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Working memory load reduces the electrocortical processing of positive pictures

Blake Barley[1] · Elizabeth A. Bauer[1] · Kayla A. Wilson[1] · Annmarie MacNamara[1]

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Abstract

To date, the emotion regulation literature has focused primarily on the down-regulation of negative emotion, with far fewer studies interrogating the mechanisms at work in positive emotion regulation. This body of work has suggested that nonaffective mechanisms, such as cognitive load have a role to play in reducing emotional response. For example, the late positive potential (LPP), which tracks attention to salient stimuli, is reduced when task-irrelevant negative and neutral stimuli are presented under high compared with low working memory load. Using positive stimuli, working memory load has been shown to reduce the LPP elicited by positive words and faces but has not previously been shown to modulate the LPP elicited by positive scenes. Emotional scenes are the predominant type of stimuli used in the broader emotion regulation literature, are more arousing than faces, and have been shown to more strongly modulate the LPP. Here, 41 participants performed a working memory task interspersed with the presentation of positive and neutral scenes, while electroencephalography was recorded. Results showed that the LPP was increased for positive compared with neutral pictures and reduced on high-load compared to low-load trials. Working memory performance was worse on high-load compared with low-load trials, although it was not significantly correlated with the LPP, and picture type did not affect working memory performance. Results bridge to the willful emotion regulation literature to increase understanding of the mechanisms underlying positive emotion regulation, which has been relatively unexamined.

Keywords Cognitive load · Emotion regulation · Distraction · Event-related potential (ERP) · Late positive potential (LPP) · Positive scenes

Introduction

Reducing or limiting positive emotion may be beneficial in certain contexts (Kalokerinos et al., 2014), such as when positive emotion motivates actions that are not in line with a person's goals. Nonetheless, most emotion regulation work has focused on the downregulation of negative emotion. This work has shown that it is possible to reduce attention toward negative stimuli through a variety of willful emotion regulation techniques (Buhle et al., 2014), but also through nonaffective tasks that are cognitively demanding, such as those that engage working memory (MacNamara, Ferri, et al., 2011a). As such, this work has provided insight into the mechanism(s) that may underlie the downregulation of emotional response and has demonstrated that reducing emotional response is possible even in the absence of a willful attempt. By comparison, only a handful of studies have examined how cognitively demanding tasks affect the processing of positive stimuli (Kopf et al., 2013; Van Dillen & Derks, 2012) and gaps in the literature (e.g., no investigation of load-related modulation of electrocortical response using positive *scenes*) limit comparison with other work. Filling these gaps would facilitate a more thorough understanding of cognitive-load-related regulation of response to positive stimuli and would help to address the relative neglect of positive emotion regulation in the field.

Event-related potentials, such as the late positive potential (LPP), provide a useful means of assessing the effects of emotion regulation and cognitive load on the processing of emotional stimuli. The LPP begins approximately 300 ms after stimulus onset, is thought to measure stimulus salience, and is larger for positive and negative compared with neutral stimuli (Cuthbert et al., 2000; Hajcak, MacNamara, et al., 2010b). The LPP is sensitive to both intrinsic (e.g., personal relevance; Tacikowski & Nowicka, 2010) and extrinsic (Schindler &

✉ Annmarie MacNamara
amacnamara@tamu.edu

[1] Department of Psychological and Brain Sciences, Texas A&M University, 4235 TAMU, College Station, TX 77843, USA

Straube, 2020; Schupp et al., 2007; Weinberg et al., 2012) modulations of stimulus significance and is believed to measure the motivational salience of stimuli. Its neural generators are widespread and include the amygdala, visual cortex, insula, and temporal cortex (Liu et al., 2012).

Willful emotion regulation techniques, such as cognitive reappraisal have been found to reduce the LPP to negative pictures (Hajcak & Nieuwenhuis, 2006; Moran et al., 2013; Moser et al., 2006; Parvaz et al., 2012). The down-regulation of negative emotion (e.g., via reappraisal) has been shown to engage the dorsolateral prefrontal cortex (dlPFC, Buhle et al., 2014), a brain region that shows a reciprocal relationship with activation in regions involved in the generation of emotional response, such as the amygdala (Banks et al., 2007). Structurally, the dlPFC has few direct connections to brain regions involve in emotion generation, such as the amygdala, but may interact with these regions via indirect connection (e.g., orbitofrontal cortex, Amaral & Price, 1984; Cavada, 2000; Ray & Zald, 2012). Therefore, down-regulation of emotional response via reappraisal might be attributed, in part, to an obligatory influence of the lateral prefrontal cortex on brain regions involved in the generation of emotional response (see also Hajcak, Anderson, et al., 2010a). In our prior work, we tested the potential for a task known to activate the dlPFC (Smith et al., 1998)—i.e., a working memory task—to reduce the processing of emotional pictures. Participants performed a letter recall task interspersed with the presentation of task-irrelevant negative and neutral pictures. Results showed that pictures that were presented on high-load (6 letters) compared with low-load (2 letters) trials elicited smaller LPPs (MacNamara, Ferri, et al., 2011a), suggesting that participants allocate less attention to task irrelevant negative and neutral pictures as cognitive load increases. This effect has been replicated several times for negative pictorial scenes (MacNamara et al., 2019; MacNamara & Proudfit, 2014) and has been shown for faces (MacNamara et al., 2012).

In contrast to the negative emotion regulation literature, there have been few investigations of positive emotion regulation or its underlying mechanisms. Reappraisal, the “gold standard” for regulation of negative emotion, has been shown to be effective for positive pictures (Kim & Hamann, 2007), although depending on stimulus intensity, it may be less effective than other strategies (Shafir et al., 2018). To date, three studies have examined the effect of working memory load on the processing of positive stimuli. Using fMRI, Erk et al. (2007) found that working memory load reduced activation in the right amygdala for negative scenes and in the left ventral striatum for positive scenes (Erk et al., 2007). These results suggest that working memory load attenuates the processing of both positive and negative emotional scenes, but it may do so via different neurocircuit mechanisms. In addition to this fMRI work, two studies investigated the effect of working memory load on positive stimuli using the LPP. In one study, Kopf et al. (2013) used an affective n-back task to assess the effect of working memory load on the LPP elicited by positive, negative, and neutral words. They found that some levels of working memory load reduced the LPP elicited by positive words, but not others, with more consistent effects observed for working memory modulation of the LPP elicited by negative words. In another study, Van Dillen and Derks (2012) found that working memory load reduced the LPP to angry and happy faces, but this effect was stronger for angry faces. However, because this study lacked a neutral “control” condition, it is difficult to know whether the observed results reflect reduced emotional differentiation under high working memory load or a stronger effect of working memory load on negative versus positive stimuli.

Together, this prior work suggests that working memory load modulates the LPP to positive words and faces but raises some questions about the robustness of this effect, and leaves untested whether working memory load modulates the LPP elicited by positive *scenes* (e.g., IAPS; Lang et al., 2008). This omission limits comparison with a broader body of work, particularly the emotion regulation literature, which has primarily used emotional scenes (Buhle et al., 2014; Picó-Pérez et al., 2017). Moreover, prior work indicates that emotional scenes are more arousing (Britton et al., 2006) and may modulate the LPP more robustly than emotional faces (Thom et al., 2014), suggesting that they might be harder to ignore/less affected by working memory load. Therefore, although we suspected that working memory load would reduce the LPP elicited by positive scenes, we set out to test this question directly.

We used a modified version of the working memory paradigm used in our prior work (MacNamara et al., 2012, 2019; MacNamara, Ferri, et al., 2011a; MacNamara & Proudfit, 2014) to determine whether working memory load would reduce the LPP elicited by positive scenes. We focused our analyses on the LPP because, as in our prior work using this task, we were interested in the effects of working memory load on the sustained processing and motivational significance of positive pictures. In addition, we wanted to be able to relate our work to prior ERP work on emotion regulation, which has primarily examined the LPP (Hajcak & Nieuwenhuis, 2006; MacNamara et al., 2009; MacNamara, Ochsner, et al., 2011b; Moran et al., 2013; Moser et al., 2006).

Based on prior work that used positive words and faces, we predicted that working memory load would reduce the positive picture-elicited LPP (Kopf et al., 2013; Van Dillen & Derks, 2012). Also, based on prior work that found that positive scenes were associated with improved working memory performance (compared to neutral scenes; Erk et al., 2007), as well as other work suggesting that positive mood might facilitate performance on working memory tasks (Storbeck & Maswood, 2016; Yang et al., 2013), we expected that positive pictures would improve letter recall on high-load trials. This prediction was in contrast to our prior work, in which negative pictures were found to interfere with working memory performance (MacNamara, Ferri, et al., 2011a).

Method

Participants

Participants were 41 undergraduates who completed the experiment for course credit (27 females; age $M = 19.82$ years, $SD = 1.94$). Sample size was decided according to the a priori decision to run the study for one semester. Study procedures were in compliance with the Helsinki Declaration of 1975 (as revised in 1983) and were approved by the Texas A&M University institutional review board.

Stimulus materials

Sixty positive pictures (e.g., cute animals, erotic scenes) and 60 neutral pictures (e.g., household objects, neutral faces) were selected from the International Affective Picture System (IAPS: Lang et al., 2008) and Emotional Picture Set (Wessa et al., 2010).[1] Compared with neutral pictures, normative ratings for positive pictures were more pleasant, $t(106.49) = 13.45, p < 0.001$ (positive: $M = 6.70, SD = 0.74$; neutral, $M = 5.12$, $SD = 0.53$) and more arousing, $t(93.87) = 13.62$, $p < 0.001$ (positive: $M = 4.77, SD = 0.87$; neutral, $M = 3.01, SD = 0.50$).

Letter strings were the same as in the original version of the task that used negative and neutral pictures (MacNamara, Ferri, et al., 2011a). In brief, letter strings were created using a random number generator (Reed, 2002). Vowels were not included in the strings; there were 60 two-consonant strings and 60 six-consonant strings (Ashcraft & Kirk, 2001).

Procedure

Participants performed a letter recall task adapted from prior work (MacNamara, Ferri, et al., 2011a) while continuous EEG was recorded. Each trial began with the presentation of either a two-letter (low-load) or six-letter (high-load) string that was displayed for 5,000 ms. This was followed by a positive or neutral picture that was presented for 2,000 ms. Following picture offset, the text “What were the letters? (then press enter):” was presented in the center of the screen. Participants were instructed to use the keyboard to enter the letters they had viewed at the beginning of the trial and to enter them in the same order they originally appeared. They were also told that they could use the backspace key to erase a letter if they made a mistake. Participants were told to enter letters with only one finger and to keep their hands in their lap when not typing. Once participants pressed the enter key, the trial ended. A white fixation cross was presented in the center of a black background during the intertrial interval, which varied randomly from 2,000 to 2,500 ms.

Participants saw all pictures and all letter strings exactly one time. Picture and letter string pairings were pseudorandom, with 120 trials in total, intermixed and presented randomly over four blocks (30 trials per block). Each trial was comprised of either a two-letter (low-load) or six-letter (high-load) string followed by either a positive or a neutral picture, for a total of four conditions with 30 trials each (low-load neutral, low-load positive, high-load neutral, and high-load positive). Participants completed four practice trials (one for each condition) before beginning the experiment. Each consisted of a low-load or high-load trial followed by a randomized positive or neutral picture that was not presented during the actual experiment.

EEG recording and data reduction

Continuous EEG recordings were collected using an ActiCap and the ActiChamp amplifier system (Brain Products GmbH, Gilching Germany). Thirty-two electrode sites were used based on the 10/20 system. The electrooculogram (EOG) was recorded from four facial electrodes: two that were placed approximately 1 cm above and below the right eye, forming a bipolar channel to measure vertical eye movement and blinks and two that were approximately 1 cm beyond the outer edges of each eye, forming a bipolar channel to measure horizontal eye movements. The EEG data were digitized at 24-bit resolution and a sampling rate of 1,000 Hz.

EEG data were processed offline using BrainVision Analyzer 2 software (Brain Products GmbH). The data were segmented for each trial beginning 200 ms before picture onset and continuing for 2,000 ms (i.e., the entire picture duration). Baseline correction was performed for each trial using the 200 ms before picture onset. The signal from each electrode was re-referenced to the average of the left and right mastoids (TP9/10) and band-pass filtered with high-pass and low-pass filters of 0.01 and 30 Hz, respectively. Eyeblink and ocular corrections used the method developed by Miller, Gratton, and Yee (1988). Artifact analysis was used to identify a voltage step of more than 50.0 μV between sample points, a voltage difference of 300.0 μV within a trial, and a maximum voltage

[1] The numbers of the IAPS images used were the following: pleasant (1440, 1460, 1601, 1604, 1721, 2034, 2060, 2160, 2332, 4006, 4233, 4311, 4240, 4525, 4530, 4550, 4561, 4574, 4611, 4624, 4625, 4641, 4647, 4669, 4672, 4698, 5010, 5480, 5661, 5825, 7220, 7283, 7325, 7340, 7482, 7489, 7508, 7515, 7580, 8193, 8205, 8208, 8460, 8461, 8540) and neutral (2036, 2280, 2515, 2840, 5000, 5532, 5534, 5635, 6150, 7001, 7012, 7014, 7020, 7021, 7025, 7031, 7033, 7036, 7052, 7205, 7217, 7224, 7236, 7705, 9360). The numbers of the EmoPicS images used were the following: pleasant (001, 005, 012, 014, 019, 022, 026, 029, 033, 039, 061, 067, 073, 332, 333) and neutral (083, 092, 110, 116, 119, 120, 122, 124, 128, 131, 138, 160, 161, 168, 169, 173, 175, 178, 181, 185, 189, 191, 200, 201, 276, 281, 284, 298, 336, 339, 340, 341, 352, 354, 366).

difference of less than 0.50 μV within 100 ms intervals. Trials also were inspected visually for any remaining artifacts, and data from individual channels containing artifacts were rejected on a trial-to-trial basis. The average percentage of trials rejected per participant and condition were as follows: low-load, neutral = 1.64% (*SD* = 5.18), low-load, positive = 1.90% (*SD* = 5.59), high-load, neutral = 1.74% (*SD* = 5.61), high-load, positive = 1.77% (*SD* = 5.70). The percentage of trials rejected did not vary by working memory load, picture type, or their interaction, all *p*s > 0.48. In line with our prior work that has used this task with negative pictures (MacNamara et al., 2012, 2019; MacNamara, Ferri, et al., 2011a; MacNamara & Proudfit, 2014), trials were not excluded from LPP analyses based on working memory performance. Based on our prior work using this task and on visual inspection, the LPP was scored by averaging amplitudes at a pooling of five sites: FC1, FC2, Cz, CP1, and CP2 between 400-2,000 ms following picture onset[2] (Holmes et al., 2009).

Working memory performance

Responses on the letter recall task were considered correct if they contained the same letters as those presented at the beginning of the trial, entered in the exact same order as originally presented. The percentage of correct responses per condition was calculated as the number of correct trials divided by 30 trials in each condition.

Data analyses

The LPP and accuracy data on the working memory task were analyzed using a 2 (working memory load: low, high) x 2 (picture type: neutral, positive) repeated measures analysis of variance (ANOVA). Statistical analyses were performed using SPSS statistical software version 25.0 (IBM, Armonk, NY).

Results

Table 1 presents means and standard deviations for all dependent variables, shown separately for each condition.

[2] The LPP was also scored at early and late windows by averaging amplitudes at a pooling of FC1, FC2, Cz, CP1, and CP2. For the early LPP window (400-1,000 ms), there was a main effect of picture type, $F(1,40) = 75.28$, $p < .001$, $\eta_p^2 = .65$ (positive > neutral). There was also a main effect of working memory load, $F(1,40) = 33.98$, $p < .001$, $\eta_p^2 = .46$ (low-load > high-load). There was no interaction between picture type and working memory load, $p > .66$. For the late LPP window (1,000-2,000 ms), there was a main effect of picture type, $F(1,40) = 57.04$, $p < .001$, $\eta_p^2 = .59$ (positive > neutral). There was also a main effect of working memory load, $F(1,40) = 62.00$, $p < .001$, $\eta_p^2 = .61$ (low-load > high-load). There was no interaction between picture type and working memory load, $p > .69$.

Working memory performance

Overall, participants performed well on the letter recall task (*M* = 84.43% correct, *SD* = 8.71). Working memory performance was lower on high-load (*M* = 70.85%, *SD* = 16.19) compared with low-load trials (*M* = 98.01%, *SD* = 2.45), $F(1,40) = 129.86$, $p < 0.001$, $\eta_p^2 = 0.77$. The effect of picture type did not reach significance, and there was no interaction between picture type and working memory load, both *p*s > 0.15.

LPP

Figure 1 presents grand-averaged waveforms at the pooling of FC1, FC2, Cz, CP1, and CP2 for each of the four conditions, as well as headmaps depicting the voltage differences between positive minus neutral (left) and low-load minus high-load (right) trials in the 400-2,000 ms window. A main effect of picture type indicated that positive pictures elicited larger LPP amplitudes than neutral pictures, $F(1,40) = 71.47$, $p < 0.001$, $\eta_p^2 = 0.64$. In addition, a main effect of working memory load indicated that pictures presented on high-load trials elicited smaller LPPs compared to pictures presented on low-load trials, $F(1,40) = 55.32$, $p < 0.001$, $\eta_p^2 = 0.58$. There was no interaction between picture type and working memory load, $p > 0.67$.

Correlations

Correlations were performed to determine whether the LPP was associated with performance on the working memory task. Difference scores reflecting the effect of working memory load were calculated separately for each of the LPP and working memory performance, i.e., low-load minus high-load positive scenes, low-load minus high-load neutral scenes. Correlations between the corresponding difference scores for the LPP and performance failed to reach significance, all *r*s > −0.23 and < 0.04; *p*s > 0.16.

Discussion

The current study examined the effect of working memory load on the processing of positive and neutral pictures. A main effect of picture type on the LPP indicated that despite the task-irrelevant nature of pictures, positive pictures received increased processing resources compared with neutral pictures. In addition, working memory load reduced the LPP elicited by positive and neutral pictures, in line with prior results observed using the same paradigm with negative pictures (MacNamara et al., 2012, 2019; MacNamara, Ferri, et al., 2011a; MacNamara & Proudfit, 2014). As expected, participants recalled more letters on low- compared to high-

Table 1. Means (and standard deviations) for the LPP and performance on the working memory task

WM load	Picture type	LPP (μv)	WM performance (% correct trials)
Low	Neutral	-0.08 (4.23)	98.13 (3.08)
Low	Positive	3.87 (4.20)	97.89 (2.66)
High	Neutral	-3.82 (3.21)	71.87 (16.61)
High	Positive	-0.28 (3.98)	69.84 (17.43)

WM, working memory.

load trials, but positive pictures neither facilitated nor interfered with working memory performance, and no significant associations between the LPP and performance on the working memory task were observed.

Our results build on prior work, which found that working memory load reduced the LPP to positive words (Kopf et al., 2013) and faces (Van Dillen & Derks, 2012). Extension of effects to emotional scenes is important, because emotional scenes may be more arousing than other types of stimuli (Britton et al., 2006) and appear to modulate the LPP more robustly than emotional faces (Thom et al., 2014). Moreover, our results facilitate comparison with a broader body of work on emotion regulation, which has primarily used standardized emotional scenes (e.g., the IAPS; Lang et al., 2008).

Our results also fit with work that suggests that cognitive effort and/or nonaffective engagement of the prefrontal cortex may account for some of the downregulation observed in willful emotion regulation (Wyczesany & Ligeza, 2017). That is, in the absence of willful attempts at emotion regulation, cognitively demanding tasks may provide a means of reducing attention to positive stimuli that are not in line with an individual's goals (e.g., high calorie food; van Dillen & van Steenbergen, 2018; see also van Dillen & Andrade, 2016). While this could be beneficial in contexts where reducing attention to positive stimuli might aid in adopting healthier behaviors (e.g., dieting), high levels of cognitive load might also play a role in positive affect impairments, such as those observed in depression (Vanderlind et al., 2020). This seems especially plausible given that states, such as rumination and worry, have been associated with increased working memory load and engagement of the dlPFC (Hayes et al., 2008; Steinfurth et al., 2017).

While prior work by Kopf et al. (2013) used an emotional n-back task and positive, negative and neutral words, Van Dillen and Derks (2012) used a paradigm that more closely resembled the one used here (i.e., emotional stimuli were task-irrelevant). Results showed a main effect of working memory load on the LPP elicited by angry and happy faces (neutral faces were not shown). In addition, Van Dillen and Derks (2012) observed an interaction between working memory load and face type, such that working memory load reduced the LPP more for angry compared with happy faces. This

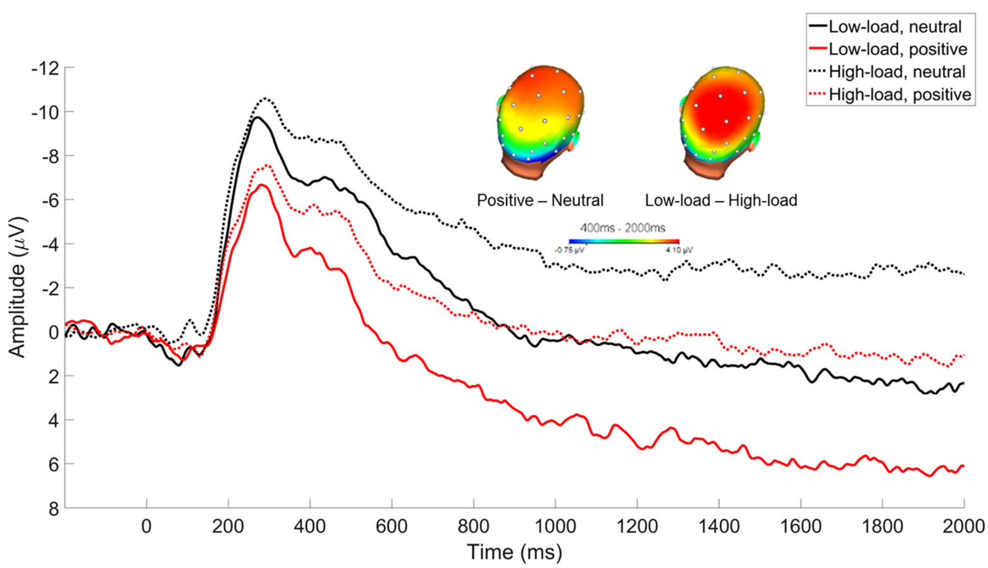

Fig. 1. Grand-averaged waveforms depict amplitudes elicited by pictures in each of the four conditions at a pooling of FC1, FC2, Cz, CP1, and CP2, where the LPP was scored. Headmaps illustrate the difference between positive minus neutral pictures (left) and pictures presented on low-load minus high-load (right) trials, between 400-2,000 ms after picture onset

interaction was attributed to a negativity bias for angry compared with happy faces (i.e., larger LPPs to angry faces) under low-load that was no longer evident when faces were presented under high-load. Here, working memory load had a similar effect for both positive and neutral pictures (i.e., there was no interaction between working memory load and picture type). Therefore, when using emotional scenes (not faces), working memory load may be insufficient to attenuate affective potentiation of the LPP; rather, overall reductions in stimulus salience are observed. Nonetheless, future work may wish to include positive, negative, and neutral pictures to compare the relative effect of working memory load on the LPP elicited by each picture type.

One reason that working memory load might reduce the processing of task-irrelevant stimuli could be to attenuate interference. We failed to observe an adverse effect of positive pictures on working memory performance, even though we had previously found that negative pictures potentiated the adverse effect of working memory load on performance (MacNamara, Ferri, et al., 2011a). The current results are in line with prior work suggesting that positive stimuli may be less likely to interfere with performance than negative stimuli (Grissmann et al., 2017) but differ somewhat from those of Erk et al. (2007), who, in the context of an fMRI study, found that positive pictures *facilitated* working memory performance. A comparison of accuracy rates from the current study and this prior work suggests that the working memory task used here may have been more difficult than that used by Erk et al. (2007), in which participants did not need to recall a string of letters but only recognize a probe letter. Therefore, one possibility is that positive stimuli might facilitate performance on tasks with relatively low, but not high working memory load. Nonetheless, positive and negative pictures can differ in terms of arousal, not just valence. Therefore, our failure to observe an effect of positive stimuli on working memory performance cannot be definitively attributed to stimulus valence, and future work might delve further into this issue by using pictures that are matched on arousal but differ on valence.

Additionally, we found that the LPP and working memory performance were not correlated. This could be due in part to the temporal separation between measurement of the LPP and behavioral response (i.e., participants viewed a picture and *then* entered the letters they recalled from the beginning of the trial). Nonetheless, even when neural and behavioral response are measured at the same point in time/to the same stimuli, behavior is more "downstream" than neural response—i.e., many intervening variables may affect behavioral response beyond attention to task-irrelevant stimuli (measured by the LPP), including motivation, decision making, motor speed, etc. (MacNamara et al., 2013). Relatedly, compensatory effects (e.g., trying harder, recruiting additional brain regions) might help to offset any potential decrements in behavioral performance among individuals who allocate more attention to task-irrelevant pictures.

From a limited capacity perspective, demanding cognitive tasks, such as the working memory task used here, may exert their effects on task-irrelevant stimuli via distraction (Van Dillen & Koole, 2007). That is, when a person is engaged with a task that is cognitively demanding, s/he may have fewer processing resources available for the processing of task-irrelevant stimuli that would normally capture attention. Distraction has been associated with reduced memory for emotional events (Richards & Gross, 2006; Sheppes & Meiran, 2008) and stimuli that elicit smaller LPPs are remembered poorly at subsequent encounter compared with pictures that elicit larger LPPs (Dolcos & Cabeza, 2002). Therefore, smaller LPPs to pictures presented on high- compared with low-load trials suggest that these pictures may not have been encoded as well as the pictures presented in the low-load condition. Future work may wish to test this possibility directly by testing the effect of working memory load on the LPP and memory for pictures at subsequent encounter.

Conclusions

In sum, results observed here reveal that working memory load reduces the LPP to positive and neutral scenes and may be useful in understanding both adaptive and nonadaptive downregulation of attention to positive stimuli. For instance, the current paradigm could be used to examine how incentives might be used to bolster modulation of attention to positive distracters (Jones et al., 2020) or to assess the role of working memory load in disorders of reduced positive affect, such as depression.

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Open practices statement The study was not pre-registered. However, all data are open and available on the Open Science Framework (https://osf.io/w9tjz/), and we report all conditions, measures, manipulations, and data exclusions.

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