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Effects of Prior Mental Effort on Picture Processing: An ERP Investigation

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Abstract

The current study examined the aftereffects of mental effort on the processing of picture stimuli using neural measures. Ninety-seven healthy young adults were randomly assigned to exercise more versus less mental effort on a writing task. Then participants viewed positive, negative, and neutral affective images while P1, N1, P2, N2, P3, and late positive potential (LPP) magnitudes to the images were assessed. We found that performing the more (versus less) effortful writing task caused more negative N2 amplitudes to all images. In addition, and consistent with past research, emotional (versus neutral) images elicited more positive amplitudes on the N2, P3, and LPP components. Thus, prior mental effort appeared to reduce early attentional engagement with visual stimuli but did not diminish later attention modulation by emotional content. These findings suggest novel implications for understanding the behavioral aftereffects of mental effort and self-control.

Effects of Prior Mental Effort on Attention to Emotional Images: An ERP Investigation

Mental effort gives rise to mixed blessings. Exerting mental effort may increase success at cognitive challenges including rational decision making, task persistence, and goal pursuit (e.g., Hirt & Markman, 1995; Scherer, Yates, Baker & Valentine, 2017; Schulkin, 2007). But mental effort also carries psychological costs ranging from feelings of strain and fatigue to a temporary bias in behavior in favor of leisure over further mental effort (Dewey, 1897; Inzlicht, Schmeichel, & Macrae, 2014; Job, Bernecker, Miketta, & Friese, 2015). As reviewed below, the costs of mental effort may also be detected at the neural level during the performance of cognitively demanding tasks. We extended this line of research in the current study by examining the effects of mental effort on subsequent electro-cortical responses during a non-demanding task (i.e., passive picture viewing).

Neural Consequences of Mental Effort

A handful of prior studies have observed aftereffects of mental effort on neural measures of attention. Participants in one study performed a visual letter working memory task for 90 minutes (Hopstaken, van der Linden, Bakker, Kompier, & Leung, 2016). As time on task increased, feelings of fatigue increased and P3 amplitudes to the letters decreased, suggesting a decrease in attentional engagement as a consequence of mental effort. In another study, participants spent three hours identifying target letters and ignoring non-target letters (Boksem, Meijman, & Lorist, 2005). As mental fatigue increased, N1 amplitudes to all the letters decreased. In addition, discriminability between target and non-target letters diminished over time, as reflected in the N2 component. Specifically, toward the end of the task N2 amplitudes to non-targets increased to equal N2s to targets, so that N2 amplitudes no longer differentiated

between the two types of stimuli. This pattern suggested increased attention to non-target stimuli and hence poorer attention control on the visual attention task.

Mental effort has also been found to reduce error monitoring. For instance, an experiment by Inzlicht and Gutsell (2007) found a reduction in the error-related negativity (ERN) on a Stroop task among participants who had previously suppressed (versus expressed) their responses to a distressing 10-minute film clip (see also Friese, Binder, Luechinger, Boesiger, & Rasch, 2013). Thus, both long bouts of effort on cognitively demanding tasks and relatively brief bouts of effortful self-control have been found to alter neural indices of attentional engagement, distractibility, and performance monitoring.

Evidence that prior mental effort reduces attention and performance on cognitively demanding tasks is consistent with a limited resource model of effortful control. In this view, expending mental effort consumes and temporarily depletes some limited inner resource or strength, and in the interim period before the resource can be replenished, further expenditures of effort are prone to failure. This temporary reduction in the inner resources for effortful control is known as a state of *ego depletion* (Muraven & Baumeister, 2000; Baumeister, Vohs, & Tice, 2007).¹ An alternative view explains the aftereffects of mental effort without reference to

¹ Despite over one hundred published studies on the ego depletion effect, the behavioral aftereffects of mental effort remain a matter of dispute. An influential meta-analysis uncovered a large effect of prior mental effort ($d = 0.62$) across a diverse array of behavioral outcomes, but this initial meta-analysis did not include unpublished studies (Hagger, Wood, Stiff, & Chatzisarantis, 2010). A more recent meta-analysis did include unpublished studies and found a smaller but reliable ego depletion effect ($g = 0.43$) that was reduced to zero after additional statistical corrections for publication bias were applied (Carter, Kofler, Forster, & McCullough, 2015). But the appropriateness and the validity of those statistical corrections have been challenged (e.g., Inzlicht, Gervais, & Berkman, 2016; Reed, Florax, & Poot, 2015), so the best estimate of the behavioral aftereffects of self-control remains in doubt. The current experiment was not concerned with the behavioral aftereffects of mental effort. Rather, we tested the aftereffects of mental effort on neural indices of attention and engagement with picture stimuli.

resources. According to the process model of ego depletion, expending mental effort causes shifts in motivation and attention toward rest or reward-seeking in lieu of further mental effort (Inzlicht & Schmeichel, 2012). Like the resource model, the process model would also predict that prior mental effort reduces performance on cognitively demanding tasks (due to changes in motivation and a corresponding shift in attention away from effortful processing). But unlike the limited resource view, the process model also anticipates aftereffects of mental effort on non-demanding tasks, insofar as these tasks are sensitive to shifts in motivation and attention (e.g., Schmeichel, Crowell, & Harmon-Jones, 2016).

The aftereffects of mental effort on attention have previously been assessed using tasks that require participants to attend selectively, respond to targets and ignore distractors, or overcome response conflict, and the results suggest that expending mental effort reduces attention and performance on cognitively demanding tasks. Prior research has not examined the consequences of mental effort for less demanding forms of attention that do not require participants to complete a task or otherwise exert effort. Does prior mental effort influence responses even to non-demanding tasks, as the process model would predict? Or does prior mental effort influence only cognitively demanding tasks, as the resource model would assume? In the current experiment we tested the hypothesis that mental effort influences event-related potentials (ERPs) during a non-demanding task—passive picture viewing.

Event-Related Potentials and Attention to Emotional Images

Event-related potentials (ERPs) are well suited to capture the unfolding of attentional processes following bouts of mental effort. ERPs reflect the summed electrical activity of the brain at the scalp, time-locked to a specific event, as measured by an electroencephalogram (EEG). In the current experiment we used ERPs to examine attention to neutral and emotional

picture stimuli during a passive viewing task. Below, we review research assessing ERP responses to affective pictures in a passive viewing context (for a review of studies using other affective picture presentation paradigms, such as oddball tasks, see Olofsson, Nordin, Sequeria, & Polich, 2008).

Early ERP Components

Passive picture viewing elicits several ERPs within 300 ms of picture onset. A picture's affective content may modulate these early ERPs, but evidence for affective modulation of early ERPs during passive viewing is mixed. For example, some studies have found increased P1 amplitudes (positive peak around 100 ms after picture onset) to emotional versus neutral pictures (Keil et al., 2001), low versus high arousal pictures (Lithari et al., 2010), or specifically to negative stimuli (Feng et al., 2014), but other studies have found no effects of emotion on P1 amplitudes in passive viewing contexts (e.g., Foti, Hajcak, & Dien., 2009; Keil et al., 2002; Weinberg & Hajcak 2010). Studies assessing the N1 (negative peak around 150 ms after picture onset) have found an enhanced (more negative) N1 during emotional versus neutral pictures (Foti et al., 2009; Hot et al., 2006; Keil et al., 2001), specifically to positive pictures (Keil et al., 2002; Pollatos et al., 2005; Weinberg & Hajcak, 2010), or specifically to negative pictures (Lithari et al., 2010). Other work has found effects of emotional content only beginning 200-300 ms after picture onset, which is later in time than both the P1 and N1 (e.g., Bradley, Hamby, Löw, Lang, 2007; Cuthbert, Schupp, Bradley, Birbaumer, & Lang, 2000; Palomba, Angrilli, & Mini, 1997). The discrepancies in results may reflect differences in sensory features of the stimuli or task parameters used across studies (Hajcak, Weinberg, MacNamara, & Foti, 2012).

Evidence for affective modulation of the P2 (positive peak around 180 ms after picture onset) is also mixed. Of the few studies that have assessed P2 amplitudes in a passive viewing

context, one found enhanced (more positive) P2s specifically to positive pictures (Lithari et al., 2010), another observed a Valence \times Arousal interaction with the largest P2 amplitudes during negative high-arousal pictures (Feng et al., 2014), and a third study did not find affective modulation of the P2 (Palomba et al., 1997). For the N2 component (negative peak around 250 ms following picture onset), some studies have observed more positive (i.e., smaller) amplitudes to emotional versus neutral pictures (Keil et al., 2001; Palomba et al., 1997), to high versus low arousal pictures (Feng et al., 2014), or to pleasant versus unpleasant pictures (Lithari et al., 2010). The N2, relative to the P2, has more often been tested and observed in passive picture viewing paradigms, and more positive N2 amplitudes have been interpreted as evidence for more neural processing or greater attentional engagement (Feng et al., 2014; Palomba et al., 1997).

In sum, the evidence that early ERPs are modulated by emotional picture content is muddled. The inconsistent findings across studies hint at contextual moderators. For instance, stimulus size and picture repetitions have been found to modulate the influence of affective content on early ERP magnitudes (Cesarei & Codispoti, 2006; Codispoti, Ferrari, Bradley, 2007). The current study held stimulus features constant across experimental conditions (i.e., all participants viewed the same images) to test again the emotion modulation of early ERPs and the effects of another possible contextual moderator—expenditure of mental effort—on ERP indices of attention.

Later ERP Components

Relative to the early ERP components reviewed above, later ERP components are more reliably influenced by emotional content. The P3 component peaks 300-500 ms following stimulus onset and is thought to reflect cognitive resource allocation (e.g., Kramer, Wickens, & Donchin, 1985) and evaluation and updating of a stimulus representation (see Polich, 2007, for

review). A large body of research has found that the P3 is magnified for emotional or arousing stimuli compared to neutral stimuli in a passive viewing task (e.g., Amrhein, Mühlberger, Pauli, & Wiedemann, 2004; Cuthbert et al., 2000; Keil et al., 2002; Lithari et al., 2010; Palomba et al., 1997; Pollatos et al., 2005), and some studies have found larger P3 amplitudes to positive versus negative stimuli (Cuthbert et al., 2000; Pollatos et al., 2005).

Similarly, the late positive potential (LPP) is a positive slow-wave that begins 200-300 ms after the onset of the stimulus and can be sustained for several seconds. The LPP is enhanced for emotionally and motivationally salient stimuli and reflects relatively deep encoding and cognitive elaboration (Cuthbert et al., 2000; Hajcak & Olvet, 2008; Schupp et al., 2000). Many passive viewing tasks have observed an enhanced LPP to emotional versus neutral pictures (Bradley et al., 2007; Foti et al., 2009; Keil et al., 2001; Palomba et al., 1997; Schupp, Junghöfer, Weike, & Hamm, 2003; Weinberg & Hajcak, 2010).

In sum, the affective modulation pattern of the P3 and LPP likely reflect the fact that emotional stimuli are motivationally relevant and attract attention and cognitive elaboration (Bradley et al., 2003; Lang, Bradley, & Cuthbert, 1997).

The Current Experiment

In the current experiment we tested the effects of prior mental effort on early and later ERPs to emotional and neutral pictures during a passive picture viewing task. The resource model proposes that expending mental effort depletes controlled processing resources—resources that are presumably irrelevant for passive picture viewing (particularly early on in picture processing). If anything, the resource model would predict aftereffects of mental effort only on later ERP components, when more controlled processing resources may influence picture processing. The process model of ego depletion proposes that expending effort on self-

control may cause shifts in motivation and attention that may be glimpsed even on non-demanding tasks and leaves open the possibility that aftereffects may emerge early or late in picture processing. We therefore tested the extent to which prior mental effort functions as a contextual influence on neural responses to the passive viewing of positive, negative, and neutral emotional images.

Method

Participants

One hundred two undergraduate students participated in exchange for credit toward a course requirement. Two participants did not complete the writing task, and three had poor (i.e., containing many artifacts) or missing EEG data. Excluding these five participants left a final sample for data analysis of 97 participants (45 women and 44 men; age $M = 18.93$, $SD = 1.14$; no demographic data available for 8 participants).

Materials and Procedure

The experiment took place in a dimly lit, sound attenuated room. After participants provided informed consent, an experimenter attached sensors to participants' heads according to the 10-20 system using 59 tin electrodes in a stretch-lycra cap (Electro-Cap International, Eaton, OH). Electrode impedances were kept below 5 Kohms. Electrodes were also placed on participants' earlobes to re-reference the EEG signal offline and around the eye to measure startle eye blinks. Startle eye blink results will not be presented here.

After cap placement and a 4-minute period for recording resting levels of electrical activity, participants completed a modified flanker task adapted from Eriksen and Eriksen (1974). The flanker task measured individual differences in neural responses to errors; results associated with this task will not be presented here.

Participants were then randomly assigned to complete a five-minute writing task that served as the manipulation of mental effort or self-control. Participants in the *free writing condition* ($n = 46$) were instructed to write a story about a recent trip they had taken. Participants in the *controlled writing condition* ($n = 51$) were also instructed to write a story about a recent trip but were further instructed not to use the letters *a* or *n*. Thus, participants in the controlled writing condition had to inhibit the use of two commonly-used letters whereas participants in the free writing condition wrote without restrictions. This writing paradigm has previously been used to manipulate mental effort and ego depletion (e.g., Lewandowski, Ciarocco, Pettenato, & Stephan, 2012; Schmeichel, 2007). Participants in the two writing conditions did not differ in age (*free writing* $M = 18.95$, $SD = 0.86$, *controlled writing* $M = 18.91$, $SD = 1.35$), $t(86) = 0.15$, $p = .883$, or gender proportion (*free writing* = 53.6% female; *controlled writing* = 47.9% female), $X^2(1) = 0.59$, $p = .672$.

Following the writing manipulation, participants viewed a series of images on a computer screen. The first four images were neutral practice trials and were not analyzed. Participants then viewed 19 positive, 19 negative and 19 neutral pictures² from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2008). Positive pictures featured individuals involved in exciting or fun activities. Neutral pictures mainly featured individuals in mundane activities. Negative pictures mainly featured acts of violence and mutilations. Pictures were presented in pre-randomized order provided that pictures of the same type (e.g., negative) never appeared in succession. During the picture viewing task participants wore headphones and occasionally heard

² Negative: 2811, 6560, 3550, 3400, 3150, 1205, 3022, 1300, 7380, 6550, 3000, 1052, 6230, 3250, 3071, 9405, 1270, 3130, 9300; Neutral: 7035, 7161, 2850, 2397, 7009, 5534, 7025, 7100, 7180, 2190, 7053, 7000, 2506, 2394, 7236, 7185, 2393, 2516; Positive: 7350, 8031, 4681, 4695, 7200, 4656, 7390, 4659, 7260, 4651, 8186, 4658, 4670, 8260, 7470, 4608, 7460, 8161, 5621

a 50-ms, 120-dB burst of white noise occurring 3.5 or 4.5 seconds into picture viewing.

Responses to the startle probes are not presented here; we focused our analyses on ERP components occurring prior to the startle probes.

Picture viewing trials proceeded as follows. A fixation cross appeared for 3 s, followed by a picture for 6 s and an inter-trial interval (ITI) of 8-12 s. Participants were instructed at the beginning of the image viewing task to ignore any sounds they may hear over the headphones. The image viewing task lasted 18 minutes.

Following the image viewing task and a brief resting period participants completed personality questionnaires. Last, participants were debriefed about the purpose of the experiment and dismissed.

Psychophysiological Recording and Quantification

EEG signals were amplified with Neuroscan SynAmps2 (El Paso, TX), bandpass filtered (0.05-100 Hz), notch filtered (60 Hz), and digitized at 500 Hz. All sites were referenced online to the left earlobe (M1). Offline, data were re-referenced to the linked earlobes (M1, M2). Eye movements were recorded from electrodes at FP1, FP2, and FPz (10-20 placement system). Artifacts (e.g., horizontal eye movements, muscle movements) were first removed by hand. Then a regression-based eye-movement correction was applied to correct for eye blinks (Semlitsch, Anderer, Schuster, & Presslich, 1986), after which the data were again visually inspected to ensure proper correction.

Data were epoched for the early components and the P3 from 100 ms before until 1000 ms after picture onset, bandpass filtered (0.1-35 Hz) at 24 dB, and baseline corrected. Data for the LPP was epoched from 100 ms before until 3500 ms after picture onset, lowpass filtered (16 Hz lowpass cutoff, 12 dB lowpass attenuation), and baseline corrected. Epochs for all ERPs

were averaged for positive, negative, and neutral pictures separately. We extracted mean amplitudes for the P1, N1, P2, N2, P3, and LPP following picture onset. We used prior research to define time windows for our ERPs (e.g., Feng et al., 2014; Foti et al., 2009; Keil et al., 2002; Lithari et al., 2010; Pollatos et al., 2005; Weinberg & Hajcak, 2010; Hajcak et al., 2012), but because the latencies of the effects may vary with different stimuli and experimental conditions we also visually inspected the grand average waveforms of our data (collapsed across picture type and writing condition) to determine approximately when the peaks manifested (Luck & Gaspelin, 2017). Ultimately we used the following time windows following picture onset to extract mean amplitudes: P1 (80-130 ms), N1 (100-170 ms), P2 (180-230 ms), N2 (220-300 ms), P3 (300-500 ms), LPP (500-1000 ms).

Results

We first ascertained where each ERP component was maximal along the midline of the scalp (Fz, Cz, Pz, Oz). Then we analyzed the effect of picture type and writing task in a 3 (Picture Type: positive, negative, neutral) \times 2 (Writing Task: free writing vs. controlled writing) mixed model ANOVA on each ERP component at the maximal site. When the assumption of sphericity for the repeated-measures factor (Picture Type) was violated, degrees of freedom were corrected with the Greenhouse-Geisser test. Please see Table 1 for each component's mean amplitude at each electrode site, collapsed across picture type and writing task.

INSERT TABLE 1 ABOUT HERE

In the event that relevant EEG channels (i.e., Fz, Cz, Pz, Oz) had impedance levels above 5 Kohms, they were not included in the analyses. Data from the Cz channel was removed for two participants, and data from the Pz channel was removed for three participants. In addition, 8 of approximately 11000 particular data points (i.e., specific ERP amplitude at a specific channel for

a particular picture type) were removed from data analysis because they were three or more standard deviations from the mean of that variable.³ Small variations in the degrees of freedom reported below reflect these exclusions.

Early ERPs

P1. The P1 component was maximal at the Oz electrode site. We found no effect of picture type, $F(2, 184) = 0.53, p = .590, \eta_p^2 = .006$, or writing task, $F(1, 92) = 0.12, p = .703, \eta_p^2 = .001$, and no Picture Type \times Writing Task interaction, $F(2, 184) = 2.36, p = .097, \eta_p^2 = .025$, on P1 amplitudes.

N1. The N1 was maximal at Fz. N1 amplitudes at Cz and Fz did not significantly differ, but descriptively the peak was greater at Fz so we focused our analyses there.⁴ We found no effect of picture type on N1 amplitude, $F(2, 190) = 0.71, p = .931, \eta_p^2 = .001$, no effect of writing condition, $F(1, 95) = 1.53, p = .220, \eta_p^2 = .016$, and no Picture Type \times Writing Task interaction, $F(2, 190) = 1.68, p = .189, \eta_p^2 = .017$.

P2. The P2 was maximal at Oz. Here, we observed a main effect of picture type, $F(2, 184) = 5.81, p = .004, \eta_p^2 = .059$, such that neutral pictures elicited more positive P2 amplitudes ($M = 7.54, SE = 0.50$) than both positive ($M = 6.00, SE = 0.60; p = .001$) and negative pictures ($M = 6.35, SE = 0.50; p = .015$); P2s to positive and negative pictures did not differ, $p = .452$.

Please see Figure 1 for a depiction of the effect of picture type on ERPs across the midline.

INSERT FIGURE 1 ABOUT HERE

³ Outliers included one N1 amplitude to negative pictures (i.e., negative N1) at Cz, one positive P1 at Oz, one negative P1 at Oz, one neutral P1 at Oz, one negative P2 at Oz, one positive P2 at Oz, one negative N2 at Fz, and one positive LPP at Cz.

⁴ Whenever the peak amplitude was similarly maximal at analogous electrode sites, we ran the same analyses at the analogous sites. In all instances, the results do not change for analogous sites so we only report results from the electrode site with the maximal mean ERP amplitude.

The main effect of writing task was non-significant, $F(1, 92) = 1.17, p = .283, \eta_p^2 = .013$, as was the Picture Type \times Writing Task interaction, $F(2, 184) = 0.51, p = .605, \eta_p^2 = .005$.

N2. The N2 was maximal at Fz, although not statistically different from Cz. We observed a main effect of picture type, $F(2, 188) = 11.45, p < .001, \eta_p^2 = .109$, such that neutral pictures ($M = -5.11, SE = 0.39$) elicited larger N2 amplitudes than both positive ($M = -3.11, SE = 0.44; p < .001$) and negative ($M = -3.94, SE = 0.44; p = .003$) pictures; N2 amplitudes to positive and negative pictures did not differ, $p = .076$ (see Figure 1).

We also observed a main effect of writing task, $F(1, 94) = 6.72, p = .011, \eta_p^2 = .067$, such that participants in the controlled writing condition exhibited larger N2 amplitudes ($M = -4.95, SE = 0.47$) compared to those in the free writing condition ($M = -3.16, SE = 0.50$). See Figure 2 for a depiction of the effect of writing task on ERPs across the midline. Writing task did not interact with picture type, $F(2, 188) = 0.18, p = .838, \eta_p^2 = .002$.

INSERT FIGURE 2 ABOUT HERE

Later ERPs

P3. The P3 was maximal at the Pz electrode site. We observed a main effect of picture type, $F(2, 182) = 68.27, p < .001, \eta_p^2 = .429$, such that P3 amplitudes were largest to positive pictures ($M = 11.28, SE = 0.67$), followed by negative pictures ($M = 9.54, SE = 0.75$), and smallest to neutral pictures ($M = 5.30, SE = 0.65$). All pairwise comparisons were significant, $p \leq .002$ (see Figure 1). We found no main effect of writing task, $F(1, 91) = 1.44, p = .233, \eta_p^2 = .016$, and no Writing Task \times Picture Type interaction, $F(2, 182) = 0.08, p = .920, \eta_p^2 < .001$, on P3 amplitudes.

LPP. The LPP was maximal at the Pz electrode site and significantly larger at Pz than at Fz and Cz ($p < .001$). The assumption of sphericity was violated for the picture type factor

(Greenhouse-Geisser $\varepsilon = 0.911$, $p = .011$), and degrees of freedom were corrected. We observed a main effect of picture type on LPP amplitudes, $F(1.823, 164.063) = 92.45, p < .001, \eta_p^2 = .507$, indicating that negative pictures ($M = 12.17, SE = 0.71$) elicited the largest LPP, followed by positive pictures ($M = 10.05, SE = 0.54$), with the smallest LPPs to neutral pictures ($M = 4.83, SE = 0.53$). All pairwise comparisons were significant, $ps \leq .001$ (See Figure 1). We found no main effect of writing task, $F(1, 90) = 0.12, p = .727, \eta_p^2 = .001$, and no Writing Task \times Picture Type interaction, $F(1.823, 164.063) = 0.05, p = .939, \eta_p^2 = .001$.

Discussion

The current experiment examined the aftereffects of mental effort on neural responses to images. There were two main sets of findings. First, we found that a prior expenditure of mental effort modulated N2 amplitudes to both emotional and neutral images. And second, we observed a positive shift in the ERP waveform for emotional versus neutral images beginning around 200 ms.⁵ Below we review the main findings from this experiment and consider the implications for understanding both emotional modulation of ERPs and the aftereffects of mental effort.

Effects of Prior Mental Effort on ERPs

The mental effort manipulation influenced the N2 component during the picture viewing task. Individuals who completed the more (versus less) effortful writing task displayed more negative N2 amplitudes across all picture types. This finding is broadly consistent with the process model of ego depletion and suggests reduced attentional engagement with visual stimuli following a brief (5 min) exertion of mental effort.

⁵ The positive shift in the ERP waveform for emotional versus neutral pictures is evident at Fz and Cz sites (see Figure 1). In contrast, the P2 component was more positive for neutral relative to emotional pictures, but this component was measured at Oz (where it was maximal).

N2 amplitudes during picture viewing tasks have been interpreted as reflecting attentional engagement with visual stimuli, such that more positive N2 amplitudes reflect preferential processing or increased attentional engagement with emotional versus neutral pictures (e.g., Carretié, Hinojosa, Martín-Lloeches, Mercado, & Tapia, 2004; Feng et al., 2014; Palomba et al., 1997). Correspondingly, more negative N2s to the pictures after more versus less mental effort suggest reduced processing and less-engaged attention. The results suggest that participants who expended more mental effort on the writing task displayed less attentional engagement to all images on the subsequent picture-viewing task.

The observed aftereffect of mental effort is generally consistent with past research suggesting that mental effort reduces attention to task stimuli (e.g., Boksem et al., 2005; Hopstaken et al., 2016; Kato, Endo, & Kizuka, 2009) and performance monitoring (e.g., Inzlicht & Gutsell, 2007). For instance, Hopstaken et al. (2016) observed a reduction in P3 amplitudes to visual stimuli over time during a 90-minute working memory task, suggesting a reduction in attention to the stimuli after a prolonged bout of mental effort. Unlike past research the current study assessed the aftereffects of a relatively brief (5 min) period of mental effort on responses to a non-demanding (passive picture viewing) task. Results revealed modulation of the N2 component to picture stimuli but not later event-related components such as the P3 or LPP. Perhaps longer, more strenuous expenditures of mental effort are required to reduce the P3 or LPP. It may also be that the aftereffects of mental effort on later components (e.g., P3 or LPP) emerge only when individuals perform more cognitively demanding tasks.

The N2 component has been implicated in cognitive control and novelty detection (for review see Folstein & Van Petten, 2008). However, unlike prior studies of mental effort that have involved cognitively demanding tasks (e.g., Boksem et al., 2005; Hopstaken et al., 2016),

cognitive control was not required during the passive picture viewing task in the current experiment. Participants did not have to attend selectively to different aspects of the pictures, they did not have to engage cognitive control during the picture viewing task, and the picture stimuli were not particularly novel or unusual. Thus, the current results cannot easily be interpreted in light of cognitive control or novelty detection perspectives.

The mental effort manipulation did not influence ERPs other than the N2, nor did the mental effort manipulation alter the patterns of emotion modulation in the EEG (as reviewed below). In sum, expending mental effort prior to the image viewing task altered an early ERP index of attention (i.e., N2) to emotional and non-emotional images alike, but did not alter the later indices of higher order processing (e.g., P3, LPP), though these later indices were influenced by emotional content.

Effects of Emotional Content on ERPs

Like several previous experiments, the current experiment tested emotional modulation of ERPs to images during a passive viewing paradigm. Emotional content did not modulate P1 or N1 amplitudes in the current study, which is inconsistent with some past research (Foti et al., 2009; Feng et al., 2014; Keil et al., 2002; Lithari et al., 2010; Pollatos et al., 2005; Weinberg & Hajcak 2010), but generally consistent with evidence that the effects of emotional picture content emerge later in time (e.g., 200 ms or more after picture onset; Bradley et al., 2007; Cuthbert et al., 2000; Palomba et al., 1997).

We did find emotion modulation of the subsequent ERP components. The P2 component (180 – 230 ms) was larger (more positive) to neutral pictures relative to emotional pictures at the midline occipital site. Few previous passive viewing studies have assessed the P2 component, and those that did found mixed results. One study found larger P2 amplitudes to positive versus

negative pictures (Lithari et al., 2010), another observed largest P2 amplitudes specifically to negative high-arousal pictures (Feng et al., 2014), and a third found no emotion modulation of the P2 (Palomba et al. 1997). The discrepancy in findings across studies may be due to scalp location of the P2 (e.g., measured at Cz versus Oz) or to variations in experimental protocol (e.g., picture viewing time).

We also found a positive shift in the N2 for emotional versus neutral pictures, which is similar to past research and consistent with greater attentional engagement with emotional versus neutral pictures (Feng et al., 2014; Keil et al., 2001; Palomba et al., 1997). Some past research has observed valence effects, such as more positive N2s to pleasant versus unpleasant pictures (Lithari et al., 2010), but we did not find differences in N2 magnitudes between positive and negative pictures in the current study.

Many of the previous studies that have found significant effects of emotional content on early ERP components tested smaller samples of participants (i.e., $N_s = 10$ to 82) compared to the current study ($N = 97$). Our relatively large sample afforded us greater power than most prior studies to detect effects of emotional content on ERP amplitudes. Specifically, the current experiment had 80% power to detect a difference of 0.29 standard deviation units (i.e., $d = 0.29$) in ERP magnitudes to emotional versus neutral images. In prior studies that have observed effects of emotional versus neutral content on early ERPs such as the P1 and N1, effect sizes have ranged from $d = 0.34$ to $d = 1.00$ (Foti et al., 2009; Feng et al., 2014; Keil et al., 2002; Lithari et al., 2010; Weinberg & Hajcak, 2010). Thus, the current study had ample statistical power to detect fairly small effects of emotional content on early ERPs, but we found none in this time range.

Differences in study design or experimental procedures may help to account for the different findings across studies. For instance, in the current study participants viewed positive, negative, and neutral images presented in random order, whereas one previous study that observed affective modulation of the N1 presented pictures in valence-specific blocks (Weinberg & Hajcak, 2010). Other studies have presented pictures randomly and observed affective modulation of the N1 or P1, but presented pictures for a shorter duration (1000-2000 ms) than in the current study (Feng et al., 2014; Foti et al., 2009; Lithari et al., 2010). But some studies used methods more closely matched to the procedure of the current study (randomly presented pictures for 6000 ms; 60 total trials) and observed affective modulation of the N1 and P1 (Keil et al., 2002; Pollatos et al., 2005). Compared to the most similar past studies, the current study had a larger sample size ($N = 97$ vs. $N = 11$ and 44 , respectively). It is also possible that the novel context of the prior writing task influenced the effects of emotional content on ERPs during picture viewing, and this may also help account for the discrepancies across studies. The most conservative conclusion to draw on the basis of the current results is that emotional content is unlikely to exert non-small effects on very early ERPs, particularly in passive viewing paradigms with several seconds of viewing time per image.

The later ERP components were modulated by emotional content in the present study in a manner consistent with a large body of past research (e.g., Cuthbert et al., 2000; Hajcak & Olvet, 2008; Schupp et al., 2000; Weinberg & Hajcak, 2010). The P3 was larger during emotional pictures compared to neutral pictures and largest specifically during positive pictures. The LPP was also larger during emotional pictures compared to neutral pictures and largest specifically during negative pictures. Thus, both the P3 and LPP were amplified for emotional pictures,

which is consistent with much prior research and likely reflects the motivated processing of emotional relative to neutral images (Lang et al., 1997).

Altogether, we found little evidence for emotional modulation of very early ERPs (P1, N1) but consistent and strong evidence for emotional modulation of subsequent ERPs (including P2, N2, P3, and LPP). The latter findings reveal a smaller (less positive) P2 to emotional versus neutral images at the midline occipital site and more positive amplitudes during emotional versus neutral pictures for the N2, P3, and LPP at frontal, central, and parietal sites, respectively. Hence, we observed differential activity in the EEG for emotional versus non-emotional images starting around 180 ms after picture onset, consistent with the idea that emotional images attract additional, more sustained processing relative to neutral images. Next, we consider how these findings relate to theories of mental effort.

Implications for Theories of Mental Effort Expenditure

The resource model of self-control proposes that expending mental effort temporarily depletes a limited inner strength needed for further mental effort or self-control (Muraven & Baumeister, 2000). The resource model does not consider possible aftereffects of mental effort on non-controlled or more automatic processes. Hence, the resource model makes no specific predictions regarding the effects of mental effort on subsequent attention insofar as this attention is automatic, routine, or otherwise free from effortful control. (The resource is hypothesized to be required for control or regulation, not more automatic or routine processes). The resource model therefore cannot readily account for the observed aftereffects of mental effort on N2 amplitudes to emotional and non-emotional images in a passive viewing paradigm.

The process model of ego depletion proposes that expending mental effort causes a temporary bias in motivation and attention toward a more exploratory (versus exploitative)

processing strategy (Inzlicht et al., 2014). Previous research related to the process model has observed that expending mental effort causes a bias in attention toward and greater responsiveness to positive or reward-related information (Schmeichel et al., 2016; Schmeichel, Harmon-Jones, & Harmon-Jones, 2010). In the current study we found that expending mental effort altered an early attention-related ERP component to all picture stimuli, consistent with decreased attentional engagement, but had no influence on later ERP components to positive (or any other type) of images.

The simplest conclusion to draw from the current findings is that expending mental effort on the more difficult writing task impacted early attentional engagement with the pictures. Although the current study cannot establish definitively whether mental effort, task difficulty, frustration, or some other element of the controlled writing task (versus free writing task) drove the observed effects, we assume that the controlled writing task is more mentally effortful than the free writing task. Indeed, the controlled writing task, relative to the free writing task, requires response inhibition (i.e., avoiding the use of the letters “a” or “n”), and has been rated as requiring more effort and been found to induce ego depletion in past research (e.g., Lewandowski et al., 2012; Schmeichel 2007). We thus believe it is safe to assume that the controlled writing task was more effortful than the free writing task in the current study, and this difference between conditions is responsible for the observed effects on subsequent picture processing. However, future work should further explore this account using a within-subjects design to minimize individual differences.

The aftereffects of expending mental effort emerged around 220 ms into the processing of a picture, and occurred for emotional and non-emotional stimuli alike, whereas emotion discrimination in the ERP waveform began around 180 ms and continued until at least one

second into picture viewing. This pattern suggests that mental effort alters the engagement of attention fairly early in the stream of processing, but does not dilute the influence of emotion on attention. Even after expending mental effort, emotional content moderated neural indices of attentional engagement and motivational salience. Thus, emotion processing appears to be robust to the effects of a short, prior bout of mental effort.

The reduction in attentional engagement after mental effort suggested by the N2 finding may help to explain why expending mental effort can undermine further self-control (i.e., ego depletion). Success at self-control relies in part on successful attention control, for example by sustaining attention to a boring task that promises long-term benefits or attending selectively to goal-relevant versus irrelevant information. A reduced tendency to engage with visual stimuli may undermine efforts to control attention or attend to relevant self-regulatory cues, which in turn may have negative consequences for self-control (see also Inzlicht & Gutsell, 2007). This perspective is broadly consistent with the process model of ego depletion, insofar as shifts in attention (rather than the depletion of resources) help to explain the resultant behavioral changes. Additional research is needed to test the extent to which the changes in N2 amplitudes observed in the current study mediate any of the behavioral aftereffects of mental effort.

The changes in attention following mental effort appear to be different from changes in attention sometimes observed under cognitive load (i.e., a concurrent mental task). Previous research has generally observed a blunting of ERP magnitudes or reduced affective modulation of ERPs under high versus low cognitive load (e.g., MacNamara, Ferri, & Hajcak, 2011; Wangelin, Löw, McTeague, Bradley, & Lang, 2011). For instance, Van Dillen and Derkx (2012) observed a reduced LPP to emotional faces when participants held an eight- versus one-digit number in working memory. In the current experiment we found no such modulations of later

ERP components after mental effort exertion. The evidence that concurrent cognitive load and the aftereffects of mental effort have different effects on ERPs suggests that the two manipulations operate through different mechanisms (see also Maranges, Schmeichel, & Baumeister, *in press*). Whereas a concurrent cognitive load distracts attention away from and reduces mental elaboration of stimuli (e.g., Crowell & Schmeichel, 2016) and can reduce emotional responding (e.g., Van Dillen, Heslenfeld, & Koole, 2009), prior mental effort reduces early attentional engagement but does not appear to reduce mental elaboration or emotional responding. The aftereffects of mental effort thus appear to be different from the effects of cognitive load.

Conclusions

The current experiment tested the hypothesis that prior mental effort influences electrocortical responses to picture stimuli. Emotional versus non-emotional images elicited a positive shift in the ERP waveform beginning around 200 ms into picture viewing, and this emotion modulation pattern was not altered by prior mental effort. Prior mental effort caused a negative shift in the N2 component, consistent with decreased attentional engagement, and this effect was evident for both emotional and non-emotional pictures. Prior mental effort did not alter later ERP components associated with motivational salience and cognitive elaboration (i.e., P3 and LPP). The current results thus suggest that expending mental effort causes shifts in attention—shifts that are not easily explained as a depletion of resources but may reflect a change in processing priorities. Prior mental effort may be a potent moderator of the N2 to visual stimuli.

References

- Amrhein, C., Mühlberger, A., Pauli, P., & Wiedemann, G. (2004). Modulation of event-related brain potentials during affective picture processing: A complement to startle reflex and skin conductance response? *International Journal of Psychophysiology*, 54, 231-240. doi:10.1016/j.ijpsycho.2004.05.009
- Baumeister, R. F., Vohs, K. D., & Tice, D. M. (2007). The strength model of self-control. *Psychological Science*, 16, 351-355. doi:10.1111/j.1467-8721.2007.00534.x
- Boksem, M. A. S., Meijman, T. F., & Lorist, M. M. (2005). Effects of mental fatigue on attention: An ERP study. *Cognitive Brain Research*, 25, 107-116. doi:10.1016/j.cogbrainres.2005.04.011
- Bradley, M. M., Hamby, S., Löw, A., & Lang, P. (2007). Brain potentials in perception: Picture complexity and emotional arousal. *Psychophysiology*, 44, 364-373. doi:10.1111/j.1469-8986.2007.00520.x
- Bradley, M. M., Sabatinelli, D., Lang, P. J., Fitzsimmons, J. R., King, W., & Desai, P. (2003). Activation of the visual cortex in motivated attention. *Behavioral Neuroscience*, 117, 369-380. doi:10.1037/0735-7044.117.2.369
- Carter, E. C., Kofler, L. M., Forster, D. E., & McCullough, M. E. (2015). A series of meta-analytic tests of the depletion effect: Self-control does not seem to rely on a limited resource. *Journal of Experimental Psychology: General*, 144, 796-815. doi:10.1037/xge0000083
- Cesarei, A. D., & Codispoti, M. (2006). When does size not matter? Effects of stimulus size on affective modulation. *Psychophysiology*, 43, 207-215. doi:10.1111/j.1469-8986.2006.00392.x

- Codispoti, M., Ferrari, V., & Bradley, M. (2007). Repetition and event-related potentials: Distinguishing early and late processes in affective picture perception. *Journal of Cognitive Neuroscience*, 19, 577-586. doi:10.1162/jocn.2007.19.4.577
- Crowell, A., & Schmeichel, B. J. (2016). Approach motivation and cognitive resources combine to influence memory for positive emotional stimuli. *Cognition and Emotion*, 30, 389-397. doi:10.1080/02699931.2014.1000829
- Cuthbert, B. N., Schupp, H. T., Bradley, M. M., Birbaumer, N., & Lang, P. J. (2000). Brain potentials in affective picture processing: Covariation with autonomic arousal and affective report. *Biological Psychology*, 52, 95-111. doi:10.1016/S0301-0511(99)00044-7
- Dewey, J. (1897). The psychology of effort. *Philosophical Review*, 6, 43-56. doi:10.2307/2175586
- Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, 16, 143-149. doi:10.3758/BF03203267
- Feng, C., Li, W., Tian, T., Luo, Y., Gu, R., Zhou, C., & Luo, Y. (2014). Arousal modulates valence effects on both early and late stages of affective picture processing in a passive viewing task. *Social Neuroscience*, 9, 364-377. doi:10.1080/17470919.2014.896827.
- Folstein, J. R., & Van Petten, C. (2008). Influence of cognitive control and mismatch on the N2 component of the ERP: A review. *Psychophysiology*, 45, 152-170. doi:10.1111/j.1469-8986.2007.00602.x
- Foti, D., Hajcak, G., & Dien, J. (2009). Differentiating neural responses to emotional pictures: Evidence from temporal-spatial PCA. *Psychophysiology*, 46, 521-530. doi:10.1111/j.1469-8986.2009.00796.x

- Friese, M., Binder, J., Luechinger, R., Boesiger, P., & Rasch, B. (2013). Suppressing emotions impairs subsequent Stroop performance and reduces prefrontal brain activation. *PLoS ONE*, 8: e60385. doi:10.1371/journal.pone.0060385
- Hagger, M. S., Wood, C., Stiff, C., Chatzisarantis, N. L. (2010). Ego depletion and the strength model of self-control: A meta-analysis. *Psychological Bulletin*, 136, 495-525. doi:10.1037/a0019486
- Hajcak, G., & Olvet, D. M. (2008). The persistence of attention to emotion: Brain potentials during and after picture presentation. *Emotion*, 8, 250-255. doi:10.1037/1528-3542.8.2.250
- Hajcak, G. Weinberg, A., MacNamara, A., & Foti, D. (2012). ERPs and the study of emotion. In S. J. Luck & E. S. Kappenman (Eds.), *The Oxford handbook of event-related potentials* (pp. 441-472). New York: Oxford University Press.
- Hirt, E. R., & Markman, K. D. (1995). Multiple explanation: A consider-an-alternative strategy for debiasing judgments. *Journal of Personality and Social Psychology*, 69, 1069-1086. doi:10.1037/0022-3514.69.6.1069
- Hopstaken, J. F., van der Linden, D., Bakker, A. B., Kompier, M. A., & Leung, Y. K. (2016). Shifts in attention during mental fatigue: Evidence from subjective, behavioral, physiological, and eye-tracking data. *Journal of Experimental Psychology: Human Perception and Performance*, 42, 878-889. doi:10.1037/xhp0000189
- Hot, P., Saito, Y., Mandai, O., Kobayashi, T., & Sequeira, H. (2006). An ERP investigation of emotional processing in European and Japanese individuals. *Brain Research*, 1122, 171-178. doi:10.1016/j.brainres.2006.09.020

Inzlicht, M., Gervais, W., & Berkman, E., Bias-correction techniques alone cannot determine whether ego depletion is different from zero: Commentary on Carter, Kofler, Forster, & McCullough, 2015 (September 11, 2015). Available at SSRN: <https://ssrn.com/abstract=2659409> or doi:10.2139/ssrn.2659409

Inzlicht, M., & Gutsell, J. N. (2007). Running on empty: Neural signals for self-control failure. *Psychological Science*, 18, 933-937. doi:10.1111/j.1467-9280.2007.02004.x

Inzlicht, M., & Schmeichel, B. J. (2012). What is ego depletion? Toward a mechanistic revision of the resource model of self-control. *Perspectives on Psychological Science*, 7, 450-463. doi:10.1177/1745691612454134

Inzlicht, M., Schmeichel, B. J., & Macrae, C. N. (2014). Why self-control seems (but may not be) limited. *Trends in Cognitive Sciences*, 18, 127-133. doi:10.1016/j.tics.2013.12.009

Job, V., Bernecker, K., Miketta, S., & Friese, M. (2015). Implicit theories about willpower predict the activation of a rest goal following self-control exertion. *Journal of Personality and Social Psychology*, 109, 694-706. doi:10.1037/pspp0000042

Kato, Y., Endo, H., & Kizuka, T. (2009). Mental fatigue and impaired response processes: Event-related brain potentials a Go/NoGo task. *International Journal of Psychophysiology*, 72, 204-211. doi:10.1016/j.ijpsycho.2008.12.008

Keil, A., Bradley, M. M., Hauk, O., Rockstroh, B., Elbert, T., & Lang, P. J. (2002). Large-scale neural correlates of affective picture processing. *Psychophysiology*, 39, 641-649. doi:10.1111/1469-8986.3950641

Keil, A., Müller, M. M., Gruber, T., Wienbruch, C., Stolarova, M., & Elbert, T. (2001). Effects of emotional arousal in the cerebral hemispheres: A study of oscillatory brain activity and

event-related potentials. *Clinical Neurophysiology*, 112, 2057-2068. doi:10.1016/S1388-2457(01)00654-X

Kramer, A. F., Wickens, C. D., & Donchin, E. (1985). Processing of stimulus properties:

Evidence for dual-task integrality. *Journal of Experimental Psychology: Human Perception and Performance*, 11, 393-408. doi:10.1037/0096-1523.11.4.393

Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (1997). Motivated attention: Affect, activation and action. In P. J. Lang, R. F. Simons, & M. Balaban (Eds.), *Attention and orienting: Sensory and motivational processes* (pp. 97-136). Hillsdale, NJ: Erlbaum.

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

Lewandowski, G. W., Ciarocco, N. J., Pettenato, M., & Stephan, J. (2012). Pick me up: Ego depletion and receptivity to relationship initiation. *Journal of Social and Personal Relationships*, 29, 1071-1084. doi:10.1177/0265407512449401

Lithari, C., Frantzidis, C. A., Papadelis, C., Vivas, A. B., Klados, M. A., Kourtidou-Papadeli, C., Pappas, C., Ioannides, A. A., & Bamidis, P. D. (2010). Are females more responsive to emotional stimuli? A neurophysiological study across arousal and valence dimensions. *Brain Topography*, 23, 27-40. doi:10.1007/s10548-009-0130-5.

Luck, S. J., & Gaspelin, N. (2017). How to get statistically significant effects in any ERP experiment (and why you shouldn't). *Psychophysiology*, 54, 146-157.
doi:10.1111/psyp.12639

- MacNamara, A., Ferri, J., & Hajcak, G. (2011). Working memory load reduces the late positive potential and this effect is attenuated with increasing anxiety. *Cognitive, Affective, & Behavioral Neuroscience, 11*, 321-331. doi:10.3758/s13415-011-0036-z
- Maranges, H., Schmeichel, B. J., & Baumeister, R. F. (in press). Comparing cognitive load and self-regulatory depletion: Effects on emotions and cognitions. *Learning and Instruction*. doi:10.1016/j.learninstruc.2016.10.010
- Muraven, M. & Baumeister, R. F. (2000). Self-regulation and depletion of limited resources: Does self-control resemble a muscle? *Psychological Bulletin, 126*, 247-259. doi:10.1037/0033-2909.126.2.247
- Olofsson, J. K., Nordin, S., Sequeria, H., & Polich, J. (2008). Affective picture processing: An integrative review of ERP findings. *Biological Psychology, 77*, 247-265. doi:10.1016/j.biopspsycho.2007.11.006
- Palomba, D., Angrilli, A., & Mini, A. (1997). Visual evoked potentials, heart rate responses and memory to emotional pictorial stimuli. *International Journal of Psychophysiology, 27*, 55-67. doi:10.1016/S0167-8760(97)00751-4
- Polich, J. (2007). Updating P300: An integrative theory of P3a and P3b. *Clinical Neurophysiology, 118*, 2128-2148. doi:10.1016/j.clinph.2007.04.019
- Pollatos, O., Kirsch, W., & Schandry, R. (2005). On the relationship between interoceptive awareness, emotional experience, and brain processes. *Cognitive Brain Research, 25*, 948-962. doi:10.1016/j.cogbrainres.2005.09.019
- Reed, R. W., Florax, R. J. G. M., & Poot, J. (2015). A Monte Carlo analysis of alternative meta-analysis estimators in the presence of publication bias. *Economic Discussion Papers, 2015-9*. Available at <http://hdl.handle.net/10419/107140>

- Scherer, L. D., Yates, J. F., Baker, S. G., & Valentine, K. D. (2017). The influence of effortful thought and cognitive proficiencies on the conjunction fallacy: Implications for dual-process theories of reasoning and judgment. *Personality and Social Psychology Bulletin, 43*, 874-887. doi:10.1177/0146167217700607
- Schmeichel, B. J. (2007). Attention control, memory updating, and emotion regulation temporarily reduce capacity for executive control. *Journal of Experimental Psychology: General, 136*, 241-255. doi:10.1037/0096-3445.136.2.241
- Schmeichel, B. J., Crowell, A., & Harmon-Jones, E. (2016). Exercising self-control increases relative left frontal cortical activation. *Social Cognitive and Affective Neuroscience, 11*, 282-288. doi:10.1093/scan/nsv112
- Schmeichel, B. J., Harmon-Jones, C., & Harmon-Jones, E. (2010). Exercising self-control increases approach motivation. *Journal of Personality and Social Psychology, 99*, 162-173. doi:10.1037/a0019797
- Schulkin, J. (2007). *Effort: A behavioral neuroscience perspective on the will*. Mahwah, NJ: Lawrence Erlbaum Associates.
- Schupp, H. T., Cuthbert, B. N., Bradley, M. M., Cacioppo, J. T., Ito, T., & Lang, P. J. (2000). Affective picture processing: The late positive potential is modulated by motivational relevance. *Psychophysiology, 37*, 257-261. doi:10.1111/1469-8986.3720257
- Schupp, H. T., Junghöfer, M., Weike, A. I., & Hamm, A. O. (2003). Emotional facilitation of sensory processing in the visual cortex. *Psychological Science, 14*, 7-13. doi:10.1111/1467-9280.01411

- Semlitsch, H. V., Anderer, P., Schuster, P., & Presslich, O. (1986). A solution for reliable and valid reduction of ocular artifacts, applied to the P300 ERP. *Psychophysiology, 23*, 695-703. doi:10.1111/j.1469-8986.1986.tb00696.x
- Van Dillen, L. F., & Derkx, B. (2012). Working memory load reduces facilitated processing of threatening faces: An ERP study. *Emotion, 12*, 1340-1349. doi:10.1037/a0028624
- Van Dillen, L. F., Heslenfeld, D. J. & Koole, S. L. (2009). Tuning down the emotional brain: An fMRI study of the effects of cognitive load on the processing of affective images. *NeuroImage, 45*, 1212-1219. doi:10.1016/j.neuroimage.2009.01.016
- Wangelin, B. C., Löw, A., McTeague, L. M., Bradley, M. M., & Lang, P. J. (2011). Aversive picture processing: Effects of a concurrent task on sustained defensive system engagement. *Psychophysiology, 48*, 112-116. doi:10.1111/j.1469-8986.2010.01041.x
- Weinberg, A., & Hajcak, G. (2010). Beyond good and evil: The time-course of neural activity elicited by specific picture content. *Emotion, 10*, 767-782. doi:10.1037/a0020242

Table 1

Mean Amplitude (μ V) for ERPs at Each Electrode Site Collapsed across Image Type and Writing Condition.

| ERP | Fz | Cz | Pz | Oz |
|--------------|--------------|--------------|-------------|-------------|
| P1 amplitude | -1.46 (0.20) | -1.75 (0.26) | 0.22 (0.28) | 3.27 (0.35) |
| N1 amplitude | -1.93 (0.23) | -1.88 (0.29) | 0.62 (0.30) | 3.13 (0.41) |
| P2 amplitude | -3.06 (.06) | -1.32 (0.48) | 2.32 (0.50) | 6.43 (0.45) |
| N2 amplitude | -3.89 (0.36) | -3.49 (0.52) | 1.02 (0.56) | 4.96 (0.59) |
| P3 amplitude | -0.31 (0.42) | 2.07 (0.60) | 8.66 (0.63) | 7.61 (0.61) |
| LPP | 1.80 (0.32) | 5.56 (0.46) | 8.78 (0.52) | --- |

Note. Standard errors are reported in parentheses.

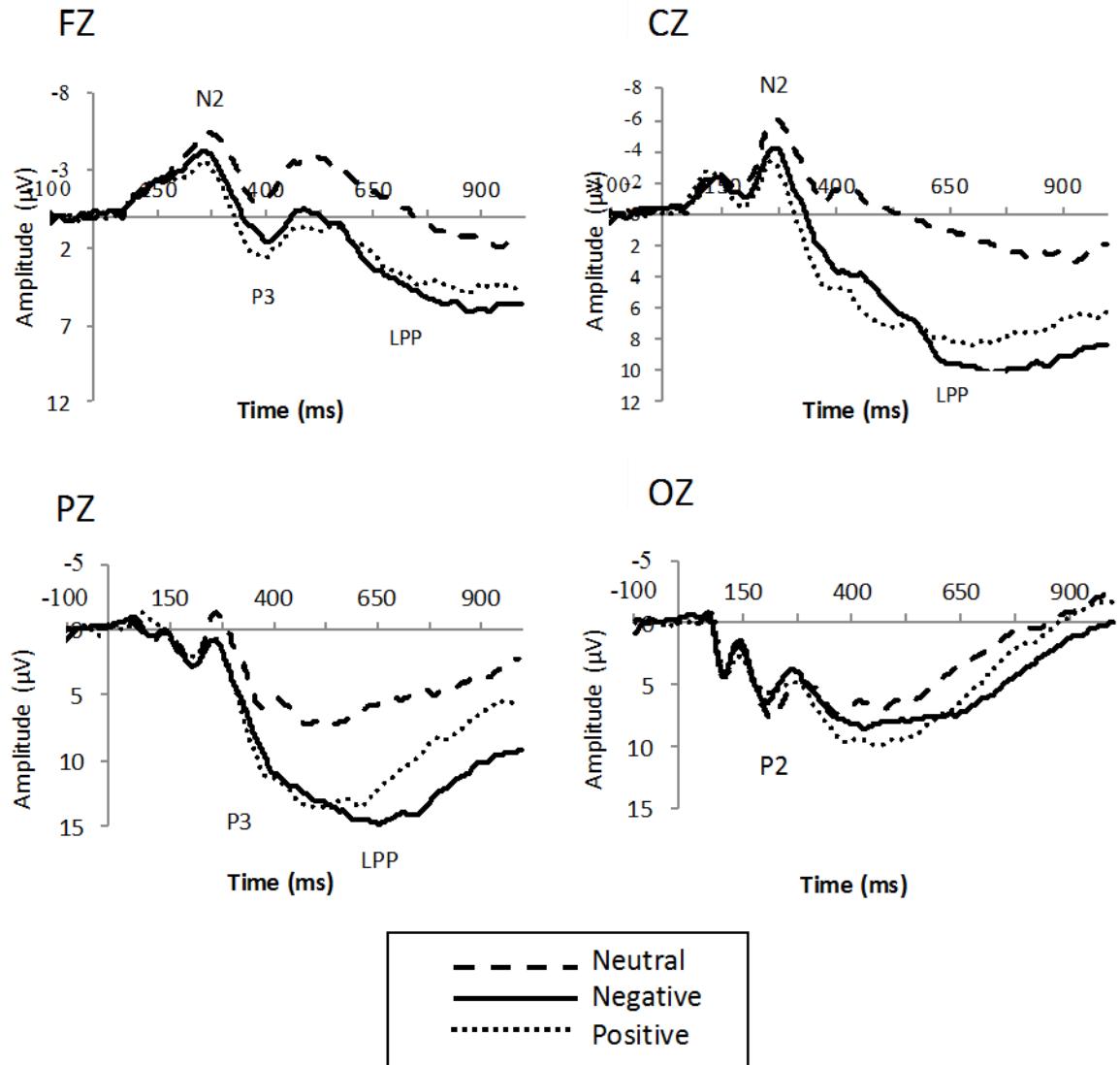


Figure 1. ERP waveforms from 100 ms before picture onset to 1000 ms after picture onset for negative, neutral, and positive images at electrode sites Fz, Cz, Pz, and Oz (collapsing across writing task conditions). Peaks are labeled at electrode sites where we observed an effect of emotional content.

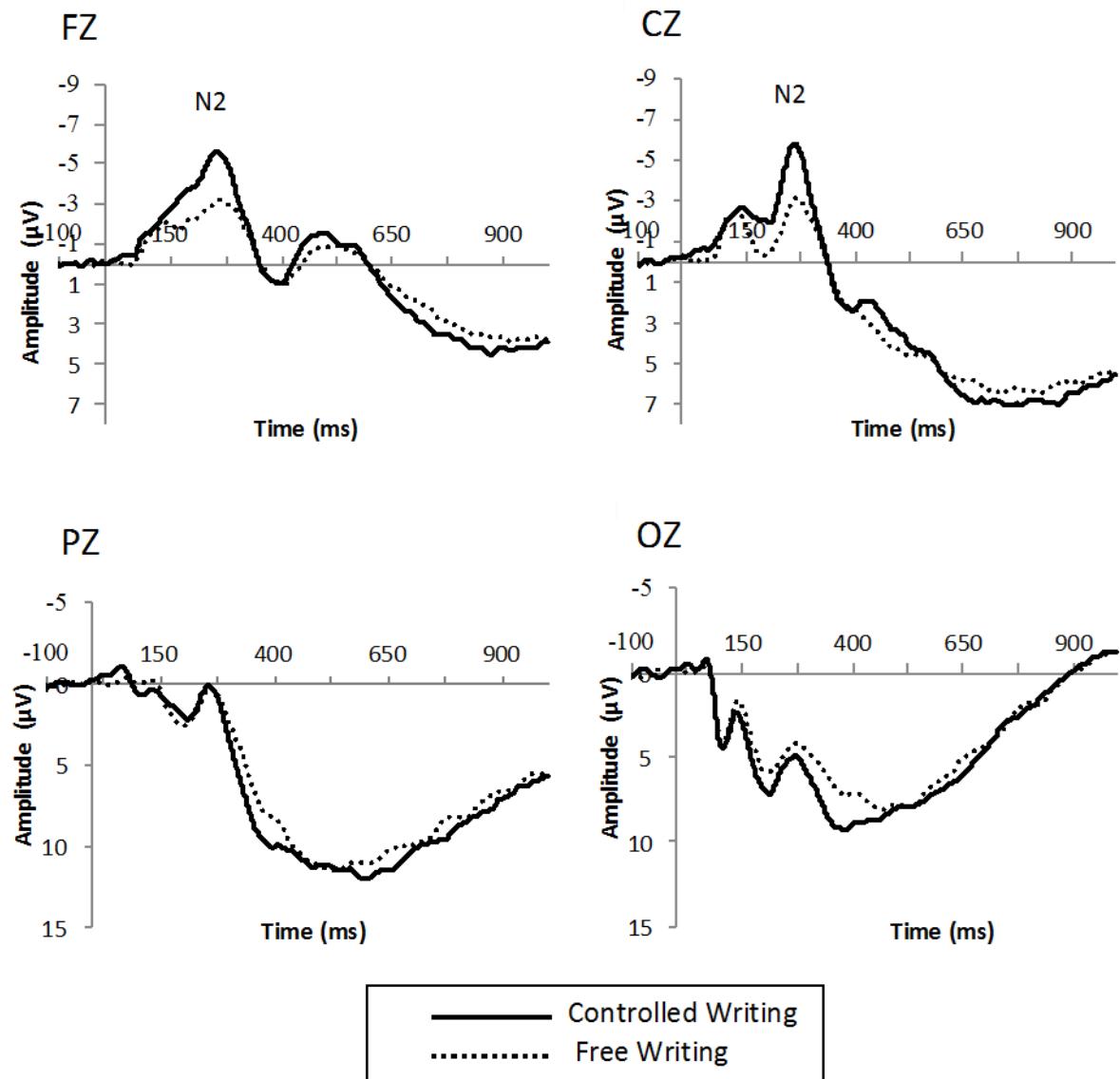


Figure 2. ERP waveforms from 100 ms before picture onset to 1000 ms after picture onset (collapsing across all picture types) at electrode sites Fz, Cz, Pz, and Oz as a function of writing condition. Peaks showing significant differences are labeled.