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High working memory load impairs reappraisal but facilitates distraction – An event-related potential investigation

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ABSTRACT

The present experiments investigated the impact of working memory (WM) load on emotion regulation (ER) efficacy using reappraisal (Experiment 1, $n = 30$) and distraction (Experiment 2, $n = 30$). Considering that WM is necessary for storage, elaboration, and manipulation of information and that reappraisal acts by storing, elaborating, and *manipulating* the stimulus meaning, we hypothesized that high (versus low) WM-load would reduce reappraisal efficacy. By contrast, given that distraction acts by *blocking* elaborated processing of the stimulus meaning, we expected that high WM-load would enhance distraction efficacy. To test these predictions, we employed a dual-task paradigm in which a low- or high WM-load task was combined with an ER (reappraisal or distraction) task. We measured the Late Positive Potential (LPP)–an electrocortical marker of sustained motivated attention, and a well-established index of emotional arousal–in response to negative pictures. Results confirmed that although reappraisal successfully reduced the LPP amplitude in the down- compared to up-regulation condition in low WM-load trials, high WM-load eliminated this difference, suggesting the disrupting influence of high WM-load on ER for reappraisal (Experiment 1). By contrast, although distraction failed to modulate the LPP amplitude in low WM-load trials, the difference between down- and no-regulation conditions was significant when distraction was combined with high WM-load, suggesting the facilitatory influence of high WM-load on ER for distraction (Experiment 2). Our findings show that the effect of WM-load on ER is strategy-dependent, and that the availability of WM resources is an important situational moderator of ER efficacy in healthy young adults.

1. Introduction

The ability to effectively regulate undesirable affective states is a core aspect of adaptive human behavior (Gross & John, 2003). Failures in implementation of emotion regulation (ER) are associated with reduced psychological well-being and may constitute one of the key factors underlying the development of various psychopathologies (Sheppes, Suri, & Gross, 2015). Cognitive forms of ER are especially well-suited for achieving various ER goals due to their broad applicability and importance for clinical practice (de Voogd, Hermans, & Phelps, 2018; Dryman & Heimberg, 2018). Among them, reappraisal, a strategy that involves changing the meaning of a stimulus, is one of the best studied and most widely acclaimed forms of ER (Gross, 2014). In neuroimaging studies, reappraisal consistently modulates (i.e., up- or down-regulates, depending on the intended direction of ER) neural markers of emotional processing, such as the activity of subcortical limbic structures, including the amygdala (Berboth & Morawetz, 2021; Buhle et al., 2014). Similarly, in electrophysiological studies, reappraisal up- or down-regulates the late positive potential (LPP), an electrocortical marker of sustained motivated attention to emotional stimuli (Paul, Simon, Kniesche, Kathmann, & Endrass, 2013; Schönfelder, Kanske, Heissler, & Wessa, 2014; Shafir, Schwartz, Blechert, & Sheppes, 2015; Shafir, Zucker, & Sheppes, 2018). Although for many years reappraisal has been regarded superior to other ER strategies (Aldao & Mennin, 2012), recent findings demonstrated that employing reappraisal may also be maladaptive under some circumstances—for instance, when the emotion-eliciting situation is of high intensity (Shafir et al., 2015; Sheppes et al. 2014; Silvers, Weber, Wager, & Ochsner, 2015), or offers few features that can be reinterpreted ("reappraisal affordances") (Suri et al. 2018; Young & Suri, 2020). These and other

Abbreviations: ER, emotion regulation; WM, working memory; LPP, late positive potential; EFs, executive functions.

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findings demonstrated that the efficacy of various ER strategies is context-dependent, which means that although one strategy may be adaptive in one context, it may cease to be in another (Aldao & Mennin, 2012; Ford & Troy, 2019). Consequently, in recent years, there has been increased interest in identifying individual, psychological, and situational factors that may moderate the efficacy of various forms of ER (Aldao, 2013; Doré, Silvers, & Ochsner, 2016; Matthews, Webb, Shafir, Snow, & Sheppes, 2021; McRae, 2016).

Since cognitive ER strategies are thought to depend on executive functions (EFs), including working memory operations (such as maintenance and updating), response inhibition, interference control and task switching (or: mental set shifting) (Friedman & Miyake, 2017), some studies sought to examine links between ER and EFs (Cohen & Mor, 2018; Garrison & Schmeichel, 2020; Hofmann, Schmeichel, & Baddeley, 2012; McRae, Jacobs, Ray, John, & Gross, 2012). Identifying such links has potentially important therapeutic implications, as the deterioration of EFs is a natural consequence of aging (Bunge & Wright, 2007) and is a symptom of various clinical conditions (Groves, Kofler, Wells, Day, & Chan, 2020; Joormann & Tanovic, 2015). Different EFs have been hypothesized to subserve different aspects of successful ER (Hofmann et al., 2012 for a review). Working memory (WM), in particular, has been suggested to provide a mental 'workspace' that is necessary for the successful regulation of emotion via reappraisal (Hofmann et al., 2012; Schmeichel & Tang, 2015), as (1) WM represents a (resource-limited) system that enables the active maintenance and manipulation of (stimulus-related) information in the service of a pursued goal (Baddeley, 2010), and (2) reappraisal acts by manipulating the stimulus meaning.

In line with this assumption, prior research demonstrated that: (1) higher WM capacity (WMC)–a capability to maintain goal-relevant information processing in the face of competing information or other distractions (Schmeichel & Demaree, 2010)–predicts better reappraisal abilities, defined as a reduction in negative affect experienced when instructed to reappraise versus respond naturally to negative emotional stimuli (McRae et al., 2012; Opitz, Lee, Gross, & Urry, 2014; Schmeichel & Tang, 2015), (2) reappraisal consistently activates brain regions implicated in WM, such as the dorsolateral prefrontal cortex (DLPFC) (Berboth & Morawetz, 2021; Buhle et al., 2014), and (3) the extent of the prefrontal activity observed during reappraisal appears to be negatively correlated with WMC, indicating reappraisal dependence on WM resources (Zaehringer, Falquez, Schubert, Nees, & Barnow, 2018). Moreover, stress, which disrupts WM and the DLPFC function, was shown to *impair* ER via reappraisal (Raio, Orederu, Palazzolo, Shurick, & Phelps, 2013), whereas increasing (or decreasing) activation of this region, either by means of transcranial direct current or magnetic stimulation, was shown to *increase* (or decrease) reappraisal effectiveness (Feeser, Prehn, Kazzer, Mungee, & Bajbouj, 2014; Zhao et al., 2021; Wyczesany et al., 2022). Finally, limited WMC, either due to advanced age and/or clinical condition, is often associated with reduced efficacy of reappraisal (Opitz, Gross, & Urry, 2012; Scheibe, Sheppes, & Staudinger, 2015; Smoski, LaBar, & Steffens, 2014). The above findings indicate that reappraisal *engages* WM operations (or *draws on* WM resources), which provides preliminary evidence for the importance of WM in reappraisal. However, as all above-described studies were of a correlational nature, direct causal evidence showing that reappraisal effectiveness *critically depends on* unoccupied WM resources is lacking. Consequently, it remains unclear how important WM in specific is for reappraisal and what the function of WM is in determining the regulatory effects of this strategy.

More direct evidence pointing to reappraisal's critical dependence on WM processes has been delivered by Gan, Yang, Chen, Zhang, and Yang (2017). In their study, Gan et al. (2017) aimed to induce an automatic or implicit form of reappraisal by instructing participants to memorize three negatively (e.g., "cancer, disease, weakness") or positively laden words (e.g., "safe, withdraw, fortunate"), either alone (low WM-load condition) or together with three abstract symbols (e.g., "* # &", high WM-load condition), prior to viewing negative pictures. They demonstrated that memorizing positively versus negatively laden words reduced the emotion-enhanced LPP amplitude when the words were memorized alone (low WM-load) but failed to do so when additional distracting symbols had to be remembered (high WM-load). These findings provide initial support for reappraisal's dependence on WM processes, as they show a decrease in the effects of positive reappraisal (manipulated by word valence) on emotional attention (LPP) when WM capacity is limited (high WM-load condition). However, in this study a novel paradigm was used in which reappraisal-inducing words served both as reappraisal manipulation and as items to remember in the WM task. Thus, the lack of an ER effect in the high WM-load condition could have resulted from certain atypical details of the experimental design. For instance, it is possible that the necessity to memorize abstract symbols (in addition to reappraisal-inducing words) required a burdensome memory search for their semantic labels, as memory is heavily language-dependent and symbol names belong to one of the least frequently used words. This could have diverted attention away from the (higher frequency) reappraisal words that were simultaneously presented, preventing their deep semantic elaboration and thus, by implication, the reappraisal-induced change in stimulus meaning. Alternatively, it is possible that the presence of abstract symbols enforced an adoption of an alternative memorization strategy that hinged upon remembering perceptual features of presented items (words or symbols) rather than their verbal rehearsal (Baddeley, 2010). It is thus conceivable that the abstract nature of the used symbols rather than high WM-load was responsible for the lack of reappraisal modulation in the high WM-load condition. For this reason, the goal of our first experiment was to provide direct causal evidence showing that reappraisal draws on WM resources and that occupying WM can disturb reappraisal-specific mechanism of cognitive change. In other words, this experiment aimed to verify if the availability of WM resources is indeed a crucial situational determinant of reappraisal efficacy.

The above considerations highlight the importance of WM operations in ER. However, WM also affects the processing of saliency of emotional events. Despite a long held assumption that emotional stimuli automatically draws attention, irrespective of the current task demands or ongoing processing (Öhman, 2007; Vuilleumier, 2005), multiple studies have demonstrated the importance of available WM resources for prioritized processing of emotional versus non-emotional incentives. For instance when WM resources are engaged in performing a high WM-load secondary task, negative but task-irrelevant stimuli in the visual (Barley, Bauer, Wilson, & MacNamara, 2021; Erk, Kleczar, & Walter, 2007; MacNamara, Ferri, & Hajcak, 2011; Van Dillen, Heslenfeld, & Koole, 2009; Van Dillen & Derks, 2012), auditory (Lv et al. 2010; San-Miguel, Corral, & Escera, 2008), and somatosensory domain (Legrain, Crombez, Verhoeven, & Mouraux, 2011; Legrain, Crombez, Plaghki, & Mouraux, 2013) are less likely to receive increased attentional processing compared to task-irrelevant neutral stimuli, or the same negative stimuli when presented together with a low WM-load secondary task. This indicates that occupying WM, or reducing the available WM resources (i.e., loading WM with neutral contents), can effectively attenuate the typically increased attentional processing of (negative) emotional events, serving as a useful ER strategy in itself.

The fact that mentally engaging cognitive activities can limit the attention-capturing power of (emotionally) salient stimuli constitutes the core regulatory mechanism of the attentional distraction strategy, which is another major form of cognitive ER that is frequently contrasted with reappraisal (Kanske, Heissler, Schönfelder, Bongers, & Wessa, 2011; McRae et al. 2010; Schönfelder et al., 2014; Shafir et al., 2015). In the ER literature, distraction has been studied either in the form of self-generated neutral thoughts or mental images (Jiang, Chen, & Guo, 2020; Paul et al., 2013; Paul, Kathmann, & Riesel, 2016; Shafir et al., 2015; Thiruchselvam, Blechert, Sheppes, Rydstrom, & Gross, 2011) or in the form of a cognitively challenging (WM) task performed while viewing an emotional stimulus (Kanske et al., 2011; Kanske, Heissler, Schönfelder, & Wessa, 2012; Koch et al. 2019; Li et al., 2017; Li, Zhu, Leng, & Luo, 2020; McRae et al., 2010; Schönfelder et al., 2014). Compared to a passive viewing condition, distraction has been shown to effectively down-regulate the enhanced processing of emotional stimuli, reducing the activity of the amygdala (Kanske et al., 2011; Koch et al., 2019; McRae et al., 2010) and decreasing the emotion-enhanced amplitude of the LPP (Li et al., 2017, 2020; Paul et al., 2013; Schönfelder et al., 2014; Shafir et al., 2015), both of which are frequently utilized indices of ER success (Hajcak, MacNamara, & Olvet, 2010).

Although the above findings indicate that WM plays a crucial role in the effectiveness of both of these cognitive ER strategies, this role seems to be markedly different for each strategy. For reappraisal, WM appears necessary for efficient generation, manipulation and/or maintenance of a new stimulus meaning (Hofmann et al., 2012). For distraction, however, decreased availability of WM resources seems to be the primary mechanism via which distraction exerts its regulatory effects (Van Dillen & Koole, 2007). Consequently, while reappraisal efficacy should suffer from an external burden imposed on WM, distraction should actually benefit from it, as such increased load would further limit the attention available for processing an emotional stimulus. As, to the best of our knowledge, no studies have yet tested this latter prediction, the goal of our second experiment was to investigate the role of WM in ER effects of attentional distraction. Investigating the impact of WM-load on the effectiveness of these two cognitive ER strategies would help to elucidate the unique role WM plays in the effects of each of them, as well as their situational efficacy.

1.1. The present experiments

To summarize, in the present investigation we sought to examine the role of WM in the regulatory effects of cognitive reappraisal (Experiment 1) and attentional distraction (Experiment 2), which are two common cognitive ER strategies. To this end, we employed a dual-task paradigm, in which each strategy was implemented concurrently with a WM task that imposed either a low or high WM-load. In both experiments, participants had to remember either a one- (LOW WM-load) or a four-letter string (HIGH WM-load), while viewing negative pictures. In Experiment 1, investigating reappraisal, these pictures were preceded by negative (up-regulation; UP-REG) or neutral (down-regulation; DOWN-REG) descriptions that aimed to induce negative or neutral reappraisal of the pictures, respectively. In Experiment 2, investigating distraction, the pictures were presented concurrently with a single-digit number to remember (no-regulation; NO-REG), or a mathematic equation to solve (down-regulation; DOWN-REG) that aimed to preserve or occupy attentional resources, respectively.

To provide an objective and quantifiable estimate of the ER effects of both strategies, we measured event-related brain potentials (ERPs), which give a direct insight into emotional information processing (see Hajcak et al., 2010 for a review). We focused on the centro-parietal late positive potential (LPP), which is a positive-going deflection that starts ~400 ms following stimulus onset. The LPP amplitude is enhanced by emotionally arousing (positive and negative) compared to neutral stimuli, reflecting sustained motivated attention for emotionally salient stimuli (Hajcak & Foti, 2020). As described above, both reappraisal and distraction have been shown to reduce the amplitude of the centro-parietal LPP evoked by emotional pictures in down-regulation relative to no-regulation conditions, indicating ER success (Foti & Hajcak, 2008; MacNamara, Foti, & Hajcak, 2009; Paul et al., 2013; Shafir et al., 2015). Importantly, the enhanced LPP amplitude in response to emotionally arousing pictures is also modulated by the concurrent WM-load, such that a high WM load reduces the LPP amplitude to a greater extent than a low WM-load (Barley et al., 2021; MacNamara, Ferri, et al., 2011; Van Dillen & Derks, 2012). Thus, if limited WM capacity disrupts reappraisal, we should observe a significant ER modulation of the LPP amplitude in low but not high WM-load conditions in case of reappraisal (Experiment 1). By contrast, if limited WMC facilitates distraction, we should observe an additive down-regulatory influence of ER and WM-load on the LPP amplitude in case of distraction (Experiment 2). In addition to the LPP, we also measured subjective negative emotion experience to verify whether our experimental manipulations would influence this other component of the emotional response. Finally, as a manipulation check, we measured accuracy rates (ACCs) and reaction times (RTs) in WM task, which were expected to reflect increased task demand in high versus low WM-load trials.

2. Experiment 1

Experiment 1 was aimed at investigating the impact of low versus high WM-load on reappraisal. To determine the effect of WM-load on the reappraisal-specific process of cognitive change (i.e., change in stimulus meaning), we contrasted two reappraisal conditions: One that aimed to up-regulate negative affect in response to negative pictures (UP-REG condition) and one that aimed to down-regulate negative affect in response to negative pictures (DOWN-REG condition). To this end, we used a well-validated reappraisal procedure, which involved the presentation of a unique negative (UP-REG) or neutral (DOWN-REG) description that preceded the presentation of each picture (Foti & Hajcak, 2008; MacNamara et al., 2009; Wang et al., 2017). This allowed us to manipulate the reappraisal-specific process of cognitive change while controlling for the mental load that is associated with the execution of reappraisal and that is known to decrease the LPP amplitude (Hajcak & Foti, 2020; Wyczesany & Ligeza, 2017).

Replicating previous studies that used the above described reappraisal procedure (Foti & Hajcak, 2008; MacNamara et al., 2009; Wang et al., 2017), we expected that in the low WM-load trials the LPP amplitude would be modulated (up- or down-regulated) according to the direction of reappraisal-induced change in meaning, reflecting successful reappraisal. By contrast, we predicted that in high WM-load trials the reappraisal effect would be attenuated, as high WM-load would limit the 'mental workspace' needed to semantically elaborate and reappraise the meaning of a particular picture according to the given (negative or neutral) description (Gan et al., 2017). In addition, we assumed that high WM-load in itself would exert a down-regulatory impact on the LPP amplitude, reducing the attentional processing of negative pictures (Barley et al., 2021; MacNamara, Ferri, et al., 2011; Van Dillen & Derks, 2012). Consequently, we expected to observe:

Hypothesis 1. a significant main effect of WM-load, showing the reduced LPP amplitude in high versus low WM-load trials, and.

Hypothesis 2. a significant WM-load x Emotion Regulation interaction, showing disruption of reappraisal in the high WM-load condition. We had the following hypotheses regarding the lower-order effects:

a) Reappraisal would successfully attenuate the centro-parietal LPP in the down-regulation condition (DOWN-REG) compared to the up-regulation (UP-REG) condition in trials with low but not high WM-load (LOW: UP-REG > DOWN-REG; HIGH: UP-REG = DOWN-REG).
b) High WM-load would disrupt the reappraisal-driven cognitive change process in the UP-REG condition, such that it would prevent the up-regulatory effect of reappraisal. Consequently, the centro-parietal LPP amplitude in the UP-REG condition would be significantly decreased in the high versus low WM-load trials (UP-REG: LOW > HIGH).
c) High WM-load would disrupt the reappraisal-driven cognitive change process in the DOWN-REG condition, such that it would prevent the down-regulatory effect of reappraisal. Consequently, there would be no additive effect of both ER and high WM load on the LPP in the DOWN-REG condition. However, since high WM-load reduces the attentional processing of emotional stimuli, we expected it would still attenuate the LPP amplitude in the DOWN-REG condition (when compared to UP-REG + low WM-load condition). Thus,

we hypothesized that the LPP would be of similar magnitude in the DOWN-REG condition between high and low WM-load trials (DOWN-REG: LOW = HIGH), although due to different reasons: in the DOWN-REG + low WM-load condition due to reappraisal-induced change in stimulus meaning, whereas in DOWN-REG + high WM-load condition due to attention blocking effect of restricted WMC.

3. Materials and methods

3.1. Participants

Sample size was pre-determined using G*Power 3 software (Faul, Erdfelder, Lang, & Buchner, 2007) with reference to prior studies that investigated the impact of WM load on emotional reactivity (MacNamara, Ferri, et al., 2011; Van Dillen & Derks, 2012) and reappraisal effectiveness (Gan et al., 2017). A priori analysis revealed that 27 participants were needed to detect a 2-way interaction effect for a repeated measures ANOVA, based on an alpha level of 0.05, power of 0.8, and a medium effect size of $\eta_p^2 = 0.06$. We chose to oversample in case of participant dropouts, EEG data collection failure, or excessive EEG artifacts. Thus, 30 adult women (mean age 21.9 ± 2.1 years) were recruited to participate in the study in exchange for monetary compensation or course credits. Only female participants were included to control for gender differences in emotional picture processing (Filkowski, Olsen, Duda, Wanger, & Sabatinelli, 2017) and use of ER (McRae, Ochsner, Mauss, Gabrieli, & Gross, 2008). All were right-handed, had normal or corrected to normal vision, and none reported a history of neurological or psychiatric disorders. In accordance with the Declaration of Helsinki, all procedures were carried out with the adequate understanding and written consent of the participants. The investigation was approved by the institutional ethics committee (approval no.#08112019).

3.2. Stimulus materials

Aversive pictures ($n = 120$; $M_{valence} = 2.95$, $M_{arousal} = 6.18$) were selected from previously validated pictorial datasets (IAPS; Lang, Bradley, & Cuthbert, 2008; NAPS; Marchewka, Żurawski, Jednoróg, & Grabowska, 2014).[1] Picture content included scenes of violence, sad, angry, or suffering people, mutilations, animal abuse, surgical procedures, and accidents.

Prior to each picture, a brief description of that picture was displayed on the screen. Half of all images were preceded by a neutral description (e.g., "This boy is shooting the balloons"), which served as the down-regulation (DOWN-REG) condition, while the other half were preceded by a negative description (e.g., "This boy defends himself against an armed attacker"), which served as the up-regulation (UP-REG) condition. Each picture was preceded by a unique (negative or neutral) description. The unique description for each picture (negative or neutral) was randomly assigned for each participant. Fifty images and corresponding descriptions were taken from Foti and Hajcak (2008), MacNamara et al. (2009) and MacNamara, Ferri, et al. (2011); the remaining picture–description pairs were prepared along the same lines. This description-based approach allows to better distinguish reappraisal-specific mechanisms of cognitive change from other cognitive processes that may have incidental down-regulatory impact on the LPP (Hajcak & Foti, 2020) and has been successfully adopted to study reappraisal in previous studies (Foti & Hajcak, 2008; MacNamara et al., 2009; MacNamara, Ochsner, & Hajcak, 2011).

In half of all trials, participants viewed a one-letter string (e.g., "P"), which served as the LOW WM-load condition, and in the other half, a four-letter string, (e.g., "RTPF"), which served as the HIGH WM-load condition. Letter strings were generated randomly from consonants only. Four-letter strings always consisted of unique, upper-case letters.

Although previous studies used letter (or number) strings comprising from six (Barley et al., 2021; Erk et al., 2007; MacNamara, Ferri, et al., 2011; Van Dillen & Derks, 2012) to up to nine elements (Dörfel et al. 2014), we faced a trade-off between the number of elements that would induce a discernible load on working memory and the need to avoid disrupting the ability to perform subsequent regulatory tasks. During a pilot study, we determined that four letters was an optimal number to evoke relatively high/distinguishable WM-load without impairing the ability to read and understand a short description presented before each picture.

3.3. Procedure

Upon arrival, participants received detailed task instructions and performed 10 practice trials to confirm their understanding of the procedure and the use of the rating scales. Following practice trials, EEG sensors were attached, and the experiment started. Testing was conducted in a sound-attenuated, air-conditioned EEG cabin.

A sample trial structure is illustrated in Fig. 1. Each trial began with a white fixation cross displayed on a gray background for 1000 ms. This was followed by: (1) a letter string memorization phase; (2) an ER phase; (3) a letter string recall phase; and (4) a rating phase. During the letter string memorization phase, a one-letter (LOW WM-load) or four-letter string (HIGH WM-load) was displayed on the screen in green font (2000 ms) and participants' task was to memorize it. The ER phase began with the presentation of a white fixation cross (300–700 ms) and subsequent presentation of a negative (UP-REG) or neutral (DOWN-REG) description (3500 ms) of an upcoming aversive picture. Then, the picture was presented (4000 ms) and followed by a white fixation cross (300–700 ms). In the letter string recall phase, participants viewed a one- or a four-letter string (depending on the WM-load condition) displayed in red font and were asked to decide whether: (1) it is the same letter they had initially seen (for LOW WM-load) or (2) the presented letters are in the same order as the letters they had initially seen (for HIGH WM-load). Half of the trials required a "yes" answer, and the other half a "no" answer. Participants provided a "yes" response with their right middle finger (right arrow on the keyboard), and a "no" response with their right index finger (left arrow on the keyboard). Then, they received feedback regarding the correctness of their response (1000 ms). Trials concluded with the subjective rating of emotion experience on the valence (1 = unpleasant; 9 = pleasant) and arousal (1 = aroused; 9 = calm) dimensions of the self-assessment manikin (SAM) (Bradley & Lang, 1994). After completion of the experimental task EEG sensors were removed and participants were asked to rank the conditions from the most to the least difficult/challenging and to indicate whether the necessity to remember one or four-letter strings (LOW or HIGH WM-load, respectively) affected their ability to read and understand the short sentences presented before each picture. None of the participants reported that memorizing letter strings disrupted their ability to do so. Then, participants were debriefed, reimbursed, and thanked for their participation in the study.

The procedure consisted of 120 trials in total (separated by one-minute breaks after every 30 trials), that were divided into four experimental conditions (Emotion-regulation x WM-load, 30 trials per

[1] Picture codes were as follows: IAPS (1050, 1201, 1302, 1930, 2120, 2130, 2141, 2205, 2399, 2661, 2683, 2688, 2691, 2700, 2710, 2716, 2750, 2810, 3168, 3220, 3301, 6020, 6190, 6212, 6250, 6311, 6312, 6313, 6350, 6570.1, 6571, 6821, 6830, 6831, 7361, 8060, 8230, 8232, 9000, 9042, 9050, 9102, 9220, 9250, 9400, 9421, 9425, 9470, 9490, 9520, 9584, 9596, 9600, 9611, 9620, 9635.1, 9800, 9901, 9911, 9920, 9921), NAPS (1, 3, 5, 6, 10, 13, 14, 17, 18, 30, 41, 45, 52, 74, 77, 78, 95, 96, 257, 263, 267, 270, 272, 273, 277, 282, 286, 297, 416, 418, 421, 422, 434, 440, 447, 448, 664, 695, 698, 709, 713, 721, 732, 735, 886, 1072, 1074, 1086, 1087, 1088, 1089, 1092, 1094, 1095, 1101, 1108, 1239, 1242, 1251). Six additional pictures were used during training: EmoPicS (208, 211, 218, 219, 221, 224, 329) (Wessa et al. 2010).

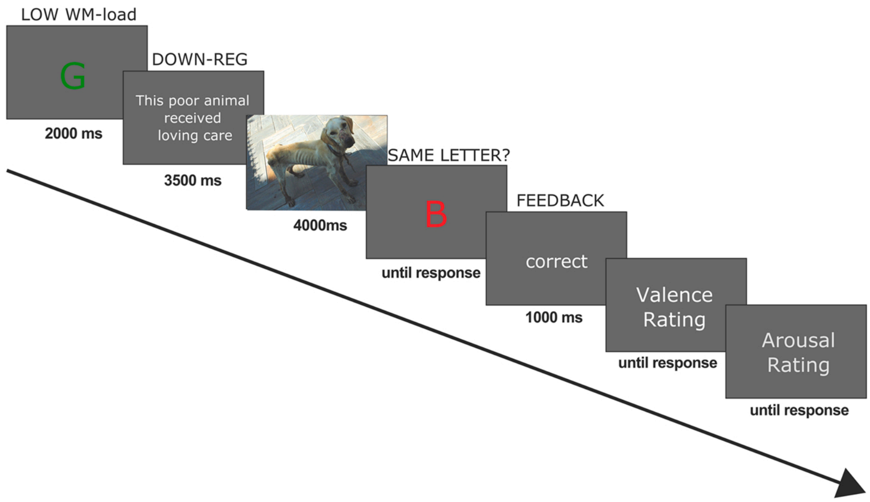

Fig. 1. Sample trial structure. *Note.* Depiction of a sample trial structure. Stimuli (scaled up, for presentation purposes) were separated by interstimulus intervals, during which a fixation cross or a blank screen was presented (see Materials and Methods for details). In compliance with copyright laws, the picture used here is similar but not identical to those presented in the study. Valence and Arousal Ratings were presented in a form of Self-Assessment Manikin (SAM) scales.

condition): UP-REG + LOW WM, DOWN-REG + LOW WM, UP-REG + HIGH WM, DOWN-REG + HIGH WM. Trial types were intermixed, and the order of trials was determined randomly for each subject. The procedure was administered on a computer equipped with 61-cm (24 in.) LCD monitor at a viewing distance of approximately 60 cm and 50° of horizontal visual angle. PsychoPy software (Peirce et al., 2019) was used to control the presentation and timing of stimuli.

3.4. Electrophysiological recording, data reduction, and analysis

Continuous EEG was recorded from 64 electrodes, based on the extended 10/20 system, as well as two electrodes placed on the left and right mastoids, using an ECI Electrocap and the ActiveTwo BioSemi system (BioSemi, Amsterdam, Netherlands). Vertical and horizontal eye movements were recorded with electrodes placed supra- and infra-orbitally at the right eye and on the left versus right orbital rim. The Common Mode Sense (CMS) active electrode and the Driven Right Leg (DRL) passive electrode formed the amplifier reference during acquisition.

EEG and EOG activity were sampled at 256 Hz and saved on a laboratory computer using ActiView software (BioSemi). The EEG data were processed and analyzed using EMEGS software (Peyk, De Cesarei, & Junghöfer, 2011). Off-line, the data was re-referenced to the average activity of the mastoids' electrodes, band-pass filtered with cutoffs of 0.1 and 45 Hz, and corrected for ocular artifact using the Biosig toolbox (Vidaurre, Sander, & Schlögl, 2011). The EEG was segmented into epochs from 100 ms before picture onset to 4000 ms after picture onset (i.e., entire duration of picture presentation). Baseline correction was performed for each trial, using the 100 ms prior to picture onset. Artifact rejection was conducted using a method for statistical control of artifacts in high density EEG/MEG data (Junghöfer, Elbert, Tucker, & Rockstroh, 2000). The average number of artifact-free trials was 26.1 per condition. Separate ERP averages were computed for the four different trial types (WM-load x Emotion Regulation). The LPP was scored by averaging amplitudes from 400 to 4000 ms following picture onset, at five centroparietal sites: CPz, Pz, P1, P2, POz (Kivity, Cohen, Weiss, Elizur, & Huppert, 2021; Moser, Hartwig, Moran, Jendrusina, & Kross, 2014; Paul et al., 2013).

4. Results

To test whether WM-load and ER instructions modulated LPPs and self-reported affect in the expected direction, mean centro-parietal LPP (400–4000 ms) amplitudes, mean valence and arousal ratings, as well as mean accuracy (ACCs) and reaction times (RTs) for the WM task were submitted to repeated measures analyses of variance (ANOVA) with two within-subject factors (WM-load: LOW vs. HIGH; emotion-regulation: DOWN-REG vs. UP-REG). *p* values were adjusted with the Bonferroni correction for multiple post hoc comparisons. Statistical analyses were performed using SPSS (Version 26.0) General Linear Model software.

4.1. Manipulation checks

Results for the manipulation check measures are depicted in Fig. 2.

4.1.1. WM task difficulty assessment

All but one participant indicated that remembering four-letter strings (HIGH WM-load condition) was more difficult than remembering a single letter (LOW WM-load condition). One participant reported that both LOW and HIGH WM-load conditions were equally easy. None of the participants reported any differences in WM task difficulty between negative (UP-REG) or neutral (DOWN-REG) descriptions.

4.1.2. Valence and arousal ratings

Due to a technical issue, arousal ratings from one participant fell out of range; this person was removed from further analysis of arousal ratings. We found a significant main effect of ER for both valence, $F(1,29) = 31.38$, $p < .001$, $\eta_p^2 = 0.52$, 95% CI [0.35, 0.76], and arousal ratings, $F(1,28) = 19.73$, $p < .001$, $\eta_p^2 = 0.40$, 95% CI [0.24, 0.66]. As expected, participants reported experiencing fewer negative emotions and less arousal in the DOWN-REG than in the UP-REG condition, irrespective of WM-load (see Fig. 2A and B, respectively). The main effect of WM-load was neither significant for valence, $F(1,29) = 0.01$, $p = .934$, $\eta_p^2 = 0.0$, 95% CI [− 0.09, 0.08], nor for arousal, $F(1,29) = 1.07$, $p = .310$, $\eta_p^2 = 0.04$, 95% CI [− 0.04, 0.13]. The WM-load x ER interaction was not significant for valence, $F(1,29) = 2.06$, $p = .162$, $\eta_p^2 = 0.07$, nor for arousal, $F(1,29) = 0.004$, $p < .947$, $\eta_p^2 = 0.00$.

4.1.3. ACCs and RTs

Confirming that our WM-load manipulation was successful, we found a significant main effect of WM-load on both ACCs, $F(1,29) = 19.76$, $p < .001$, $\eta_p^2 = 0.40$, 95% CI [2.94, 7.95], and RTs, $F(1,29) = 229.22$, $p < .001$, $\eta_p^2 = 0.89$, 95% CI [0.41, 0.54], showing that in trials with LOW versus HIGH WM-load, participants were more accurate and responded faster (see Fig. 2C and D, respectively). As expected, differences in ACCs, $F(1,29) = 2.09$, $p = .159$, $\eta_p^2 = 0.06$, 95% CI

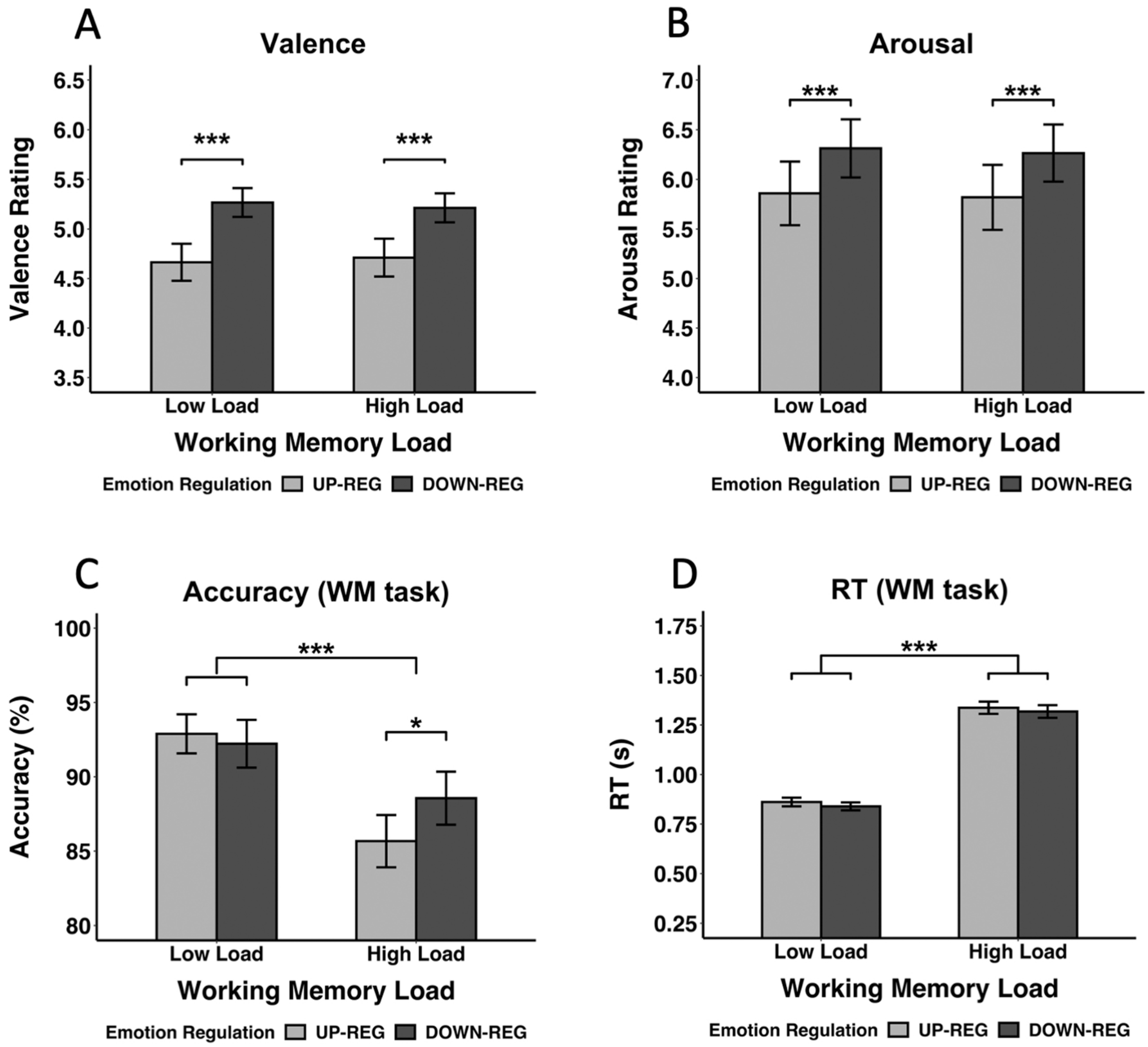

Fig. 2. Results for the manipulation checks. *Note.* Valence Rating (1 = unpleasant, 9 = pleasant), Arousal Rating (1 = aroused, 9 = calm); $^*p < .05$, $^{***} p < .001$.

[− 2.68, 0.46], and RTs, $F(1,29) = 3.41$, $p = .075$, $\eta_p^2 = 0.10$, 95% CI [0.0, 0.04], in the WM task did not differ between DOWN-REG and UP-REG trials, indicating that the task demand was similar in both conditions. Interestingly, replicating results by Gan et al. (2017), the WM-load x ER interaction for ACCs approached significance, $F(1,29) = 3.59$, $p = .068$, $\eta_p^2 = 0.11$. Follow-up comparisons revealed that participants were slightly more accurate in the WM task in the DOWN-REG than in the UP-REG condition in case of HIGH, $F(1,29) = 4.49$, $p = .043$, $\eta_p^2 = 0.13$, 95% CI [0.10, 5.68], but not LOW WM-load, $F(1,29) = 0.41$, $p = .527$, $\eta_p^2 = 0.01$, 95% CI [− 2.80, 1.46], (see Fig. 2C). The WM-load x ER interaction for RTs was not significant, $F(1,29) = 0.02$, $p = .890$, $\eta_p^2 = 0.0$.

4.2. ERP results

4.2.1. Centro-parietal LPP

Fig. 3 presents the results for the LPP. In line with our predictions, we found a main effect of WM-load, $F(1,29) = 3.87$, $p = .059$, $\eta_p^2 = 0.12$, 95% CI [− 0.01, 0.67], indicating that the centro-parietal LPP amplitude was reduced in HIGH compared to LOW WM-load trials (Hypothesis 1). As expected, no main effect of ER was observed, $F(1,29) = 2.43$, $p = .130$, $\eta_p^2 = 0.08$, 95% CI [− 0.01, 0.67]. Contrary to our prediction, a WM-load x ER interaction failed to reach statistical significance threshold, $F(1,29) = 3.55$, $p = .079$, $\eta_p^2 = 0.11$ (Hypothesis 2). However, as we formulated specific a priori lower-order predictions regarding the impact of WM-load on reappraisal conditions, we conducted planned comparisons. This revealed that the LPP amplitude was significantly decreased in the DOWN-REG compared to the UP-REG condition when ER was implemented concurrently with LOW WM-load, $F(1,29) = 5.09$, $p = .032$, $\eta_p^2 = 0.15$, 95% CI [0.06, 1.14], suggesting ER success (Hypothesis 2a; see Fig. 2A and B). However, the LPP amplitude difference between the DOWN-REG and UP-REG condition was not significant when ER was implemented concurrently with HIGH WM-load, $F(1,29) = 0.003$, $p = .957$, $\eta_p^2 = 0.0$, 95% CI [− 0.50, 0.47] (Hypothesis 2a). Moreover, in line with our predictions, the LPP amplitude was significantly *reduced* when the UP-REG condition was paired with HIGH versus LOW WM-load, $F(1,29) = 7.83$, $p = .009$, $\eta_p^2 = 0.21$, 95% CI [0.17, 1.10] (Hypothesis 2b). Finally, in line with our final prediction (Hypothesis 2c), in the DOWN-REG condition the LPP amplitude was not significantly different between HIGH and LOW WM-load trials, $F(1,29) = 0.008$, $p = .927$, $\eta_p^2 = 0.0$, 95% CI [− 0.48, 0.53] (see, Fig. 2B).

5. Summary and conclusions

First, participants reported experiencing more or less negative emotion and arousal in line with the direction of ER, i.e., up- or down-regulation, respectively, confirming that description-based reappraisal was successful in modulating subjective emotional experience, irrespective of WM load condition. Second, confirming that our WM

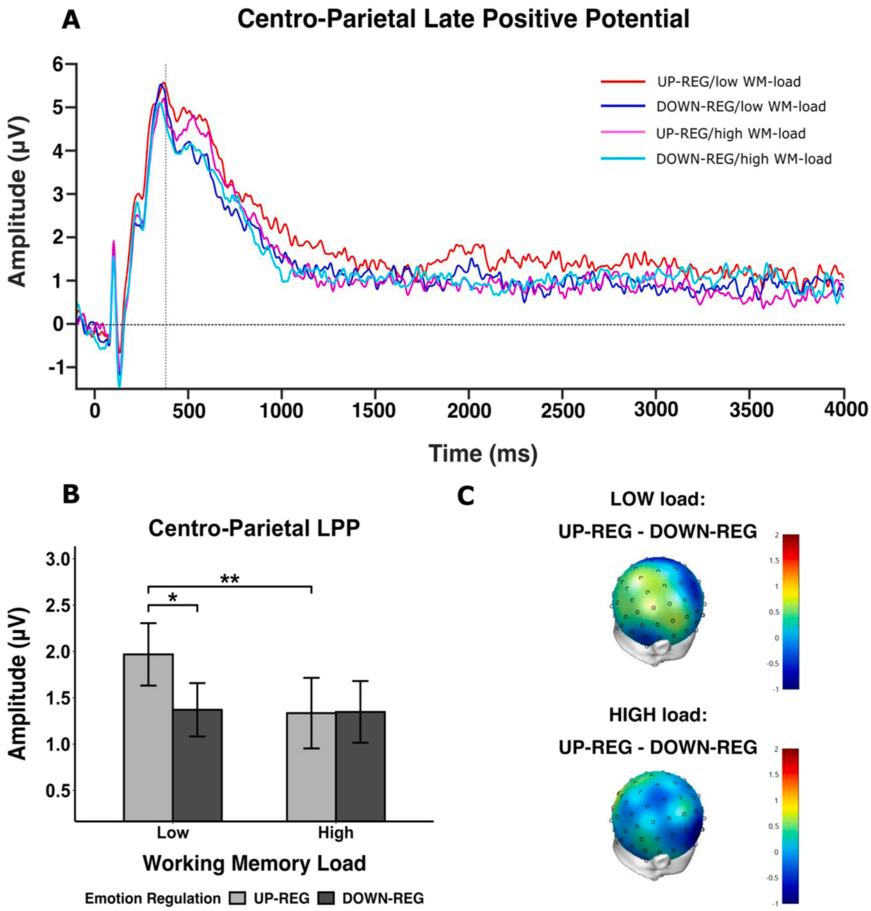

Fig. 3. ERP results. *Note.* A. Picture-locked LPP amplitudes for up-regulation (UP-REG) and down-regulation (DOWN-REG) conditions for low and high WM-load, separately. The vertical dotted line indicates the start of the LPP time window submitted to statistical analysis (i.e., 400–4000 ms after picture onset). The x-axis runs from the beginning of the baseline (100 ms prior to picture onset) to the end of the picture presentation (4000 ms after picture onset). Waveforms are averaged across CPz, Pz, P1, P2, and POz electrodes. B. Mean centro-parietal LPP amplitudes for up-regulation (light gray) and down-regulation (dark gray) conditions, for low WM-load (left) and high WM-load (right), separately. Asterisks indicate simple contrasts between conditions. $*p < .05$, $** \ p < .01$. C. Scalp topography of the difference between negative pictures preceded by negative (UP-REG) and neutral (DOWN-REG) descriptions for low WM-load (top) and high WM-load (bottom) condition, separately.

manipulation was effective, we found a significant main effect of WM-load on ACCs and RTs, showing that participants responded more slowly and made more mistakes when performing ER tasks concurrently with HIGH versus LOW WM-load. Third, no difference in ACCs and RTs in the WM task between the DOWN-REG and UP-REG condition was observed. This suggests that both conditions were well-balanced with respect to the amount of difficulty and that they differed only in terms of the direction (up- or down-regulation) of ER. Finally, although the WM-load x ER interaction for the LPP was non-significant ($p = .079$), planned comparisons provided suggestive evidence in favor of all our hypotheses, demonstrating that: (i) WM-load exerted a down-regulatory influence on the LPP, as indicated by the decreased LPP amplitude in HIGH compared to LOW WM-load trials (Hypothesis 1), (ii) reappraisal was effective when implemented concurrently with low WM-load, but ineffective when implemented with high load, as indicated by the significant LPP amplitude difference between the UP- and DOWN-REG conditions in LOW but not HIGH WM-load trials (Hypothesis 2a); (iii) high WM-load diminished the up-regulatory effect of reappraisal, as indicated by the decreased LPP amplitude in the UP-REG condition when it was implemented concurrently with HIGH versus LOW WM-load (Hypothesis 2b), and (iv) high WM-load impaired the down-regulatory effect of reappraisal (i.e., HIGH WM-load did not exert an additive down-regulatory influence on the LPP amplitude in the DOWN-REG condition), as indicated by the lack of difference in the LPP amplitude between HIGH and LOW WM-load trials in the DOWN-REG condition (Hypothesis 2c). Together these findings indicate that the decrease in the LPP amplitude in the DOWN-REG + *LOW* WM-load condition (compared to UP-REG + LOW WM-load condition) was caused by the *down-regulatory effect of reappraisal*. However, considering the main effect of WM-load on the LPP (HIGH < LOW) and the down-regulatory effect of high WM-load on the LPP in the UP-REG condition (UP-REG: HIGH < LOW), the reduced LPP amplitude in the DOWN-REG + *HIGH* WM-load condition (compared to the UP-REG + LOW WM-load condition) was most probably driven by *high WM-load* rather than the down-regulatory effect of reappraisal.

6. Experiment 2

Experiment 2 was aimed at investigating the impact of low versus high WM-load on the effectiveness of distraction. As distraction involves limiting executive/attentional resources that can be devoted to processing an emotional stimulus (Sheppes et al., 2014), we contrasted two conditions that differed with respect to the level of difficulty associated with their execution: A cognitively demanding one that aimed to suppress the emotional response to a negative picture by engaging attentional resources into task-related processing (DOWN-REG condition), and a less cognitively demanding one that aimed to preserve attentional resources and thus allow an emotional response to develop (NO-REG condition). As in Experiment 1, we hypothesized that high versus low WM-load would limit attentional processing of emotional pictures and thus reduce the LPP amplitude (Barley et al., 2021; MacNamara, Ferri, et al., 2011; Van Dillen & Derks, 2012). However, in contrast to Experiment 1, we assumed an additive down-regulatory influence of DOWN-REG and HIGH WM-load manipulation on the LPP amplitude (i.e., we expected that the DOWN-REG + HIGH WM-load condition would reduce the LPP amplitude to a greater extent than the DOWN-REG + LOW WM-load condition). Thus, we expected to observe:

Hypothesis 1. a significant main effect of WM-load, showing the reduced LPP amplitude in high versus low WM-load trials (LOW > HIGH),

Hypothesis 2. a significant main effect of Emotion Regulation, showing the reduced LPP amplitude in the DOWN-REG compared to NO-REG condition (NO-REG > DOWN-REG).

7. Materials and methods

7.1. Participants

As in Experiment 1, sample size was pre-determined using G*Power 3 software (Faul et al., 2007). The same input parameters were used based on previous studies that investigated the impact of WM load (MacNamara, Ferri, et al., 2011; Van Dillen & Derks, 2012) and distraction (Paul et al., 2013; Schönfelder et al., 2014) on the emotion-enhanced LPP amplitude, indicating that 27 participants were needed to detect a 2-way interaction effect for repeated measures ANOVA. Accordingly, 30 adult women (mean age 21.4 ± 2.5 years) were recruited. We applied the same exclusion criteria as in Experiment 1. The investigation was approved by the local ethics committee (approval no.#08112019).

7.2. Stimulus materials

The same set of 120 aversive images as in Experiment 1 was used. Following previous studies (Kanske et al., 2011; Li et al., 2017; Schönfelder et al., 2014), a cognitively engaging task involving mental arithmetic was used as a distraction strategy on half of all trials. In these trials picture presentation was accompanied by a simple arithmetic equation (e.g., "6 + 5 – 4 = ?"), which served as the down-regulation (DOWN-REG) condition. A less engaging cognitive task served as the control (no-regulation, NO-REG) condition on the other half of all trials. In these trials, only a single-digit number (e.g., "7") was presented instead of the equation. All arithmetic equations were formed with three operands, including a subtraction and an addition, and consisted of single-digit numbers. The equations were generated pseudo-randomly and were assigned randomly to each picture. Again, the order of presentation of stimuli was random for each participant. The WM-load manipulation was the same as in Experiment 1.

7.3. Procedure

Upon arrival, participants received detailed task instructions and performed 10 practice trials to confirm their understanding of the procedure and the use of the rating scales. Following practice trials, EEG sensors were attached, and the experiment started. Testing was conducted in a sound-attenuated, air-conditioned EEG cabin.

A sample trial structure is illustrated in Fig. 4. Each trial began with a white fixation cross displayed on a gray background for 1000 ms. This was followed by: (1) a letter string memorization phase; (2) an ER phase; (3) a letter string recall phase; and 4) a rating phase. During the letter string memorization phase, a one-letter (LOW WM-load) or four-letter string (HIGH WM-load) was displayed on the screen in green font (2000 ms) and participants' task was to memorize it. The ER phase began with the presentation of a white fixation cross (300–700 ms) which was followed by an aversive picture (4000 ms) presented along with either an arithmetic equation (DOWN-REG condition) or a single-digit number (NO-REG condition) displayed on top of the picture (with 80% opacity) for the entire picture presentation duration. After that, a number in red font was displayed on the screen, preceded, and followed by a blank screen (300–700 ms), and participants had to decide whether this number was: (1) a solution to the previously displayed equation (DOWN-REG condition) or (2) the same number that had previously been presented (NO-REG condition). Half of the trials required a "yes" answer and half a "no" answer. To ensure that participants made calculations, and not merely estimated the solution, in case of the "no" trials, the displayed number always differed from the correct answer by one. Participants provided a "yes" response with their right middle finger (right arrow on the keyboard), and a "no" response with their right index finger (left arrow on the keyboard). After that, feedback regarding the correctness of their response was displayed (1000 ms), followed by a white fixation cross (300–700 ms).

In the letter string recall phase, participants viewed a one- or a four-letter string (depending on the WM-load condition) displayed in red font and were asked to decide whether: (1) it is the same letter they had initially seen (for LOW WM-load) or (2) the presented letters are in the same order as the letters they had initially seen (for HIGH WM-load). Half of the trials required a "yes" answer, and the half a "no" answer. Participants provided a "yes" response with their right middle finger (right arrow on the keyboard), and a "no" response with their right index finger (left arrow on the keyboard). Then, they received feedback regarding the correctness of their response (1000 ms). Trials concluded with the subjective rating of emotion experience on valence (1 = unpleasant; 9 = pleasant) and arousal (1 = aroused; 9 = calm) dimensions of the self-assessment manikin (SAM) (Bradley & Lang, 1994). After completion of the experimental task EEG sensors were removed and participants were asked to rank the conditions from the most to the least difficult/challenging. Then, all participants were debriefed, reimbursed, and thanked for their participation in the study.

The procedure consisted of 120 trials in total (separated by one-minute breaks after every 30 trials), that were divided into four

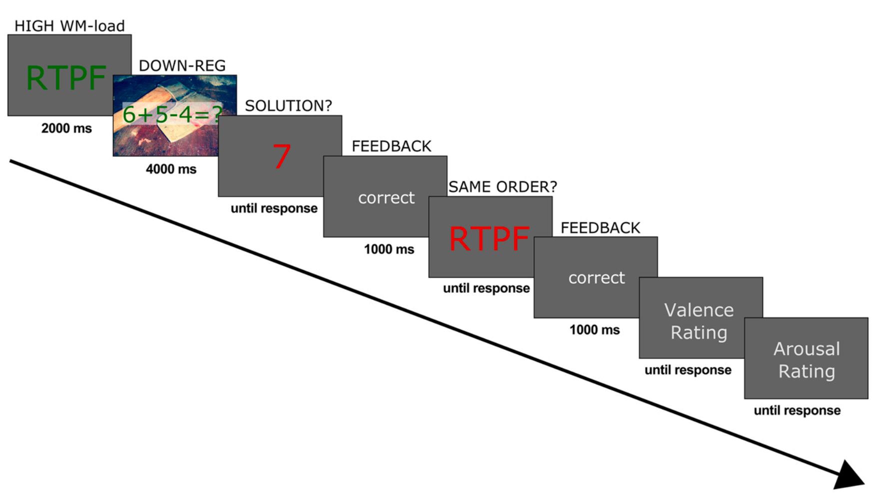

Fig. 4. Sample trial structure. *Note.* Depiction of a sample trial structure. Stimuli (scaled up, for presentation purposes) were separated by interstimulus intervals, during which a fixation cross or a blank screen was presented (see Materials and Methods for details). In compliance with copyright laws, the picture used here is similar but not identical to those presented in the study. Valence and Arousal Ratings were presented in a form of Self-Assessment Manikin (SAM) scales.

experimental conditions (Emotion-regulation x WM-load: 30 trials per condition): NO-REG + LOW load, DOWN-REG + LOW load, NO-REG + HIGH load, DOWN-REG + HIGH load. Trial types were intermixed, and the order of trials was determined randomly for each subject. Details concerning the equipment and experimental software are the same as in Experiment 1.

7.4. Electrophysiological recording, data reduction, and analysis

Data acquisition, pre-processing and analysis was conducted in the

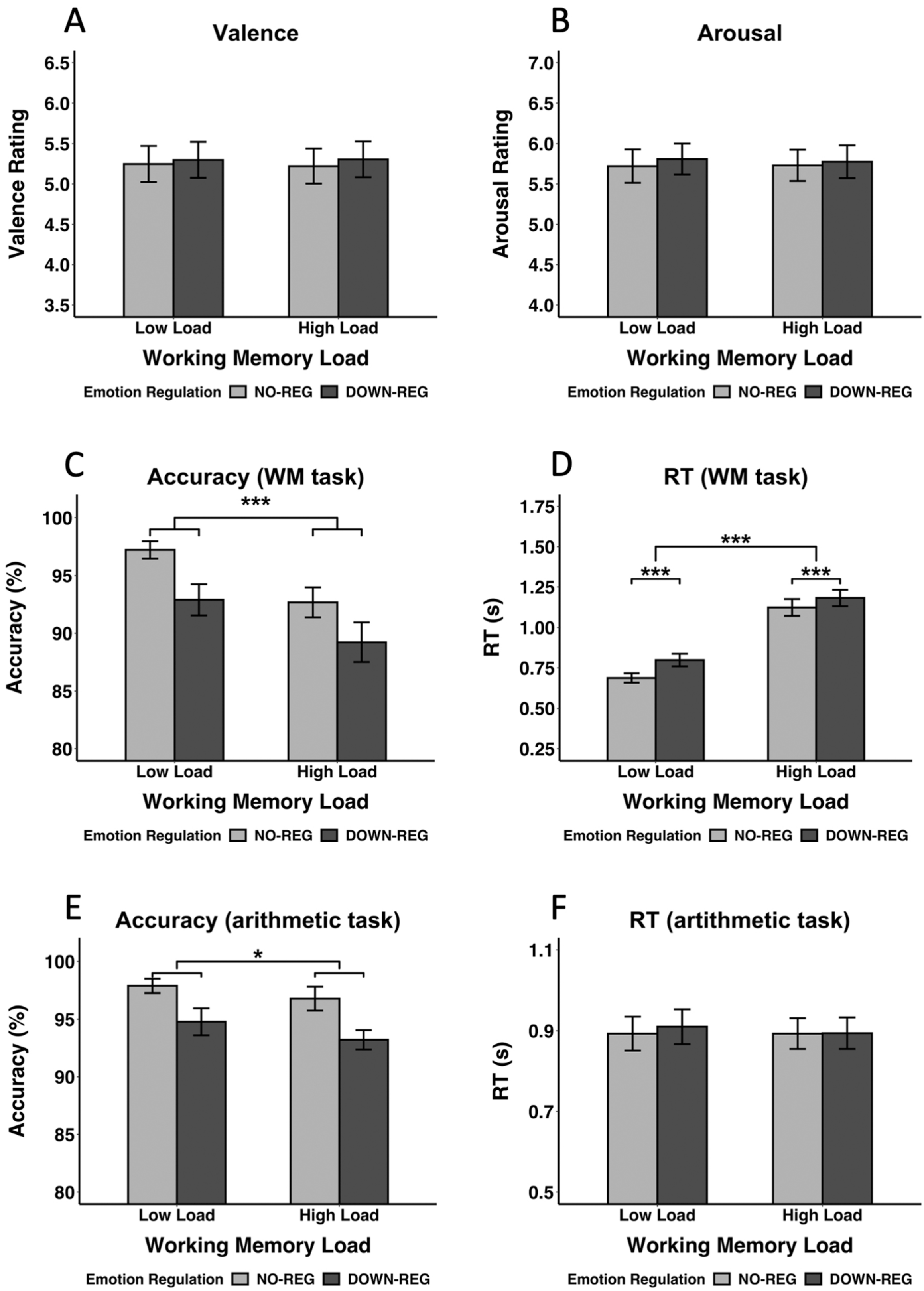

Fig. 5. Results for the manipulation checks. *Note.* *$p < .05$, *** $p < .001$. Valence Rating (1 = unpleasant, 9 = pleasant), Arousal Rating (1 = aroused, 9 = calm).

same way as in Experiment 1. The average number of artifact-free trials was 25.8 per condition. Separate ERP averages were computed for the four different trial types (WM-load x Emotion Regulation). The LPP was scored by averaging amplitudes from 400 to 4000 ms following picture onset at the same five centroparietal sites (CPz, Pz, P1, P2, POz) that were used in the Experiment 1.

8. Results

To test whether WM-load and ER instructions modulated LPPs and self-reported affect in the expected direction, mean centro-parietal LPP (400–4000 ms) amplitude, mean valence and arousal ratings, as well as mean ACCs and RTs for the WM task and for the mental arithmetic and a control task were submitted to repeated measures analyses of variance (ANOVA) with two within-subject factors (WM-load: LOW vs. HIGH; emotion-regulation: DOWN-REG vs. NO-REG). *p* values were adjusted with the Bonferroni correction for multiple post hoc comparisons. Statistical analyses were performed using SPSS (Version 26.0) General Linear Model software.

8.1. Manipulation checks

Fig. 5 presents the results for the manipulation checks.

8.1.1. Task difficulty assessment

All participants indicated that remembering four-letter strings (HIGH WM-load condition) was more difficult than remembering a single letter (LOW WM-load condition). All but one participant indicated that solving the equation (DOWN-REG condition) was more demanding than remembering a single-digit number (NO-REG condition); one participant reported that remembering one letter (LOW WM-load) and solving the equation (DOWN-REG condition) was more difficult, as she focused on the latter task and sometimes did not pay sufficient attention to remembering one letter.

8.1.2. Valence and arousal ratings

No effects were observed for valence and arousal ratings (see Fig. 5A and B). Main effect of ER for valence, $F(1,29) = 1.90$, $p = .179$, $\eta_p^2 = 0.06$, 95% CI [− 0.17, 0.33], and arousal, $F(1,29) = 1.55$, $p = .224$, $\eta_p^2 = 0.05$, 95% CI [− 0.17, 0.04]. Main effect of WM-load for valence, $F(1,29) = 0.06$, $p = .811$, $\eta_p^2 = 0.0$, 95% CI [− 0.08, 0.10], and arousal, $F(1,29) = 0.08$, $p = .784$, $\eta_p^2 = 0.0$, 95% CI [− 0.07, 0.10]. The WM-load x ER interaction for valence, $F(1,29) = 0.22$, $p = .640$, $\eta_p^2 = 0.0$, and arousal, $F(1,29) = 0.17$, $p < .688$, $\eta_p^2 = 0.0$.

8.1.3. ACCs and RTs

Confirming that our WM-load manipulation was successful, we found a significant main effect of WM-load on both ACCs, $F(1,29) = 18.64$, $p < .001$, $\eta_p^2 = 0.40$, 95% CI [2.21, 6.0], and RTs, $F(1,29) = 215.28$, $p < .001$, $\eta_p^2 = 0.88$, 95% CI [0.35, 0.47], showing that in trials with LOW versus HIGH WM-load, participants were more accurate and responded faster (Fig. 5C and D, respectively). We also found a main effect of ER on both ACCs, $F(1,29) = 11.70$, $p = .002$, $\eta_p^2 = 0.29$, 95% CI [1.56, 6.21], and RTs, $F(1,29) = 31.75$, $p < .001$, $\eta_p^2 = 0.52$, 95% CI [0.05, 0.12], showing that participants responded slower and made more mistakes in DOWN-REG compared to NO-REG trials, suggesting that greater task demand was present in the DOWN-REG than NO-REG condition. The WM-load x ER interaction for RTs approached significance, $F(1,29) = 3.77$, $p = .062$, $\eta_p^2 = 0.12$, but it was not significant for ACCs, $F(1,29) = 0.16$, $p = .689$, $\eta_p^2 = 0.0$.

We also analyzed ACCs and RTs in response to the ER mental arithmetic (DOWN-REG condition) and control task (NO-REG condition). We found a significant main effect of ER on ACCs, $F(1,29) = 25.59$, $p < .001$, $\eta_p^2 = 0.47$, 95% CI [1.99, 4.68], which indicated that participants were more accurate in less cognitively demanding NO-REG trials than in DOWN-REG trials (see, Fig. 5E). Moreover, in line with our results for the WM task, we also found a significant main effect of WM-load on ACCs, $F(1,29) = 4.32$, $p = .047$, $\eta_p^2 = 0.13$; 95% CI [0.02, 2.65], which showed that participants were more accurate in LOW versus HIGH WM-load trials (see, Fig. 5E), confirming greater task demand present in trials with a concurrent HIGH versus LOW WM-load. No significant effects for RT were observed (see, Fig. 5F). Main effect of ER for RTs, $F(1,29) = 0.32$, $p = .577$, $\eta_p^2 = 0.01$, 95% CI [− 0.04, 0.02]. Main effect of WM-load for RTs, $F(1,29) = 0.34$, $p = .566$, $\eta_p^2 = 0.01$, 95% CI [− 0.02, 0.04]. The WM-load x ER interaction for RTs, $F(1,29) = 0.42$, $p = .521$, $\eta_p^2 = 0.01$.

8.2. ERP results

8.2.1. Centro-Parietal LPP

Fig. 6 presents the results for the LPP. In contrast to Hypothesis 1, the main effect of WM-load on the LPP was not significant, $F(1,29) = 2.72$, $p = .110$, $\eta_p^2 = 0.09$, 95% CI [− 0.09, 0.86]. In line with Hypothesis 2, we found a significant main effect of ER on the LPP amplitude, $F(1,29) = 6.74$, $p = .015$, $\eta_p^2 = 0.19$, 95% CI [0.17, 1.41], showing that the LPP amplitude was significantly reduced in the DOWN-REG compared to NO-REG condition. To our surprise, our results also suggested a potential interaction between WM-load and ER, $F(1,29) = 3.55$, $p = .070$, $\eta_p^2 = 0.11$. Visual inspection of the ERP waveforms (Fig. 6 A) indicated that the downregulation of the LPP amplitude in the DOWN-REG compared to NO-REG condition was stronger in the HIGH than in the LOW WM-load trials. Exploratory follow-up comparisons confirmed this observation, showing that the LPP amplitude was significantly decreased in the DOWN-REG compared to the NO-REG condition when ER was implemented concurrently with HIGH WM-load, $F(1,29) = 14.45$, $p = .001$, $\eta_p^2 = 0.33$, 95% CI [0.62, 2.06], but not with LOW WM-load, $F(1,29) = 0.26$, $p = .615$, $\eta_p^2 = 0.009$, 95% CI [− 0.74, 1.23] (see, Fig. 6 A and B). Furthermore, comparison of the LPP amplitude differences between HIGH and LOW WM-load trials for each ER condition separately revealed that the LPP amplitude was significantly decreased for HIGH versus LOW WM-load in the DOWN-REG condition, $F(1,29) = 7.02$, $p = .013$, $\eta_p^2 = 0.20$, 95% CI [0.21, 1.64]. However, the LPP amplitudes for HIGH versus LOW WM-load trials did not differ in the NO-REG condition, $F(1,29) = 0.18$, $p = .675$, $\eta_p^2 = 0.006$, 95% CI [− 0.96, 0.63] (see, Fig. 6 A and B).

9. Summary and conclusions

First, in contrast to expectations, participants reported experiencing similar levels of negative emotion and arousal irrespective of ER or WM-load condition (Fig. 5A and B). Second, confirming that our WM manipulation was effective, we found a significant main effect of WM-load on ACCs and RTs, showing that participants responded more slowly and made more mistakes when performing ER tasks concurrently with HIGH than with LOW WM-load (Fig. 5C and D). Third, a significant main effect of ER on ACC and RT in the WM task, and on ACC in the mental arithmetic task, indicated that participants responded more slowly and made more mistakes in the DOWN-REG compared to NO-REG condition (Fig. 5E). This shows that the ER mental arithmetic task was more cognitively demanding than the control task, confirming that our distraction manipulation was successful. Finally, we observed the predicted main effect of ER on the LPP, which showed that the LPP amplitude was significantly decreased in the DOWN-REG compared to the NO-REG condition (Hypothesis 2). In addition, the results suggested that there was an unexpected potential ER x WM-load interaction. More specifically, the exploratory follow-up analyses revealed that: (i) high WM-load and the DOWN-REG condition exerted additive down-regulatory impact on the LPP, as indicated by a significant decrease in the LPP amplitude in the DOWN-REG condition implemented concurrently with high versus low WM-load; (ii) high WM-load facilitated the down-regulatory effect of distraction as indicated by the significantly reduced LPP amplitude in the DOWN-REG compared to NO-REG

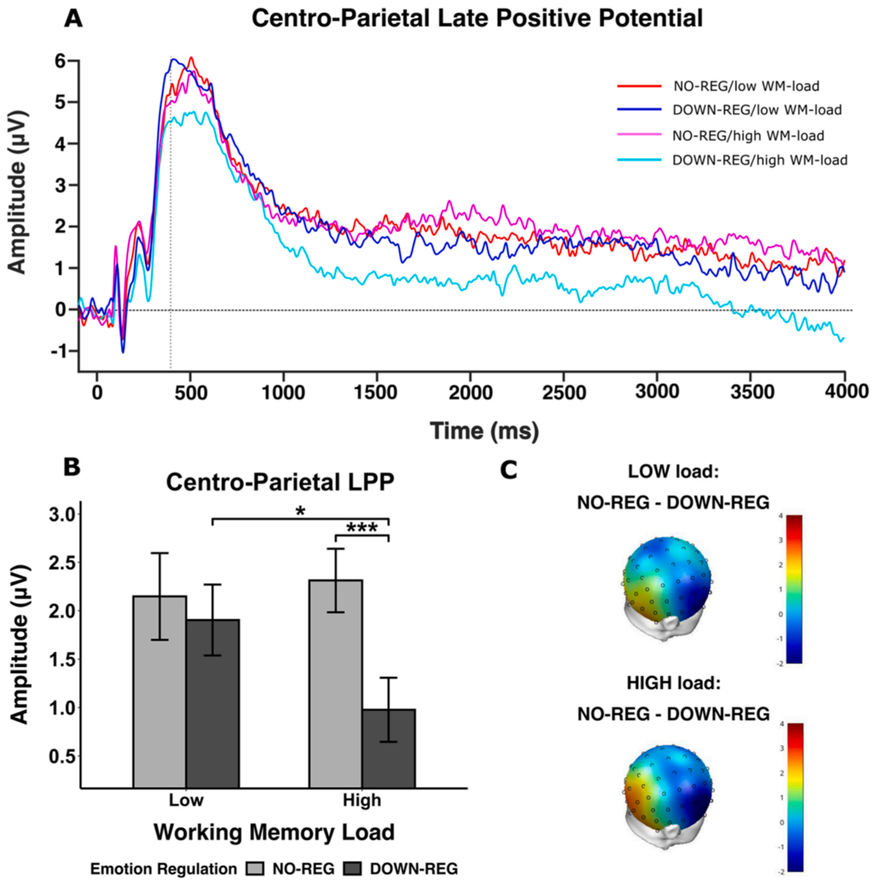

Fig. 6. ERP results. *Note*. A. Picture-locked LPP amplitudes for no-regulation (NO-REG) and down-regulation (DOWN-REG) conditions for low and high WM-load, separately. The vertical dotted line indicates the start of the LPP time window submitted to statistical analysis (i.e., 400–4000 ms after picture onset). The x-axis runs from the beginning of the baseline (100 ms prior to picture onset) to the end of the picture presentation (4000 ms after picture onset). Waveforms are averaged across CPz, Pz, P1, P2, and POz electrodes. B. Mean centro-parietal LPP amplitudes for no-regulation (light gray) and down-regulation (dark gray) conditions, for low WM-load (left) and high WM-load (right), separately. Asterisks mark comparison between conditions. *$p < .05$, *** $p < .001$. C. Scalp topography of the difference between negative pictures presented with a single digit number (NO-REG) and arithmetic equation (DOWN-REG) for low WM-load (top) and high WM-load (bottom) condition, separately.

condition in HIGH WM trials. Contrary to our predictions, however, WM-load failed to modulate the LPP amplitude in the NO-REG condition, where we found no difference between HIGH and LOW WM-load trials. This may explain the non-significant main effect of WM-load on the LPP (Hypothesis 1). Moreover, exploratory follow-up analyses showed that although the effect of ER was significant in HIGH WM trials, there was no significant difference between DOWN-REG and NO-REG conditions for LOW WM-load trials (Fig. 6B).

10. General discussion

In the present investigation, we explored the role of WM in the efficacy of ER effects of reappraisal and distraction, two major cognitive ER strategies. To this end, the availability of WM resources was manipulated by requiring participants to remember either a one- (low WM-load) or a four-letter string (high WM-load), while viewing negative pictures. In Experiment 1, investigating reappraisal, these pictures were preceded by negative (UP-REG) or neutral (DOWN-REG) descriptions. In Experiment 2, investigating distraction, the pictures were presented concurrently with a single-digit number to remember (NO-REG), or a mathematic equation to solve (DOWN-REG). To obtain an objective estimate of ER cognitive effects, we measured the LPP, an electrocortical marker of sustained motivated attention, in response to the negative pictures.

Replicating previous findings (Gan et al., 2017) with the use of well-established reappraisal (Foti & Hajcak, 2008;; MacNamara, Ochsner, et al., 2011; Wang et al., 2017) and WM-load methodology (Erk et al., 2007; MacNamara, Ferri, et al., 2011; Van Dillen et al., 2009), Experiment 1 demonstrated that reappraisal is effective when it is implemented concurrently with low WM-load, but ineffective when implemented concurrently with high WM-load. This was indicated by: (i) the significant attenuation of the LPP during down- versus up-regulation in the low WM-load trials, indicating reappraisal success under low WM-load (LOW: DOWN-REG < UP-REG); (ii) the *lack* of difference in the LPP amplitude between down- and up-regulation conditions under high WM-load, suggesting reappraisal failure under high WM-load (HIGH: DOWN-REG = UP-REG); (iii) a significant attenuation of the LPP amplitude in the UP-REG condition for high compared to low WM-load trials, suggesting counter-effective reappraisal up-regulation under high WM load (UP-REG: HIGH < LOW); and (iv) the *lack* of significant difference in the LPP amplitude between high and low WM-load trials in the DOWN-REG condition, suggesting counter-productive reappraisal down-regulation under high WM-load (DOWN-REG: LOW = HIGH). Given the observed pattern of findings, we suggest different processes responsible for the reduction in the LPP amplitude in DOWN-REG + low WM-load and DOWN-REG + high WM-load conditions. More specifically, we argue that in the (DOWN--REG) low WM-load condition, the decrease in the LPP amplitude was caused by the reappraisal-induced change in stimulus meaning. Conversely, given the main effect of WM-load (HIGH < LOW) and the down-regulatory effect of high WM-load on the LPP amplitude in the UP-REG condition (UP-REG: HIGH < LOW), we suggest that the decreased LPP amplitude in the (DOWN-REG) high WM-load condition was driven primarily by high WM-load rather than a reappraisal-induced change in meaning. In other words, this pattern of results suggests that high WM-load impeded the up-regulatory effect of reappraisal, causing a *decrease* in the LPP amplitude for high compared to low WM-load trials in the UP-REG condition (UP-REG: HIGH < LOW), and likewise that it impeded the down-regulatory effect of reappraisal, as evidenced by the *lack of difference* between low versus high WM-load trials in the DOWN-REG condition. Consequently, there was no difference between the two (up and down) regulation conditions when they were implemented concurrently with high WM-load (HIGH: DOWN-REG = UP-REG, see Fig. 3). Together, these results provide converging evidence that reappraisal efficacy is dependent on WM resources in healthy young adults and that additional processing load on the WM system can attenuate the reappraisal-driven mechanism of cognitive change, potentially interfering with deep semantic elaboration and reinterpretation of emotionally evocative visual contents (Hofmann et al., 2012; Ochsner, Silvers, & Buhle, 2012).

Some of the down-regulatory effects of reappraisal can be attributed to cognitive demand associated with the need to come up with one's own (re)interpretation (Hajcak & Foti, 2020; Wyczesany & Ligeza, 2017). As the aim of Experiment 1 was to examine the impact of WM-load on the reappraisal-*specific* mechanism of cognitive *change*, we provided participants with ready-made reinterpretations (Foti & Hajcak, 2008; MacNamara et al., 2009; Wang et al., 2017) in order to manipulate the cognitive change process while controlling for cognitive demand. Although we were successful in doing so (as evidenced by the lack of significant differences in RTs and ACCs between both DOWN-REG and UP-REG conditions), it also made the reappraisal task easier compared to a situation when one needs to come up with their own reinterpretation (cf., Paul et al., 2013; Shafir et al., 2015, 2018). Given the down-regulatory effect of cognitive demand on the LPP amplitude (Barley et al., 2021; Erk et al., 2007; MacNamara, Ferri, et al., 2011; Van Dillen & Derks, 2012), it might be argued that if we had used this more demanding form of reappraisal, high WM-load would have *facilitated* (rather than impaired) LPP downregulation. However, in such a case the downregulation of the LPP amplitude would most likely be driven by cognitive demand rather than the cognitive change process that we were interested in. Alternatively, high WM-load, when combined with a cognitively demanding reappraisal task, could also disrupt the very ability to generate alternative interpretations or induce task switching (between the WM and reappraisal tasks), thus affecting task performance rather than the cognitive change process per se.

Despite evidence for ineffective ER via reappraisal under high WM load on the neural level, participants reported experiencing fewer negative emotions and less arousal in the down- versus up-regulation condition, irrespective of WM-load. This finding can be interpreted in two ways. First, our WM-load manipulation might have been too subtle to produce discernible effects of reduced reappraisal effectiveness at the subjective experience level. In the only study that explored the disrupting effect of high WM-load on ER via reappraisal, subjective emotion experience was not measured, so it is challenging to evaluate this possibility (Gan et al., 2017). Alternatively, the necessity to focus on performing the WM task (which was evaluated on each trial, immediately after the picture offset) could have impaired participants' ability to closely monitor their affective state while viewing emotional pictures. Consequently, they could have based their evaluations of the retrospectively experienced affect on the content of the reappraisal-inducing sentences (and the resulting expectations of how they were supposed to have felt) rather than their actual experiences, providing biased responses (Adamczyk, Ligeza, & Wyczesany, 2020; Lieberman, Inagaki, Tabibnia, & Crockett, 2011). It is important to note here that participants have strong beliefs of how different ER strategies should affect their subjective emotion experience. For instance, Lieberman et al. (2011) demonstrated that although affect labeling (i.e., putting feelings into words) leads to reduced distress, people did not believe nor predict it to be an effective ER strategy, even after personally experiencing reduction in negative emotions when using this ER strategy. Thus, it is possible that participants in our study had similar convictions about reappraisal *efficacy* which was reflected in the subjective ratings.

Previous studies demonstrated that increasing processing demands of a focal task can reduce attention to negative information (Erk et al., 2007; Legrain et al., 2011; Legrain *et al.* 2012; Lv et al., 2010; MacNamara, Ochsner, et al., 2011; Van Dillen & Derks, 2012). More specifically, it was demonstrated that under high processing load, working memory facilitates attention to task-relevant information at the expense of task-irrelevant information, even when such information is emotionally salient. As such, working memory can serve as a useful top-down attentional control mechanism that can enable the achievement of goals and standards by shielding them from external interference (Oberauer, 2019).

In line with the above reasoning, Experiment 2 demonstrated that increasing WM-load by performing two *different* WM-dependent tasks (one which served as WM-load manipulation and one as distraction manipulation) can enhance top-down attentional control, reducing attentional interference from negative, task-irrelevant stimuli as indicated by: (i) the significant decrease in the LPP amplitude in the DOWN-REG (distraction) versus NO-REG (control) condition under high WM-load (HIGH: DOWN-REG < NO-REG); and (ii) the reduction of the LPP in high compared to low WM-load trials in the DOWN-REG condition (DOWN-REG: HIGH < LOW). Our study shows for the first time that ER effects of distraction can be enhanced by additional WM-load, which supports the notion that limiting attention to emotional stimuli by loading WM with neutral contents is a core regulatory mechanism of the distraction strategy (Sheppes et al., 2014; Van Dillen & Koole, 2007). Importantly, this finding also indicates that when executive resources are constrained (e.g., by situational demands), distraction can have an advantage over reappraisal as it is a less demanding ER strategy (Scheibe et al., 2015; Sheppes, Catran, & Meiran, 2009; Strauss, Ossenfort, & Whearty, 2016).

Although, we observed the hypothesized main effect of ER (Hypothesis 2), our results also revealed a potential ER x WM-load interaction (as did the results of the Bayes Factor analysis, see the Supplementary Material). Exploratory follow-up comparisons revealed that, unexpectedly, a decrease in the LPP amplitude between DOWN-REG and NO-REG condition in low WM-load trials was not significant (see Fig. 6A and B). Research suggests that when loading WM, there might a be a crucial inflection point at which attentional resources get re-allocated from emotional processing to processing task demands as WM-load increases. In their study, Vytal, Cornwell, Arkin, and Grillon (2012) used a threat of shock paradigm to induce anxiety while participants performed an *n*-back task with parametrically modulated task difficulty (WM-load). They measured the startle reflex and self-reports as indices of physiological and subjective levels of anxiety, respectively. It was observed that although low-to-moderate WM-load failed to modulate the experienced level of anxiety, as evidenced by lack of modulation of the startle reflex between the threat-of-shock and safe (no-threat-of-shock) conditions, there was a crucial transition point at which high WM-load started to down-regulate physiological arousal (i.e., the magnitude of the startle response) and at which the previously significant difference in task performance between the threat-of-shock and the safe condition disappeared. Considering the above, it is possible that our distraction manipulation (mental arithmetic task) might not have been demanding enough to re-allocate attentional resources from processing the task-irrelevant, emotional stimulus when paired with low WM-load task (remembering a one letter sting, low WM-load). Astonishingly, however, when paired with only a slightly more challenging WM-load task (remembering a four-letter string, high WM-load), the mental arithmetic task produced a marked LPP modulation (see Fig. 6A and B), indicating that this higher cognitive load might have exceeded a critical 'attention re-allocation' point at which executive resources were diverted from emotional stimulus and shifted toward increased task demands.

Despite evidence for successful distraction from emotional stimuli at the neural level, participants reported experiencing similar level of negative emotions and arousal, irrespective of WM or ER condition. As already mentioned, the observed lack of modulation of subjective affect could have resulted from the retrospective assessment of experienced emotions and/or the necessity to focus on (WM and arithmetic) tasks, which could have impaired the ability to monitor one's affective state. With no external cues to fall back on (such as content of reappraisal sentences), participants might have failed to adequately register subtle changes in their affective experience.

In a similar vein, in neither experiment did we observe the main effect of WM-load on subjective ratings (Fig. 2A and B, and Fig. 5A and B for reappraisal and distraction, respectively). Results of previous studies show that the more effortful the cognitive activity, the stronger the neutralization of (negative or positive) emotions (Erber & Tesser, 1992). In previous studies that examined the effect of WM-load on emotion experience, more cognitively-taxing conditions were used as high WM-load condition, including letter or number strings that ranged from six (Barley et al., 2021; Erk et al., 2007; MacNamara, Ferri, et al., 2011; Van Dillen & Derks, 2012) to up to nine elements (Dörfel et al., 2014). Thus, it is possible that our high WM-load condition was less distracting than those used in prior studies (Van Dillen & Koole, 2007). However, it is challenging to confirm this possibility as most studies did not include measurement of subjective emotion experience (Barley et al., 2021; MacNamara, Ferri, et al., 2011; Van Dillen & Derks, 2012), and those that did explicitly suggested to participants that WM-load manipulation should serve as an ER strategy, which may have affected the ratings (Dörfel et al., 2014).

In the present investigation, our primary goal was to examine the role of WM load on the core regulatory mechanisms of reappraisal and distraction. For this reason, in Experiment 1, we focused on manipulation of cognitive change/stimulus meaning (Gan, Yang, Chen, & Yang, 2015; MacNamara et al., 2009; Wang et al., 2017), which is a primary regulatory mechanism of reappraisal, while keeping the cognitive demand constant across ER conditions (McRae, 2016). Conversely, in Experiment 2, we explicitly manipulated the level of cognitive demand between the ER conditions, by loading WM with an arithmetic task (Kanske et al., 2011; Li et al., 2017; Schönfelder et al., 2014), as WM-driven modulation of attention is assumed to be a regulatory mechanism of distraction (Van Dillen & Koole, 2007). Although this experimental design allowed us to 'isolate' the core regulatory effects of each strategy, it did not permit direct between-group comparisons between both experiments. Thus, we encourage future studies to compare the effects of WM-load on each strategy using a design that is optimized for such a direct comparison. In the current study we included only healthy female participants to limit the potentially confounding impact of gender differences in the processing and regulation of responses to emotional stimuli (Filkowski et al., 2017; McRae et al., 2008). Thus, a replication study should include a mixed gender sample, to verify if the results generalize to male participants. Finally, it deserves to be noted that although planned comparisons replicated previous findings (Gan et al., 2017) and supported all three lower-order predictions concerning the impact of high and low WM-load on reappraisal (Hypotheses 2a, 2b, 2c), the WM-load x ER interaction was non-significant ($p = .079$, Hypothesis 2). This non-significant effect may have resulted from the lack of power associated with the use of a less demanding high WM-load condition. As mentioned earlier, we used four, instead of six-to-nine (Barley et al., 2021; Dörfel et al., 2014; MacNamara, Ferri, et al., 2011; Van Dillen & Derks, 2012) items as high WM-load, in order not to disrupt the participants' ability to read and understand the reappraisal descriptions. Moreover, we also used a description-based reappraisal task (Foti & Hajcak, 2008; MacNamara, Ochsner, et al., 2011; Wang et al., 2017) that was much better controlled but may have been less demanding (cf., Paul et al., 2013; Schönfelder et al., 2014; Shafir et al., 2015), and as a result produced significant but relatively small reappraisal effects in the 'baseline' low WM-load condition (Fig. 3A). One possible explanation for this weak reappraisal effects is that even a low WM-load could already have interfered with cognitive change mechanisms. It is also possible that there was a by-participant and/or by-item variability in how effective up- and down-regulation descriptions were. Future studies could thus include a condition with no WM-load (for instance, a condition where one letter would be presented, but it would not have to be memorized) or individually calibrated (or generated) reappraisal descriptions to resolve these potential limitations and to gain higher statistical power.

Taken all into account, although our study and that of Gan et al. (2017) provided converging findings using entirely different reappraisal paradigms, given the lack of significant interaction and significant but small reappraisal effect observed in the 'baseline' low WM load condition, our results should be called suggestive rather than robust (but see the results of the Bayes Factor analysis included in the Supplementary Material). Thus, to prevent potential loss-of-power that might have been observed in our experiments, we advise future studies to replicate and extend these findings using a bigger sample size, a person-tailored reappraisal manipulation, and a WM task with parametrically modulated (Vytal et al., 2012) or individually calibrated (Buhle & Wager, 2010) WM-load to provide more evidence on the disrupting impact of high WM-load on the reappraisal-specific process of cognitive change.

To summarize, our results support previous, predominantly correlational, findings (McRae et al., 2010, 2012; Schmeichel & Tang, 2015; Zaehringer et al., 2018) providing more direct evidence for the importance of WM for cognitive ER (Hofmann et al., 2012). Importantly, they extend these earlier findings by demonstrating the dissimilar role WM plays in different cognitive ER strategies. Finally, they highlight the important role of experimental studies in disentangling the unique contribution of executive control processes in regulatory effects of different ER strategies. For instance, although the DLPFC–a region systematically activated across a wide range of WM tasks (Barbey, Koenigs, & Grafman, 2013)–has been implicated in both distraction and reappraisal (Dörfel et al., 2014; Hermann, Kress, & Stark, 2017; Kanske et al., 2011; McRae et al., 2010) the 'mechanistic' contribution of this brain structure to regulatory effects of each strategy has remained unclear. By showing that loading WM with neutral contents (a manipulation which should activate the DLPFC) hinders reappraisal but exacerbates distraction, our study potentially sheds light on the divergent role the DLPFC plays in the regulation of emotions by means of these two cognitive ER strategies. More specifically, in case of reappraisal, the DLPFC appears to be implicated in supporting semantic elaboration of a source of emotional arousal. In case of distraction, however, the DLPFC seems to be involved in task-related processing, limiting semantic elaboration of emotionally salient, but task-irrelevant external input.

Our findings, which demonstrate that effects of decreased executive resources on ER are strategy-specific, fit within a larger body of work aiming at identifying individual and contextual factors that may boost or inhibit efficacy of particular ER strategies (Aldao, 2013; Doré et al., 2016; Young & Suri, 2020). Importantly, they uphold to the view that reappraisal is not an universally adaptive form of ER (Ford & Troy, 2019) as has been long believed (Aldao, Nolen-Hoeksema, & Schweizer, 2010), and highlight the need to consider situational context when selecting a particular ER strategy (Sheppes et al., 2014). An increasing body of research shows that deterioration of EFs can contribute to emotion dysregulation across a wide range of clinical conditions (Berryman *et al.* 2013; Groves et al., 2020; Huang-Pollock, Shapiro, Galloway-Long, & Weigard, 2017; Joormann & Tanovic, 2015). Moreover, temporary reductions in executive functions appear to be a common situational risk factor underlying failures at self-regulation (Hofmann et al., 2012). As such, our findings may help to guide the development of better-tailored ER interventions, taking into account both the regulatory circumstances and the individual characteristics of those struggling with emotion regulation difficulties.

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Declaration of interest

None.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.biopsycho.2022.108327.

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