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Electrocortical and ocular indices of attention to fearful and neutral faces presented under high and low working memory load

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ABSTRACT

Working memory load reduces the late positive potential (LPP), consistent with the notion that functional activation of the DLPFC attenuates neural indices of sustained attention. Visual attention also modulates the LPP. In the present study, we sought to determine whether working memory load might exert its influence on ERPs by reducing fixations to arousing picture regions. We simultaneously recorded eye-tracking and EEG while participants performed a working memory task interspersed with the presentation of task-irrelevant fearful and neutral faces. As expected, fearful compared to neutral faces elicited larger N170 and LPP amplitudes; in addition, working memory load reduced the N170 and the LPP. Participants made *more* fixations to arousing regions of neutral faces and faces presented under high working memory load. Therefore, working memory load did not induce avoidance of arousing picture regions and visual attention cannot explain load effects on the N170 and LPP.

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1. Introduction

Recent work on the neural circuitry involved in emotion regulation has highlighted the role of the prefrontal cortex (PFC) in the processing of emotional stimuli. For example, when participants are asked to reduce the emotional salience of stimuli, activity decreases in the amygdala and *increases* in the dorsolateral prefrontal cortex (DLPFC; Beauregard et al., 2001; Hariri et al., 2003; Lévesque et al., 2003; Ochsner et al., 2002, 2004; Phan et al., 2005), an area of the PFC associated with cognitive control and the goal-directed maintenance of stimulus processing priorities (Miller and Cohen, 2001). Activity in the DLPFC has also been negatively correlated with activity in the amygdala during emotion regulation tasks, suggesting a reciprocal relationship between these areas (Banks et al., 2007). Although no direct anatomical connection seems to exist between the DLPFC and subcortical emotion-processing brain regions such as the amygdala, reciprocal modulation might take place via recruitment of the orbitofrontal and cingulate cortices (Amaral and Price, 1984; Ghashghaei and Barbas, 2002; Porrino et al., 1981; Ray and Price, 1993).

Further evidence for DLPFC-mediated suppression of emotion-processing comes from studies that have used tasks to activate the DLPFC. Van Dillen et al. (2009) required participants to view neutral and unpleasant pictures interspersed with the presentation of difficult or easy math problems. Difficult math problems were associated with increased activity in the DLPFC as well as decreased amygdala activity and reduced self-reported negative emotion in response to unpleasant pictures. Functional activation of the DLPFC via *working memory* tasks has also been shown to reduce the processing of emotional pictures. For instance, participants in studies by Erk and colleagues performed working memory tasks while anticipating (Erk et al., 2006) or viewing (Erk et al., 2007) emotional pictures. Working memory load was found to reduce neural activity elicited by pictures, in line with the notion that DLPFC activation may inhibit the processing of emotional stimuli.

In addition to the hemodynamic response, electroencephalography (EEG) can be used to track the dynamic allocation of attention to emotional stimuli. Specifically, the late positive potential (LPP) is a positive-going event-related potential (ERP) component beginning approximately 300 ms following stimulus onset that is larger for emotional compared to neutral pictures and words (Cuthbert et al., 2000; Dillon et al., 2006; Foti et al., 2009; Hajcak et al., 2010a,b). The LPP is also sensitive to more fine-grained distinctions in stimulus salience. For example, the LPP is larger for pictures with greater biological relevance, such as erotic or threatening images (Weinberg and Hajcak, 2010). The LPP is also larger for neutral pictures that contain people, compared to neutral pictures without people, despite similar ratings of arousal and valence (Weinberg and Hajcak, 2010). Therefore, the LPP provides an index of stimulus salience that is related to (Hajcak and Nieuwenhuis, 2006) but not redundant with subjective ratings of picture emotionality. The LPP has also been used to index the effects of emotion

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regulation. For example, the LPP is smaller when participants are asked to reduce their response to emotional pictures by reappraising picture meaning (Hajcak and Nieuwenhuis, 2006).

Similar to other neural indices of emotion-processing, the LPP is reduced in response to DLPFC activation. For example, Hajcak and colleagues found that physiological stimulation of the DLPFC reduced the LPP elicited by unpleasant pictures (Hajcak et al., 2010a). Moreover, these results suggested regional specificity: a reduced LPP was found during stimulation of the DLPFC, but not the frontopolar cortex (Hajcak et al., 2010a). In addition, the LPP seems to be sensitive to *functional* activation of the DLPFC: using a working memory task, MacNamara et al. (2011a) had participants memorize 2 or 6 letters, and presented either unpleasant or neutral pictures during the retention interval. Consistent with the notion that DLPFC activation may attenuate the processing of motivationally salient stimuli, higher working memory load reduced the LPP elicited by task-irrelevant pictures (MacNamara et al., 2011a).

Together, the fMRI and ERP studies described above suggest that DLPFC activation exerts a suppressive influence on emotional processing. Moreover, this influence has been found using a variety of experimental paradigms and may reflect an obligatory, neurophysiological relationship between the DLPFC and neural regions involved in the processing of emotional stimuli (Drevets, 1998). Nevertheless, more overt attentional mechanisms may also play a role in the regulation of attention toward salient stimuli. For instance, looking away from arousing picture regions could reduce neural indices of emotion-processing elicited by these pictures.

Using fMRI and eye-tracking, van Reekum et al. (2007) found that shifts in eye gaze accounted for a significant proportion of the variance in neural activity observed during emotion regulation. In a similar vein, Dunning and Hajcak (2009) found that emotional modulation of the LPP was reduced or absent when participants were directed to fixate on less arousing compared to more arousing picture regions (e.g., a rock versus the face of a dead child; see also Hajcak et al., 2009, in press). One possibility, then, is that working memory load could reduce the processing of salient stimuli by altering visual attention. For instance, under high working memory load, participants may divert their gaze from arousing picture regions. If this were the case, then working memory load might impact the processing of visual stimuli via more overt changes in attention (i.e., where individuals fixate). Indeed, evidence from other paradigms suggests that participants may look away from arousing stimuli when asked to perform cognitively demanding tasks (e.g., recall tasks). Glenberg et al. (1998) asked participants to answer questions of varying difficulty (e.g., general knowledge questions, autobiographical questions) while they monitored whether participants looked away from the experimenter. Across several studies, participants looked away from the experimenter with greater frequency as the difficulty of questions increased (Glenberg et al., 1998). Gaze aversion was also associated with better task performance; thus, the authors concluded that participants averted their gaze to reduce environmental stimulation and enhance cognitive processing. In a similar way, working memory load might also induce shifts in visual attention away from arousing picture content, and these shifts could underlie changes observed in neural indices of emotional processing.

In the present study, we set out to replicate the effect of working memory load on the LPP (MacNamara et al., 2011a). We also sought to extend this work by examining the role of overt attention, and to do so, we employed facial stimuli. Because prior work indicates that the eye region of faces is particularly arousing (Conty et al., 2010; Leppänen et al., 2008; Morris et al., 2002), we were interested in the proportion of fixations participants allocated to the eyes when faces were viewed under high compared to low working memory load. To this end, participants performed a working memory task while EEG and eye-tracking were simultaneously recorded. The working memory task was identical to that employed by MacNamara et al. (2011a), however instead of viewing pictures from the International Affective Picture System (IAPS; Lang et al., 2005) during a 2000 ms retention interval, participants viewed fearful and neutral faces.

MacNamara et al. (2011a) reported effects of emotion and working memory load on later ERPs sensitive to stimuli salience (i.e., the LPP). In the present study, an earlier component – the N170 – was also examined. The N170 is a negative-going component that peaks at bilateral temporoparietal sites between 130 and 180 ms following stimulus onset and is larger for faces compared to other types of stimuli (e.g., Bentin et al., 2007; Joyce and Rossion, 2005; Rossion and Jacques, 2008; Wheatley et al., 2011). The N170 is “face-sensitive” and appears to track the structural encoding of facial stimuli (Carmel and Bentin, 2002; Jeffreys, 1989; Wheatley et al., 2011). In addition, the N170 is larger for emotional compared to neutral faces and may be especially enhanced to *fearful* faces (Batty and Taylor, 2003; Blau et al., 2007; Righart and de Gelder, 2008). In the present study, the N170 and the LPP were used in conjunction to examine effects of emotion and working memory load on earlier (i.e., the N170) versus later (i.e., the LPP) indices of neural activity related to facial processing.

Prior work has examined the effect of working memory load on the processing of facial stimuli. For example, Morgan et al. (2008) asked participants to memorize 1–4 simultaneously presented faces. Following this, participants viewed a target face and indicated whether this face had been present in the initial display. Results showed that the number of faces initially presented reduced the N170 elicited by target faces. These results suggest that increased working memory load reduced early neural indices of face processing. However, because Morgan et al. (2008) used faces to vary working memory load, it is unclear whether attenuation of the N170 to the target face would have occurred if working memory load were manipulated using other (i.e., non-face) stimuli. In another study, Van Dillen and Derks (2012) found that working memory load reduced the LPP elicited by faces during a gender discrimination task, however they did not measure the N170.

Based on Morgan et al.’s (2008) findings and our prior work (MacNamara et al., 2011a), we hypothesized that increased working memory load would attenuate N170 and LPP amplitudes. Moreover, we expected that working memory load would reduce eye gaze toward arousing picture regions (Glenberg et al., 1998), and that participants would avoid looking at the eye region of threatening facial stimuli (Hunnius et al., 2011). Exploratory analyses included an examination of the effect of emotion and working memory load on the number of fixations per trial and the trial scanpath length. Trial scanpath length refers to the total distance (in degrees of visual angle) traversed during the presentation of faces and therefore provides an index of the total extent of the gaze, irrespective of the number of fixations. Correlations were also performed between ERP and eye-tracking measures.

2. Method

2.1. Participants

Sixteen undergraduate students (7 female) participated in the study. The study was approved by the Stony Brook University Institutional Review Board (IRB) and participants received course credit.

2.2. Stimulus materials

Ten fearful (5 female) and 10 neutral faces (5 female) were selected from the NimStim database[1] (MacArthur Research Network on Early Experience and Brain Development, 2002). The same actors displayed both fearful and neutral expressions (i.e., 10 actors and 20 images in total). Faces were presented in color on a white background; they were centered on the monitor screen (which measured 34 cm × 27 cm) and filled the screen vertically; approximate viewing angle was 30° × 25°. Letter strings were the same as those used by MacNamara et al. (2011a); there were 60 2-consonant strings and 60 6-consonant strings (Ashcraft and Kirk, 2001).

2.3. Procedure

Participants were told that they would be performing a task that would involve memorizing letters. They were told that they would also see some pictures, which would be unrelated to their task, and that they should keep their eyes on the screen at all times. Each trial began with a drift check, during which time participants fixated on a black circle that was centrally presented against a white background, and pressed the space bar on the keyboard. In addition to recording any shift in eye position that had occurred since calibration (see Section 2.4 below), this also indicated that the participant was ready to begin the trial. Following the drift check, participants viewed 6 letters (high working memory load) or 2 letters (low working memory load) for 5000 ms. Following this, a black fixation cross was presented on a white background for 500–1000 ms. Next, participants viewed a neutral or fearful face for 2000 ms. After face offset, participants were asked to recall the letters presented at the beginning of the trial; they were told that they should enter the letters in the same order in which they had originally been presented. Participants made their responses using the keyboard, and were told that they could use the backspace key to correct any mistakes. To discourage participants from placing their fingers on the keyboard as a memory aid, participants were asked to enter their responses using only one finger (MacNamara et al., 2011a). The trial ended when participants pressed the 'enter' key. The inter-trial interval was set to vary randomly between 2000 and 2500 ms, during which time a black fixation cross was displayed on a white background. Each face was presented 3 times under high working memory load and 3 times under low working memory load. Therefore, there were 120 trials in total: 30 low-load neutral, 30 low-load fearful, 30 high-load neutral, and 30 high-load fearful. Trial order varied randomly for each participant. Prior to beginning the experiment, participants performed 4 practice trials to familiarize themselves with the procedure.

2.4. Data recording

Eye-movements were recorded using an Eyelink 1000 eyetracker operating in remote mode, with a sample rate of 500 Hz. The experiment began with a thirteen-point calibration routine used to map eye position to screen coordinates. Calibrations were not considered acceptable unless the average error was less than .49° and the maximum error was less than .99°. Participants were seated approximately 60 cm from the monitor. The eye-tracker was interfaced with a computer that stored eye-movement and behavioral data, controlled stimulus display (using Experiment Builder software, SR Research, Ltd.) and sent event codes to another computer that recorded and stored the EEG data. Default saccade settings were used to determine the number and duration of fixations made during picture presentation.

Continuous EEG was recorded using an elastic cap and a BioSemi Active Two system. Thirty-four sintered Ag/AgCl electrodes were used (standard 32-channel setup plus FCz and Iz), as well as one electrode on each of the left and right mastoids. The electrooculogram generated from eyeblinks and eye movements was recorded from four facial electrodes: vertical eye movements and blinks were measured with two electrodes placed approximately 1 cm above and below the right eye; horizontal eye movements were measured using two electrodes that were placed approximately 1 cm beyond the outer edge of each eye. The EEG signal was pre-amplified at the electrode to improve the signal-to-noise ratio. The data were digitized at 24-bit resolution with a Least Significant Bit (LSB) value of 31.25 nV and a sampling rate of 1024 Hz, using a low-pass fifth order sinc filter with a −3 dB cutoff point at 208 Hz. The voltage from each active electrode was referenced online with respect to a common mode sense (CMS) active electrode producing a monopolar (non-differential) channel.

2.5. Data analyses

2.5.1. Working memory performance

The percentage of trials on which participants correctly recalled the string of letters presented at the beginning of the trial was calculated separately for each condition. Only trials on which participants entered the letters in exactly the same order in which they had been presented at the beginning of the trial were considered correct.

2.5.2. Eye-movements

Offline, eye-movements that occurred during the presentation of faces were examined using DataViewer software (SR Research, Ltd.). Initial fixations lasting less than 200 ms were discarded (Salthouse and Ellis, 1980). Number of fixations and scanpath length were used to measure the extent to which participants visually explored the pictures. The eye region for each face was defined in line with the procedure used by Barton and colleagues (Barton et al., 2006). The percentage of fixations to the eye region was calculated relative to the total number of fixations made during picture presentation on a trial-by-trial basis. Percentages were then normalized to account for differences in the size of eye regions across faces (Dahl et al., 2009).[2] Therefore, positive numbers indicate that the eye region was fixated more than would be expected given a random looking strategy and negative numbers indicate that the eye region was fixated less than would be expected.

The order in which the eyes were fixated was also examined. Because participants made an average of 4.3 (*SD* = .83) fixations per trial, we calculated the cumulative probability of fixating the eyes by each of the 1st, 2nd, 3rd and 4th fixations[3]. Cumulative probabilities were normalized for the chance probability of fixating the eyes by a given fixation, assuming a random looking strategy. Any value above zero indicates that the eye region was fixated earlier than would be expected given a random looking strategy, and any number below zero indicates that the eyes were fixated later than would be expected given a random looking strategy.

2.5.3. EEG data

Off-line analyses of the EEG data were performed using Brain Vision Analyzer software (Brain Products, Gilching, Germany). Data were re-referenced offline to the average of all scalp electrodes and band-pass filtered with low and high cutoffs of 0.01 and 30 Hz, respectively. The EEG was segmented for each trial beginning 200 ms prior to picture onset and continuing for 1200 ms. Baseline-correction was performed for each trial using the 200 ms prior to picture onset. Eye blink and ocular correction of the EEG data was performed using the method developed by Gratton et al. (1983). Noisy data due to technical problems on isolated electrodes necessitated the removal of data from Iz in 2 participants and FC1 and FC2 in 1 participant. Artifact analysis identified voltage steps of 50.0 μV or greater between sample points, voltage differences of 100.0 μV or greater within a trial, and required a minimum voltage difference of at least .5 μV per 100 ms interval. An initial artifact rejection was also performed prior to ocular correction using the same criteria, however the maximum voltage permitted per trial was set more liberally to 300.0 μV.[4]

The N170 was scored using mean amplitudes from 130 to 180 ms at P7 and P8 (Rossion and Jacques, 2008; Su et al., 2011; Tanskanen et al., 2005). The LPP was scored at four centro-parietal sites where the LPP was maximal: CP1, CP2, Cz and Pz (MacNamara and Hajcak, 2009, 2010) from 400 to 1000 ms following picture onset (MacNamara et al., 2011a).

2.5.4. Statistics

Working memory performance and LPP amplitudes, number of fixations per trial, scanpath length and the percentage of fixations made to the eye region were evaluated using a 2 (working memory load: low, high) × 2 (emotion: neutral, fearful) repeated measures analysis of variance (ANOVA). For the N170, laterality (left, right) was also a factor in the ANOVA. The cumulative probability of fixating the eye region by each of the first four fixations was analyzed using a 2 (working memory load: low, high) × 2 (emotion: neutral, fearful) × 4 (fixation order: first, second, third, fourth) repeated measures ANOVA. Bonferroni corrections were performed for all follow-up *t*-tests and only significant results are reported. Correlations were performed to determine whether the effect of working memory load or emotion on one measure (e.g., percentage of fixations to the eye region) corresponded to effects on another measure (e.g., the LPP). Statistical analyses were performed using PASW (Version 18.0) General Linear Model software and *p* values were adjusted using Greenhouse–Geisser corrections as necessary.

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[1] All faces were open-mouthed. The faces used were: female, 06, 03, 10, 12 and 17; male, 28, 30, 34, 40 and 41. Practice faces were: female, 14 and 18; male, 37 and 39.

[2] For each trial, the percentage of fixations to the eye region was normalized by subtracting the percentage of area taken up by the eye region relative to the rest of the screen.

[3] Only data that corresponded to the maximum number of fixations made in a trial was included in the averages. In other words, if only 2 fixations were made in a given trial, this trial did not contribute data to the calculation of averages for the 3rd fixation onwards.

[4] When artifact rejection was semi-automated and performed only once (i.e., in line with MacNamara et al., 2011a), results were unchanged.

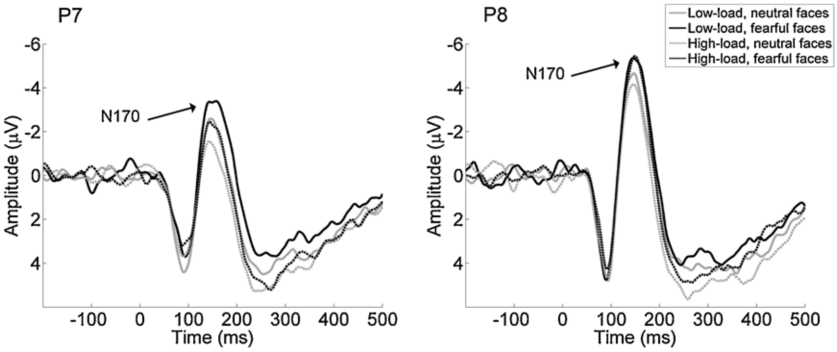

Fig. 1. Grand average ERP waveforms elicited by neutral and fearful faces presented under low and high working memory load, at parietal sites, P7 (left) and P8 (right). Low-load trials were those on which participants were asked to memorize 2 letters; high-load trials were those on which participants were asked to memorize 6 letters. On each trial, participants viewed a task-irrelevant picture of a fearful or neutral face for 2000 ms during the retention interval.

3. Results

3.1. Working memory performance

Table 1 presents the mean percentage of trials on which letter strings were recalled correctly, by condition. As expected, participants performed better on low-load compared to high-load working memory trials [$F(1,15) = 25.5$, $p < .001$, $\eta_p^2 = .63$]. There was no effect of emotion, and working memory load and emotion did not interact to affect performance (*ps* > .38).

3.2. ERPs

3.2.1. N170

Mean amplitudes of the N170 elicited by faces in each condition are presented in Table 1. Fig. 1 depicts grand average waveforms at left and right parietal sites (P7, left and P8, right) where the N170 was maximal. As is suggested by Fig. 1, the N170 was maximal at right hemispheric sites [$F(1,15) = 5.8$, $p < .05$, $\eta_p^2 = .28$]. In addition, fearful compared to neutral faces [$F(1,15) = 25.1$, $p < .01$, $\eta_p^2 = .63$] and faces presented under low compared to high working memory load [$F(1,15) = 5.8$, $p < .05$, $\eta_p^2 = .28$] elicited larger N170 amplitudes. Two- and three-way interactions did not reach significance (all *ps* > .17).

3.2.2. LPP

Table 1 presents LPP amplitudes elicited by fearful and neutral faces presented under low and high working memory load. Fig. 2 depicts grand average waveforms elicited by pictures at centroparietal sites where the LPP was maximal (left) and scalp distributions of voltage differences for fearful minus neutral faces from 400 to 1000 ms after picture onset (top right) and for faces presented under low compared to high working memory load (bottom right). As is suggested by Fig. 2, fearful compared to neutral pictures [$F(1,15) = 8.0$, $p < .01$, $\eta_p^2 = .42$] and faces presented on low-load compared to high-load trials [$F(1,15) = 17.2$, $p < .01$, $\eta_p^2 = .53$] elicited larger LPPs. Emotion and working memory did not interact to impact the LPP ($p > .31$).

3.3. Eye-movements

3.3.1. Number of fixations per trial

Table 2 presents the average number of fixations made in each trial. Participants made more fixations on low-load compared to high-load trials [$F(1,15) = 8.6$, $p < .05$, $\eta_p^2 = .36$]. The effect of emotion and the interaction between working memory load and emotion did not reach significance (*ps* > .07).

3.3.2. Scanpath length

Trial scanpath lengths are presented separately for each condition in Table 2. Participants engaged in more visual scanning when faces were neutral compared to fearful [$F(1,15) = 4.6$, $p < .05$, $\eta_p^2 = .24$] and when faces were presented under low compared to high working memory load [$F(1,15) = 13.7$, $p < .01$, $\eta_p^2 = .48$]. The interaction between working memory load and emotion did not reach significance ($p > .67$).

3.3.3. Percentage of fixations made to the eye region

Overall, participants allocated a significant percentage of fixations to the eye region of faces (the raw percentage was $M = 46.7\%$; $SD = 11.6$). Percentages for each condition were corrected for the size of the eye region relative to the rest of each image (see Section 2) and are presented separately in Table 2. Participants made more fixations to the eyes when faces were neutral compared to fearful [$F(1,15) = 20.8$, $p < .001$, $\eta_p^2 = .58$] and when faces were presented under high compared to low working memory load [$F(1,15) = 5.3$, $p < .05$, $\eta_p^2 = .26$]. The interaction between working memory load and emotion did not reach significance ($p > .21$).

3.3.4. Cumulative probability of fixating the eye region

To determine whether emotion and working memory load affected the order in which the eye region was fixated, the cumulative probability of fixating the eyes by each of the 1st, 2nd, 3rd and 4th fixations was calculated as a function of condition; these values are depicted in Fig. 3. Not surprisingly, participants were more likely to fixate the eye region as the number of fixations increased [$F(3,45) = 172.9$, $p < .0001$, $\eta_p^2 = .92$]. Participants were also more likely to fixate the eye region when faces were neutral compared to fearful [$F(1,15) = 7.4$, $p < .05$, $\eta_p^2 = .33$] and when faces were presented under high compared to low working memory load [$F(1,15) = 4.0$, $p = .06$, $\eta_p^2 = .21$]. Only one interaction reached significance: fixation order and working memory load [$F(3,45) = 6.8$, $p < .01$, $\eta_p^2 = .31$; all other *ps* > .22].

This interaction was followed up by paired *t*-tests performed separately for each of the first four fixations. Results revealed that participants were more likely to fixate the eyes on the 1st fixation when faces were presented under high compared to low working memory load [$t(15) = 3.0$, $p < .01$]. There was no effect of working memory load on the cumulative probability of fixating the eyes for subsequent fixations [using Bonferroni correction for 4 tests with a critical $p = .05/4 = .0125$, 2nd fixation: $t(15) = 2.3$, $p = .03$; 3rd fixation: $t(15) = .82$, $p = .42$; 4th fixation: $t(15) = .56$, $p = .58$]. Therefore, load effects on the probability of fixating the eye region seem to have been driven primarily by initial fixations, and were not significant for later fixations.

Table 1
Mean percentage of trials on which letters were recalled correctly (and standard deviations) as well as amplitudes corresponding to the N170 and LPP (and standard deviations) elicited by neutral and fearful faces presented under low and high working memory load.

	Accuracy (% correct)	N170 130–180 ms (μV)		LPP 400–1000 ms (μV)
		Left	Right	
Low-load, neutral faces	99.2 (1.5)	−1.9 (4.7)	−3.6 (4.9)	2.4 (1.3)
Low-load, fearful faces	98.5 (2.4)	−3.0 (3.8)	−4.6 (5.0)	3.4 (1.7)
High-load, neutral faces	74.4 (20.3)	−.88 (4.3)	−3.1 (5.3)	1.4 (2.2)
High-load, fearful faces	75.8 (20.5)	−1.8 (4.3)	−4.4 (4.6)	1.8 (1.7)

Table 2
Number of fixations per trial, scanpath length and percentage of fixations made to the eyes (and standard deviations) for neutral and fearful faces presented under low and high working memory load.

	Number of fixations per trial	Scanpath length (°) (visual angle)	Percentage of fixations to the eyes^2 (%)
Low-load, neutral faces	4.7 (1.0)	9.2 (4.4)	42.6 (12.4)
Low-load, fearful faces	4.4 (.93)	8.5 (3.7)	36.5 (11.9)
High-load, neutral faces	4.1 (.81)	7.1 (3.4)	46.0 (12.1)
High-load, fearful faces	4.1 (.87)	6.7 (3.1)	42.9 (14.3)

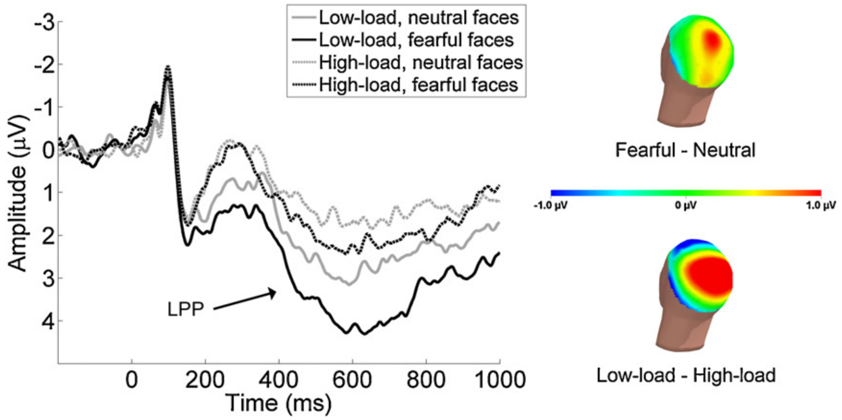

Fig. 2. Left: grand average ERP waveforms elicited by neutral and fearful faces presented under low and high working memory load, at centro-parietal pooling, CP1, CP2, Cz and Pz. Right: scalp topographies of the difference in amplitude between fearful and neutral faces, from 400 to 1000 ms after picture onset (right top) and for pictures presented on low-load compared to high-load trials, from 400 to 1000 ms after picture onset (right bottom).

3.4. *Correlations across measures*

Correlations were performed to determine whether ERP amplitudes covaried with the percentage of fixations to the eye region. Difference scores for fearful minus neutral faces, and low minus high working memory load, were calculated separately for each measure. Using these difference scores, bivariate correlations were performed between the percentage of fixations to the eye region and N170 and LPP amplitudes.[5] Correlations were also performed between the percentage of fixations to the eye region and the percentage of correct trials, as well as between ERP amplitudes and the percentage of correct trials; Bonferroni corrections were used for multiple comparisons. None of these correlations reached significance (all *ps* > .13).

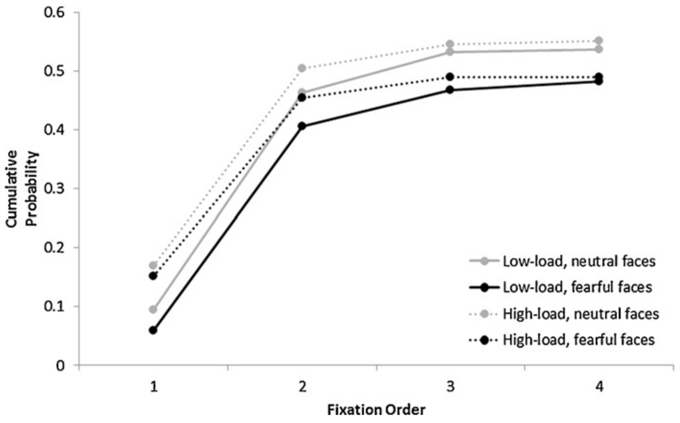

Fig. 3. The cumulative probability of fixating the eyes according to fixation order and condition. Probabilities were corrected according to the cumulative probability of fixating a region of the same size as the eye region; probabilities greater than 0 indicate that the eyes were more likely to be fixated than would be expected, given a random looking strategy.

4. Discussion

In line with past work, fearful compared to neutral faces elicited larger N170 amplitudes (Batty and Taylor, 2003; Blau et al., 2007; Foti et al., 2010), maximal at right temporoparietal sites (Joyce and Rossion, 2005). Fearful compared to neutral faces also elicited larger LPPs (Foti et al., 2010; Holmes et al., 2008; Mühlberger et al., 2009); as has been found previously, emotional modulation of the LPP appeared to begin early – by 300 ms after stimulus onset (e.g., Cuthbert et al., 2000; Hajcak et al., 2006; Hajcak and Nieuwenhuis, 2006; Moser et al., 2006). Replicating prior results, working memory load reduced the N170 (Morgan et al., 2008) and the LPP

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[5] Given that experimental effects did not interact with electrode site to affect the N170, difference scores were created by averaging amplitudes at P7 and P8.

(MacNamara et al., 2011a; Van Dillen and Derks, 2012) elicited by task-irrelevant pictures.

Morgan et al. (2008) examined the effect of working memory load on the N170 by varying the number of faces participants were asked to memorize before the presentation of a target face. Results showed that the N170 elicited by target faces was reduced when participants were asked to commit more faces to memory. Working memory load reductions in the N170 observed in the present study are in line with these findings – and, because the present study used letters instead of faces to vary working memory load, reductions in the N170 observed here cannot be attributed to *face-specific* capacity limits. Furthermore, the results indicate that even the structural encoding of faces is subject to modulation by higher-order cognitive processes (see also Holmes et al., 2003).

In regards to the later, more sustained processing of visual stimuli, recent work suggests that the LPP might reflect both bottom-up and top-down evaluations of stimulus salience (Hajcak et al., 2006; MacNamara et al., 2009, 2011b; Weinberg et al., 2012). Moreover, this work suggests that the PFC may play an important role in *boosting* the processing of salient stimuli (Moratti et al., 2011; Pessoa and Adolphs, 2010). One possibility, then, is that working memory load may have interfered with PFC-related evaluations of stimulus salience necessary for the sustained processing of emotional stimuli (Compton, 2003). In other words, working memory load may have consumed sufficient processing resources in the PFC so as to reduce the elaborated processing of salient stimuli, resulting in an attenuated LPP. More direct tests would be needed, however, to confirm this hypothesis.

To determine how working memory load and emotion affected visual attention toward task-irrelevant faces, the present study incorporated eye-tracking. In line with prior work, there was no difference between the number of fixations made to fearful compared to neutral faces (Hunnius et al., 2011). Scanpath lengths, however, were shorter for fearful compared to neutral faces, suggesting less exploration of threatening compared to non-threatening faces. Participants also looked at the eyes *less* when faces were fearful compared to neutral, suggesting avoidance of arousing regions. In a passive viewing task, Hunnius et al. (2011) similarly found that participants made fewer fixations to the eye region of fearful compared to neutral faces. Although Becker and Detweiler-Bedell (2009) did not examine fixations to the eye region, they found that participants avoided looking at fearful compared to neutral faces presented simultaneously in a passive viewing task. Therefore, healthy individuals may avoid looking at threatening faces when possible.

In contrast to this idea, evolutionary theories suggest that threatening stimuli should capture attention preferentially because the enhanced detection of these stimuli facilitates survival (e.g., LeDoux, 1996). In line with this notion, evidence from two eye-tracking studies has suggested that participants look at negative stimuli preferentially, even when they are instructed to *avoid* looking at these pictures (Calvo and Lang, 2004; Nummenmaa et al., 2006). It is worth noting, however, that both of these studies used complex emotional scenes (i.e., IAPS pictures; Lang et al., 2005), which may be more arousing than threatening faces used in the present study (Bradley et al., 2003). Thus, one possibility is that healthy individuals may attend preferentially to *highly* threatening stimuli yet avoid *mildly* threatening stimuli (Mogg and Bradley, 1998). A direct comparison of faces and IAPS pictures would be necessary to test this hypothesis – and although this has not been done using eye-tracking, behavioral evidence from the dot-probe task has supported this notion (Mogg et al., 2000).

In the present study, threatening stimuli did not interfere with working memory performance. This is in contrast to our prior work using the same task, which found that participants recalled fewer letters when they viewed unpleasant IAPS pictures during the retention interval (MacNamara et al., 2011a). As noted above, facial stimuli are less arousing than IAPS pictures (Bradley et al., 2003; Britton et al., 2006). Moreover, facial stimuli may consume fewer processing resources than IAPS pictures.[6] Additionally, compared to pictures in the MacNamara et al.'s (2011a) study, faces were repeated more often, which may have led to decreased arousal.

Because prior work suggests that fixation location is a strong modulator of the LPP (Dunning and Hajcak, 2009; Hajcak et al., in press) and that visual attention away from arousing picture regions might underlie emotion regulation effects observed using hemodynamic indices of picture processing (van Reekum et al., 2007), we sought to determine whether working memory load would affect eye gaze toward arousing picture regions. To this end, we examined fixations to task-irrelevant pictures during the retention interval. Results showed that overall, participants made fewer fixations when pictures were presented on high-load compared to low-load trials; in addition, scanpath lengths were shorter on high-load trials. Together, these results suggest less visual exploration of task-irrelevant stimuli presented under high-load and suggest that participants allocated fewer attentional resources toward these stimuli as task load increased. These results are in keeping with prior work which found that participants made less extensive saccades as the difficulty of an auditory counting task increased (May et al., 1990).

Importantly, results also showed that participants made more fixations to the eye-region of pictures that were presented under *high* compared to low working memory load. These results are in line with Lavie et al.'s (2004) suggestion that cognitive load should increase prepotent response tendencies – which may have included a tendency to look toward the eye region of faces (Henderson et al., 2005). Nevertheless, this effect was present primarily for initial fixations, and therefore may reflect a tendency for participants to be less accurate in fixating the center of the screen *prior* to each trial (i.e., before face onset), rather than a tendency for participants to gravitate toward arousing picture regions per se. In line with this notion, prior work suggests that cognitive load may increase errors on a tracking task (Strayer and Johnston, 2001).

Whereas the cumulative fixation analysis did not reveal a significant effect of working memory load beyond the first fixation, the trend in the data was identical across the first four fixations (as is suggested by the main effect of working memory load, Fig. 3). Overall, then, working memory load appeared to *increase* rather than *decrease* fixations to the eye region of pictures. As discussed previously, participants also allocated more fixations to the eye region of neutral compared to fearful faces. Therefore, the direction of effects appeared to differ for visual attention and ERPs; moreover, there were no significant correlations between ERPs and eye movements. As such, variation in the N170 and LPP *cannot* be attributed to where participants looked. Based on the current results, the most likely explanation for working memory load effects on these ERP components seems to be an interaction between bottom-up and top-down attention arising in fronto-parietal attention networks (Moratti et al., 2011; Pessoa and Adolphs, 2010). Nevertheless, future work will be necessary to rule out other potential mechanisms and to further explicate the relationship between the DLPFC and the electrocortical processing of emotional stimuli.

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[6] A comparison of the magnitude of the LPP in the present and prior work (MacNamara et al., 2011a) suggests that this is the case. That is, LPP difference scores elicited by IAPS in the MacNamara et al. (2011a) study were larger than those elicited by faces in the present study: unpleasant minus neutral IAPS, $M = 4.4\ \mu V$, $SD = 2.9$; fearful minus neutral faces, $M = .71\ \mu V$, $SD = .85$.

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