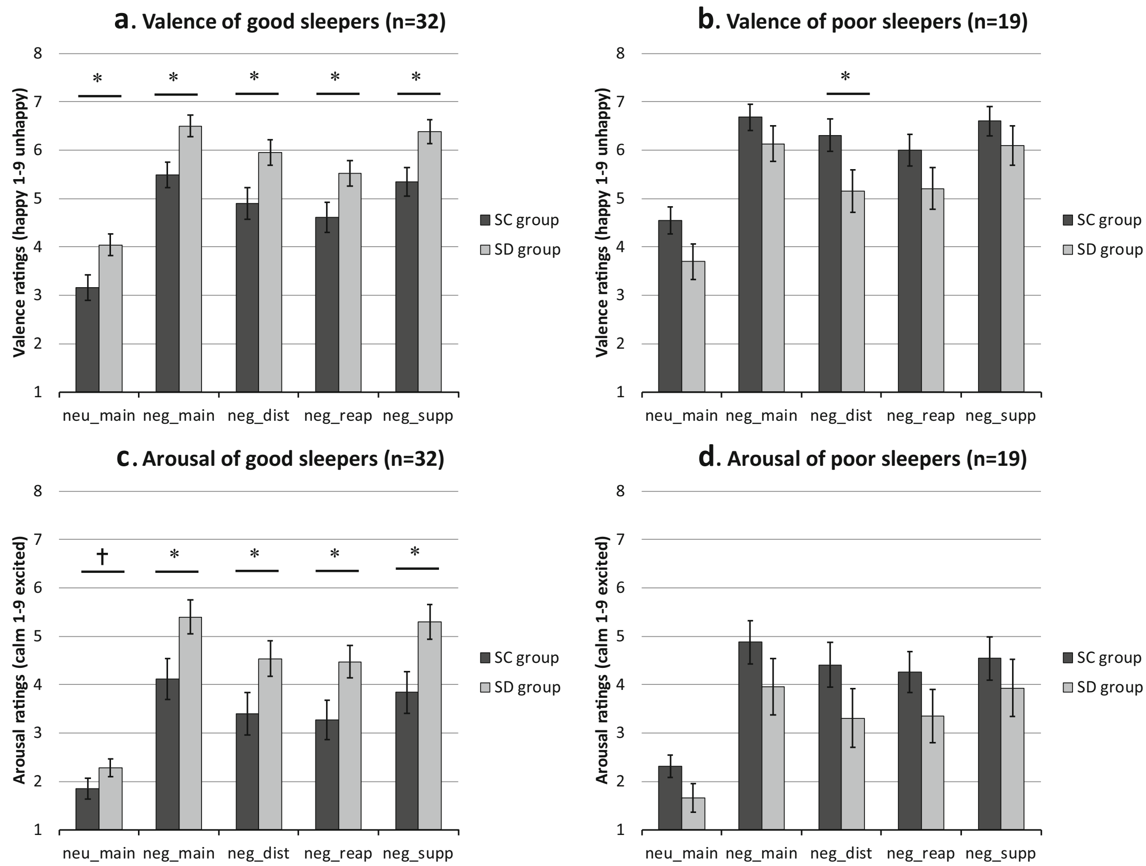

Fig. 2 Valence ratings and arousal ratings among habitual good sleepers (**a** and **c**) and poor sleepers (**b** and **d**). The range of valence ratings was 1 (extremely happy) to 9 (extremely unhappy). The range of arousal ratings was 1 (extremely calm) to 9 (extremely excited). The ratings were in five conditions: neutral-maintain (neu_main), negative-maintain (neg_main), negative-distract (neg_dis), negative-reappraise (neg_reap), and negative-suppress (neg_supp). (*p < 0.05; † 0.05 < p < 0.10; error bars: 1 SEM).

Preinstruction LPP

As there should be no effect of strategy use in preinstruction LPP, a 2 (group) × 2 (PSQI type) × 2 (picture: neutral vs. negative) repeated-measures ANOVA was conducted on 300-800 ms LPP. As expected, the analysis revealed a main effect of picture on the preinstruction LPP, $F(1, 45) = 25.22$, $p < 0.001$, $\eta^2 = 0.359$, with lower LPP amplitude for neutral pictures ($M = -0.326$, $SE = 0.690$) than negative pictures ($M = 1.831$, $SE = 0.666$; Fig. 3a). There was no significant three-way interaction, no significant two-way interaction, or other significant main effect, $ps > 0.05$.

Postinstruction LPP

Previous studies have suggested that LPP to IAPS picture stimuli can last as long as 5 seconds. Thus, we calculated the postinstruction LPP right from the offset of auditory instruction (1,900 ms) to 5,000 ms after picture onset (Fig. 3). A 2 (group) × 2 (PSQI type) × 5 (condition) repeated-measures ANOVA revealed a group by condition interaction, $F(4, 180) = 2.990$, $p = 0.020$, $\eta^2 = 0.062$, and a main effect of condition, $F(4, 180) = 3.270$, $p = 0.013$, $\eta^2 = 0.068$. However, there was no three-way interaction or interaction between PSQI type and group/condition, $ps > 0.05$. Therefore, in the subsequent analyses, we did not include PSQI type as a between-subject factor. After PSQI type was excluded in the analysis, a 2 (group) × 5 (condition) repeated-measures ANOVA also showed a significant group by condition interaction, $F(4, 188) = 3.389$, $p = 0.014$, $\eta^2 = 0.067$, and a main effect of condition, $F(4, 188) = 3.808$, $p = 0.005$, $\eta^2 = 0.075$.

To follow-up, the 2 (group) × 5 (condition) interaction, we first performed a 2 (group: SC vs. SD) × 2 (condition: neutral-maintain vs. negative-maintain) repeated-measures ANOVA to examine the effect of image type and sleep deprivation on postinstruction LPP (Fig. 3a). As expected, a significant main effect of condition showed that the negative-maintain condition ($M = 2.667$, $SE = 0.531$) elicited a larger LPP amplitude than the neutral-maintain condition ($M = 0.785$, $SE = 0.691$), $F(1, 47) = 15.62$, $p < 0.001$, $\eta^2 = 0.249$. There also was a main effect of group, $F(1, 47) = 5.23$, $p = 0.027$, $\eta^2 = 0.100$, showing that the SD group ($M = 0.525$, $SE = 0.735$) generally had smaller LPP amplitude than the SC group ($M = 2.927$, $SE = 0.751$). There was no group by condition interaction, $p > 0.05$.

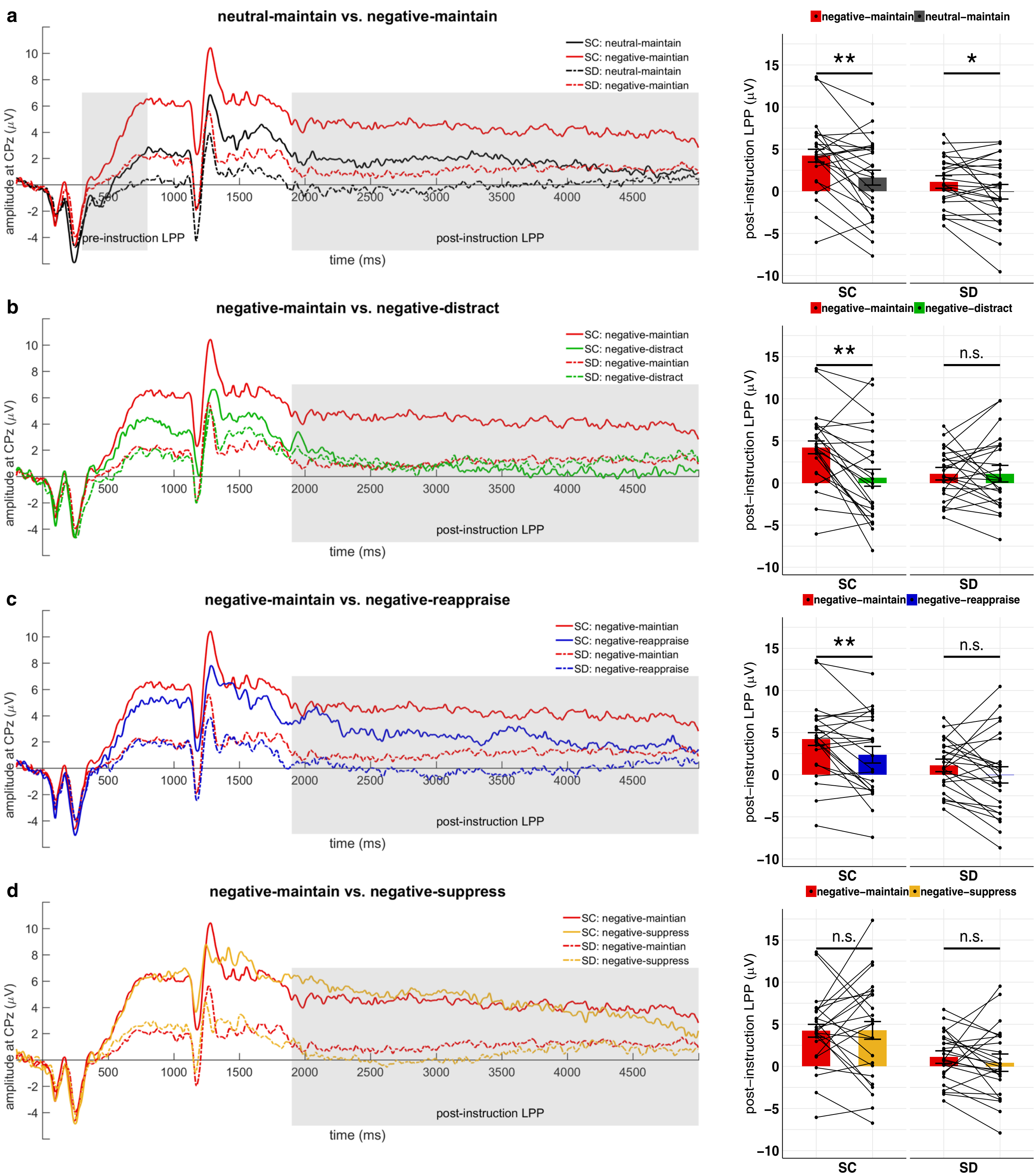

Fig. 3. ERP plots and bar plots of post-instruction LPP amplitudes in the SC and SD group. The plots start from −200 ms to 5,000 ms in reference to the picture onset (at CPz, positive up). The auditory instruction is between 1,000-1,900 ms. Preinstruction LPP is between 300-800 ms, and postinstruction LPP is between 1,900-5,000 ms. (**a**) neutral-maintain condition vs. negative-maintain condition; (**b**) negative-maintain condition vs. negative-distract condition; (**c**) negative-maintain condition vs. negative-reappraise condition; (**d**) negative-maintain condition vs. negative-suppress condition. Left column: ERP plots; right column: bar plots of the group mean of postinstruction LPP amplitudes at CPz and individual lines representing within-subject cross-condition changes of individual participants. $^{**}p < 0.01$; $^{*}p < 0.05$; n.s.: not significant; error bars: 1 SEM.

To examine the influence of sleep deprivation on the effectiveness of emotion regulation strategies, we then performed a 2 (group: SC vs. SD) × 4 (condition: negative-maintain, negative-distract, negative-reappraise, negative-suppress) repeated-measures ANOVA on postinstruction LPP amplitudes. The analysis revealed a main effect of condition, $F(3, 141) = 3.682$, $p = 0.014$, $\eta^2 = 0.073$, a main effect of group, $F(1, 47) = 4.210$, $p = 0.046$, $\eta^2 = 0.082$, and importantly, a significant group by condition interaction, $F(3, 141) = 4.274$, $p = .006$, $\eta^2 = 0.083$. The interaction between group and condition indicated differential effects of emotion regulation strategies in attenuating LPP amplitudes between the SC and the SD groups. To test the influence of sleep deprivation on distraction, reappraisal, and suppression individually, the interaction between group and condition were followed by planned post-hoc paired-samples *t*-tests in the SC and the SD groups separately. For distraction (Fig. 3b), paired *t*-tests showed that negative-distract LPP amplitude ($M = 0.627$, $SE = 1.006$) was significantly smaller than negative-maintain LPP ($M = 4.230$, $SE = 0.759$) in the SC group, $t(23) = 4.032$, $p = 0.001$, Cohen's $d = 0.84$, but the SD group had similar LPP amplitudes in the negative-distract condition ($M = 1.107$, $SE = 0.986$) and the negative-maintain condition ($M = 1.104$, $SE = 0.744$), $t(24) = -0.004$, $p = 0.997$. For reappraisal (Fig. 3c), a paired *t*-test in the SC group showed smaller LPP amplitude in the negative-reappraise condition ($M = 2.372$, $SE = 0.987$) than the negative-maintain condition, $t(23) = 2.931$, $p = 0.008$, Cohen's $d = 0.61$. In the SD group, however, the negative-reappraise LPP ($M = -0.022$, $SE = 0.967$) was similar to the negative-maintain LPP in amplitudes, $t(24) = 1.488$, $p = 0.150$. For suppression, the negative-suppress LPP amplitude (SC group: $M = 4.273$, $SE = 1.052$; SD group: $M = 0.438$, $SE = 1.031$) was similar to the negative-maintain LPP amplitude in both the SC group, $t(23) = -0.040$, $p = 0.969$, and the SD group, $t(24) = 0.895$, $p = 0.380$.

Discussion

The objective of this study was to examine the impact of experimental sleep deprivation on explicit emotion regulation (use of distinct emotion regulation strategies). Among participants with good habitual sleep quality, the behavioral ratings showed the expected effects of sleep deprivation in that they rated their feelings towards the stimuli as generally unhappier and more aroused than their counterparts with nighttime sleep. However, such effects of sleep deprivation were not pronounced among habitual poor sleepers. Behavioral ratings showed that reappraisal and distraction, not suppression, were effective in regulating emotions towards negative pictures regardless of sleep manipulation. The behavioral ratings did not show an effect of sleep deprivation on emotion regulation. Our ERP data replicated previous findings that negative stimuli elicit greater LPP than neutral stimuli. In line with the behavioral data, the ERP data showed that only distraction and reappraisal were effective in attenuating LPP amplitudes towards negative pictures among individuals with adequate sleep. Our ERP data further showed that sleep deprivation significantly impaired the regulatory effect of distraction and reappraisal. To our knowledge, this work is the first to report both subjective (behavioral) and objective (electrophysiological) evidence of the modulation effects of experimental sleep deprivation on the effectiveness of emotion regulation strategies.

Subjective ratings after sleep deprivation: dissociation between good sleepers and poor sleepers

Previous studies have reported behavioral ratings of emotional/non-emotional stimuli after sleep deprivation but with mixed results (Watling et al., 2016). Some studies reported a negative bias in valence ratings or categorization of emotional/nonemotional pictures among sleep-deprived individuals (Daniela et al., 2010; Yoo et al., 2007). Nevertheless, when presented with neutral and positive pictures in an increasingly emotional manner, sleep-deprived participants had a positive bias in emotional categorization of the stimuli compared with the control group (Gujar et al., 2011). In a more recent study, participants rated negative pictures (mixed with neutral and positive pictures) as less negative after sleep deprivation (Alfarra et al., 2015). There also are studies finding null effects of sleep deprivation on behavioral ratings (Cote et al., 2015; Franzen et al., 2009). As suggested by Watling et al. (2016), although sleep deprivation seems to increase emotional intensity and lability of stimuli, the direction of emotional bias after sleep loss is not clear.

Our data were consistent with the general findings of heightened emotional reactivity after sleep deprivation (Watling et al., 2016; Yoo et al., 2007). Interestingly, but as expected, we found a dissociation of the influence of sleep deprivation on valence/arousal ratings between habitual good sleepers and poor sleepers. Regardless of picture and strategy categories, sleep-deprived good sleepers seemed to perceive stimuli as generally more negative and more arousing than their well-rested counterparts. Among poor sleepers, however, no significant effects of sleep deprivation were observed except for the arousal rating in the negative-distract condition. It should be noted that poor sleepers' valence ratings were more negative and their arousal ratings were higher than good sleepers at the baseline (in the SC group) (Fig. 2), suggesting that the effect of sleep deprivation on habitual poor sleepers' perception of emotional stimuli may be subject to a ceiling effect. Taken together, our data suggest that the detrimental influences of sleep deprivation on emotional perception may be more apparent in habitual good sleepers than poor sleepers. Our finding also suggests that in addition to methodological disparities, individual differences may be possible reasons for the inconsistency in existing findings of the impact of sleep loss on emotional perception as mentioned earlier (Watling et al., 2016; Van Dongen et al., 2004; Beattie et al., 2015). Future studies in this field are suggested to take individual differences into consideration, such as habitual sleep quality, gender (van der Helm et al., 2010; Short & Louca, 2015), and baseline variables pertaining to emotions.

Emotion regulation strategies and sleep deprivation

Both results of behavioral ratings and LPP amplitudes supported our successful instruction of distinct emotion regulation strategies. Reappraisal and distraction modulated the ratings towards less unhappy/less aroused compared with the "negative-maintain" condition, but suppression did not generate significant reductions in behavioral ratings (Fig. 2). The LPP amplitudes across different conditions in the SC group showed a similar pattern (attenuated LPP in the "reappraise"/"distract" conditions compared with the negative "maintain" condition; Fig. 3). Corroborating with our finding, a meta-analysis on emotion regulation concluded that reappraisal and distraction were the two most effective emotion regulation strategies while other strategies were less effective (Augustine & Hemenover, 2009). Suppression, on the contrary, was usually reported to be ineffective or even maladaptive in decreasing negative emotional experience (see Gross, 2015 for a review). Unexpectedly but in line with a recent sleep restriction study in adolescents (Reddy et al., 2016), the behavioral ratings showed effects of sleep deprivation on the reactivity to negative pictures but did not show effects of sleep deprivation on the effectiveness of emotion regulation strategies.

Our LPP data indicated that distraction and reappraisal were impaired by sleep deprivation. LPP amplitudes indicate allocated attention in a relatively late stage of stimuli perception after top-down regulation/evaluation (Hajcak et al., 2010), and therefore it is used to reflect the effectiveness of emotion regulation strategies (Thiruchselvam et al., 2011; Paul et al., 2013). Individuals in the SC group successfully attenuated LPP amplitudes using distraction while they were viewing negative pictures, but their sleep-deprived counterparts failed to accomplish that, suggesting that the effectiveness of distraction was impaired by sleep deprivation. As distraction primarily involves redirecting attention (Gross, 1998), this finding is consistent with previous finding that sleep loss affects attention control (Goel et al., 2009; Chuah et al., 2010). Similarly, the LPP amplitude in the negative-reappraise condition was lower than that in the negative-maintain condition in the SC group but individuals in the SD group had similar "reappraised" and "maintained" LPP amplitudes, suggesting unsuccessful regulation of stimuli-elicited negative emotions by the reappraisal strategy after sleep deprivation. Along with this, poor sleep quality has been associated with lower ability to reappraise films containing negative contents (Mauss et al., 2013) and hypoactivation of the PFC during reappraisal implementation (Minkel et al., 2012). Effective emotion regulation is important to mental well-being (Gross & Muñoz, 1995; Berking, & Wupperman, 2012). Our data provide the first evidence that sleep deprivation may impair the effectiveness of distraction and reappraisal, which are two adaptive and commonly recommended emotion regulation strategies (Augustine & Hemenover, 2009; Gross, 1998). Our results help explain the contribution of sleep disturbances to the development and maintenance of emotional disorders (Harvey, 2011; Wulff et al., 2010).

Intriguingly, the impact of sleep deprivation on emotion regulation strategies were not evident in subjective ratings but were shown in objective LPP data. Apparently, a possible reason was that participants rated their feelings towards stimuli primarily subject to their own or the experimenter's expectation instead of what they actually felt. However, in case that our participants did "honestly" report their feeling in behavioral ratings, our data might suggest a dissociation of subjective evaluation of emotional states from the neurophysiological (objective) measures. In accordance, previous studies also have revealed dissociations between behavioral and neural findings after sleep deprivation (Alfarra et al., 2015; Cote et al., 2015). Our finding also corresponds with the distinction between objectively measured attention deficits and subjective ratings of sleepiness after sleep deprivation (Krause et al., 2017). Such potentially biased subjective emotional perception from objective measures after sleep deprivation may be maladaptive to emotional well-being. This subjective-objective dissociation in emotional state seems consistent with the discrepancy between subjective and objective measures of sleep commonly found in individuals with insomnia (Orff, Drummond, Nowakowski, & Perlis, 2007). Future studies are needed to clarify the implications of such discrepancies. Given the importance of objective measures, future studies are suggested to incorporate objective measures in the investigation of sleep-emotional functioning relationship. Given that emotion regulation strategies are usually involved in clinical therapies, our subjective rating data and LPP data together suggest that clinicians may benefit from an awareness of the detrimental influence of sleep loss on emotion regulation even when patients report effective use of emotion regulation strategies.

Limitations

Some limitations of our study should be noted. First, it should be noted that our result of the moderation effect of habitual sleep quality on how sleep deprivation influences perception of emotional pictures was based on an uneven distribution of good and poor sleepers in the SC and SD groups and that this moderation effect was only found in the behavioral rating data but not the ERP data. Thus, its implication should be interpreted cautiously. Second, we only required participants to maintain time in bed for at least 7 hours and get up before 10:00. A stricter requirement on the go-to-bed time and the wake-up time (e.g., set a time window for nighttime sleep) may be a more precise control of the hours awake before assessment in the two groups. Third, our participants were all in young adulthood (age range: 18-24 years). Such sample composition limited the generalizability of our finding in other age groups.

Conclusions

Our ERP findings demonstrate that the emotion regulation strategies of distraction and reappraisal may be impaired by sleep deprivation. Suppression is ineffective in down-regulating negative emotion even in well-rested individuals in our data, and therefore we are not able to conclude on the influence of sleep deprivation on suppression. Because reappraisal and distraction are important components in cognitive therapy, this study implies that sleep deprivation may compromise the effectiveness of cognitive therapy when involving emotion regulation. However, the subjective valence and arousal ratings failed to reflect an effect of sleep deprivation on the effectiveness of the strategies. It suggests that objective measures may be more reliable to reflect the effectiveness of emotion regulation strategies than subjective measures. Moreover, the subjective rating data suggests that sleep deprivation may have differential effects on the subjective perception of emotional states between habitual good sleepers and poor sleepers.

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