

# An unpleasant emotional state reduces working memory capacity: electrophysiological evidence

Jessica S. B. Figueira,<sup>1</sup> Leticia Oliveira,<sup>1</sup> Mirtes G. Pereira,<sup>1</sup> Luiza B. Pacheco,<sup>1</sup> Isabela Lobo,<sup>1,2</sup> Gabriel C. Motta-Ribeiro,<sup>3</sup> and Isabel A. David<sup>1</sup>

<sup>1</sup>Laboratório de Neurofisiologia do Comportamento, Departamento de Fisiologia e Farmacologia, Instituto Biomédico, Universidade Federal Fluminense, Niterói, Brazil, <sup>2</sup>MograbiLab, Departamento de Psicologia, Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro, Brazil, and <sup>3</sup>Laboratório de Engenharia Pulmonar, Programa de Engenharia Biomédica, COPPE, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

Correspondence should be addressed to Isabel A. David, Departamento de Fisiologia e Farmacologia, Instituto Biomédico, Universidade Federal Fluminense, Rua Hernani Pires de Mello, 101, Niterói, RJ 24210-130, Brazil. E-mail: isabeldavid@id.uff.br.

## Abstract

Emotional states can guide the actions and decisions we make in our everyday life through their influence on cognitive processes such as working memory (WM). We investigated the long-lasting interference that an unpleasant emotional state had on goal-relevant WM representations from an electrophysiological perspective. Participants performed a change detection task that was preceded by the presentation of unpleasant or neutral task-irrelevant pictures in a blocked fashion. We focused on the contralateral delay activity (CDA), an event-related potential that is sensitive to the number of task-relevant items stored in WM. We found that the asymptotic limit for the CDA amplitude was lower during the unpleasant emotional state than during the neutral one; that is, an emotional state was capable of reducing how many task-relevant items the participants could hold in WM. Furthermore, both the individuals who experienced more intrusive thoughts and those who were dispositionally anxious were more susceptible to the influence of the emotional state. We provide evidence that an unpleasant emotional state diminished visual WM for task-relevant items, particularly in susceptible individuals. These results open new avenues to uncover the emotional-cognitive processing that underlies maladaptive WM representations and the role of such processing in the development of mental illness.

**Key words:** anxiety; event-related potential; emotional state; negative emotions; working memory

## Introduction

Many studies have suggested that the processing of emotion-laden stimuli is prioritized because of the relevance of such stimuli to survival (Öhman *et al.*, 2001; Vuilleumier and Schwartz, 2001; Anderson *et al.*, 2003; Oliveira *et al.*, 2013; Deweese *et al.*, 2016; Shackman *et al.*, 2016). Emotional stimuli can influence cognition through beneficial or detrimental effects (e.g. enhanced processing of goal-relevant emotional stimuli or increased distraction due to goal-irrelevant emotional stimuli) (Dolcos and McCarthy, 2006; MacNamara *et al.*, 2011;

van Dillen and Derks, 2012; Luo *et al.*, 2014; Uher *et al.*, 2014). Previous studies that applied various cognitive tasks have suggested that the processing of task-relevant stimuli is impaired when emotional distracters are presented before (Pereira *et al.*, 2006, 2010) or during the task (Vuilleumier and Schwartz, 2001; Erthal *et al.*, 2005; Fernandes *et al.*, 2013). Nonetheless, understanding the detrimental effects of emotional states on cognitive processes is still a topic of great interest.

Working memory (WM) is an example of a cognitive process that is related to our everyday life experience. One of the

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functions of WM is to temporarily keep goal-relevant information in mind, ready to be manipulated or used, while irrelevant information is kept out of mind (Goldman-Rakic, 1996; Cowan, 2001; Baddeley, 2012). Although evidence suggests that we can maintain representations of three to four items at a time in WM (Luck and Vogel, 1997; Cowan, 2001), this limit varies across individuals (Todd and Marois, 2005; Vogel et al., 2005).

A well-validated electrophysiological correlate of the maintenance of representations in WM is called contralateral delay activity (CDA) (Vogel and Machizawa, 2004; Luria et al., 2016). In a bilateral version of the change detection task, CDA can be measured as a slow wave extracted from parietal and occipital electrode sites during a retention interval (Vogel and Machizawa, 2004). In this task, volunteers must maintain a pre-cued memory array of visual stimuli in WM during a short retention interval. After the retention interval, a test array is presented and the participants are required to answer whether the test array is identical to or different from the previous memory array. The CDA is the difference between the contralateral and ipsilateral slow potentials evoked in response to the to-be-remembered array (Vogel and Machizawa, 2004). An important feature regarding the CDA's amplitude is its relationship with the amount of items held in WM. The CDA amplitude increases as the number of items in the to-be-remembered array increases but reaches an asymptote at three to four items. As demonstrated by several studies, this change in amplitude is not due to the overall task difficulty and is instead due to the WM capacity (Vogel and Machizawa, 2004; Luck and Vogel, 2013; Luria et al., 2016).

Prior research on the interaction between CDA and emotion has focused on emotional faces stimuli (Sessa et al., 2012; Stout et al., 2013; Meconi et al., 2014). The influence of the emotional stimulus-driven effect on WM has also been described in terms of behavioural measures. For example, Lindström and Bohlin (2012) showed that threat stimuli (snake and spider) impaired WM performance by causing prolonged response times to WM items. In fact, emotional stimuli can undermine an individual's ability to ignore irrelevant information while maintaining task-relevant information (Vuilleumier and Schwartz, 2001; Dolcos and McCarthy, 2006).

An important distinction should be made between stimulus-driven and state-dependent emotional effects on WM. In the latter, a sustained affective state (e.g. mood, anxiety) is induced by presenting very unpleasant images, music, movies, or a mild electric shock prior to the performance of a task (Shackman et al., 2006, 2011; van Dillen and Koole, 2007; Joormann and Gotlib, 2008; Robinson et al., 2013; Vytal et al., 2013; Morgan and D'Mello, 2016). Additionally, a sustained unpleasant state can be induced by presenting unpleasant stimuli in a blocked fashion. This method usually produces enhanced and sustained emotional interference (Bradley et al., 1996; Sutton et al., 1997; Smith et al., 2005; Pereira et al., 2006, 2010). In our everyday life, it is common to experience sustained emotional states. Unavoidably, daily unpleasant events, such as discontent with work, watching a sad movie, visiting someone in the hospital or even being stuck in a traffic jam, may have long-term emotional consequences that can affect the rest of the day or even longer. In this vein, sustained unpleasant states influence the actions and decisions we make during our everyday life experiences. Intense unpleasant states tend to be experienced more by dispositionally negative individuals, which increases the possibility of physical and mental health problems (for review see Shackman et al., 2016).

Despite the importance of sustained unpleasant states in everyday life, the influence of negative mood on WM using the CDA as a neurophysiological index has not been explored. In the present work, we investigated whether a sustained unpleasant state influences WM capacity, as indexed by the CDA, in healthy participants. We presented very unpleasant distracter images in a blocked fashion before the memory array to capture the effects of long-lasting emotional interference on the subsequent task. We predicted that during a sustained unpleasant state, WM capacity would be impaired. Specifically, we expected a lower asymptotic limit for the CDA during the unpleasant emotional state compared to during the neutral state. Notably, to the best of our knowledge, the present study is the first to investigate how unpleasant emotional states influence WM capacity, as indexed by CDA.

Additionally, we investigated if this effect would be magnified in individuals with high anxiety or in those who experience intrusive thoughts more often. A recent meta-analysis showed that measures of anxiety are related to lower scores on measures of WM capacity (Moran, 2016). Anxiety should enhance the negative effect of a sustained unpleasant state on WM capacity, considering that anxiety can occupy WM (Shackman et al., 2006; Moriya and Sugiura, 2012; Meconi et al., 2014; Qi et al., 2014). Difficulties with ignoring irrelevant unpleasant information in WM have also been associated with intrusive thoughts, worry, rumination and depression, which are symptoms or comorbidities of anxiety (Joormann and Gotlib, 2008; Stout et al., 2015).

## Materials and methods

### Participants

Thirty-three right-handed (according to Oldfield, 1971) undergraduate students at Fluminense Federal University participated in this study. Two students were excluded due to their production of extremely noisy data, another two for excessive behavioural errors (>25%), and three for extensive eye movements. The final sample consisted of 26 volunteers [18 women, age:  $M = 22.24$ ,  $SD = 5.51$  years] who reported no psychiatric or neurological problems and were free of any central nervous system drugs. The participants were naive to the purpose of the experiment. All participants reported normal colour vision and normal or corrected-to-normal visual acuity. The Research Ethics Committee of Fluminense Federal University approved the experiment, and all participants gave informed consent before any experimental procedure was conducted.

### Apparatus and stimuli

The experiment was conducted in a sound-attenuated room under dim ambient light. Eprime v2.0 software (E-Prime® software-Psychology Software Tools Inc., Pittsburgh, PA, USA) was used to control stimulus timing and presentation as well as for the collection of responses. The participants positioned themselves on a head-and-chin rest 47 cm from the screen.

One hundred-twenty pictures ( $20^\circ \times 16^\circ$ ) that were equally distributed across two categories were used to create a neutral (intact bodies) or an unpleasant (mutilated bodies) emotional state. Thirty-six (16 neutral and 20 unpleasant) pictures were taken from the International Affective Picture System (IAPS) (Lang et al., 2008), and the remaining images were obtained from the worldwide web. Following the protocol developed by Lang and colleagues (Lang and Greenwald, 1988; Lang et al., 2008), all of the images were previously assessed on a 1–9 scale

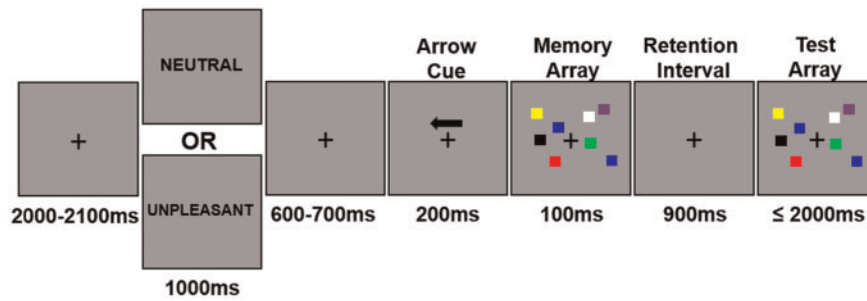


Fig. 1. Example of the sequential order of events in a trial. Neutral or unpleasant pictures were presented in a blocked manner. After the picture offset, the participants were cued to remember the colour of the squares in the left or the right hemifield of the screen according to the direction of the arrow. After a retention interval, the participants made a forced-choice comparison response. The figure depicts a memory array for the 4 squares condition in which the colour of the squares in the left hemifield (as indicated by the arrow) should be remembered. The test array depicts a no-change trial.

in terms of valence (from negative to positive) and arousal (from low to high) by a different group of graduate students. Overall, the neutral and unpleasant pictures differed significantly from each other with respect to both valence ( $M = 5.06$ ,  $SD = .42$  and  $M = 2.08$ ,  $SD = .52$ , respectively,  $t(59) = 35.06$ ;  $P < 0.01$ ) and arousal ( $M = 3.29$ ,  $SD = 0.48$  and  $6.89$ ,  $SD = 0.49$ , respectively,  $t(59) = -41.41$ ;  $P < 0.01$ ) ratings. The neutral and unpleasant pictures did not differ with regard to brightness ( $t(59) = -0.54$ ;  $P = 0.60$ ), contrast ( $t(59) = -0.32$ ;  $P = 0.27$ ), or spatial frequency ( $t(59) = -0.19$ ;  $P = 0.84$ ), according to the procedure described by Bradley et al. (2007).

In the change detection task described by Vogel and Machizawa (2004), the stimulus arrays were composed of coloured squares ( $1.2^\circ \times 1.2^\circ$  of visual angle). We used seven colours: red (RGB values: 255, 0, 0), green (0, 255, 0), yellow (255, 255, 0), blue (0, 0, 255), white (255, 255, 255), black (0, 0, 0) and purple (72, 61, 139). The coloured squares were presented within two  $7^\circ \times 8.5^\circ$  regions that were displaced  $5.5^\circ$  to the left and right of a central fixation cross presented on a grey background (60, 60, 50). A central arrow cue that appeared  $2^\circ$  above the fixation cross instructed the participants to remember the items in either the left or the right hemifield. The position of the squares inside the bilateral regions was randomized on each trial, and the within-hemifield distance between them was at least  $2.5^\circ$  (centre to centre).

There were two sequential bilateral stimulus arrays: the memory array and the test array. Each array consisted of 2 or 4 coloured squares ( $1.2^\circ \times 1.2^\circ$ ) in each hemifield. The same colour did not appear more than once per hemifield. The colour of one square in the memory array differed from the corresponding item in the test array in 50% of trials; on the remaining trials, the colours of both were identical. Only the colour of squares positioned in the precued hemifield changed.

## Design and procedure

The experimental session began with a practice block composed of a set of 30 neutral pictures of objects from the IAPS (Lang et al., 2008) with trial-to-trial feedback. This practice block was not included in the analysis. Following this block, there were four test blocks of sixty trials each. There was a brief interval (3 to 5 min) between blocks. Emotional stimuli were presented in a blocked manner; two neutral blocks (with 60 trials each) and two emotional blocks (with 60 trials each) were presented to induce a sustained modulatory effect of emotional picture viewing (Pereira et al., 2006). Block order was counterbalanced between volunteers with respect to emotional state. The sequence of events for each trial is illustrated in Figure 1. Every

trial was initiated by the presentation of a fixation cross on a grey background, and the volunteers were instructed not to deviate from fixation throughout the whole trial. Approximately, 2000 to 2100 ms afterwards, a neutral or unpleasant picture was presented for 1000 ms.

The change detection task began approximately 600 to 700 ms after the offset of the picture. An arrow cue was presented above the fixation cross for 200 ms; the arrow pointed to the left in 50% of the trials and to the right in 50% of the trials. The volunteers were required to pay attention to the hemifield cued by the arrow without deviating their eyes from the fixation cross. Next, the memory array was displayed on the screen for 100 ms, followed by a 900 ms retention interval. The test array then appeared, and the volunteers had to indicate whether a square changed colour by pressing one of two buttons (Choice Reaction Time).

At the end of the session, the electrodes were removed and the participants completed the State-Trait Anxiety Inventory (STAI-T) (Biaggio et al., 1977; Spielberger et al., 1983) and the Thought Control Ability Questionnaire (TCAQ) (Luciano et al., 2005). The total duration of the experiment was approximately 2 h.

## EEG recording and pre-processing

The electroencephalogram (EEG) was recorded at 64 scalp sites using active electrodes placed on an elastic cap (BrainProducts, München, Germany) according to the International 10–20 System. Saccadic eye movements were monitored using a bipolar horizontal electrooculogram (HEOG) recorded from the outer canthi of both eyes.

The EEG data were recorded (PyCorder 1.0.2) at 500 Hz, referenced to the Cz electrode, and grounded at Fpz. The impedance of all electrodes was kept below  $20 \text{ k}\Omega$ . BrainVision Analyzer 2.0 software (BrainProducts, München, Germany) was used to complete the offline pre-processing steps. The data were re-referenced to the average of the mastoid electrodes (Vogel et al., 1998; Vogel and Machizawa, 2004) and filtered using a 0.01 Hz high-pass filter and a 30 Hz low-pass filter (roll-off of 12 dB/octave).

We removed eye blink components from the data using independent component analysis (ICA) available in BrainVision Analyzer 2.0 software. These components were excluded from the data only after visual inspection of topographical maps demonstrating their proximity to the ocular area and of their resemblance to established waveform characteristics (Jung et al., 2000).

The epoch was set to 1200 ms, beginning 200 ms prior to the onset of the arrow cue and ending 1000 ms later. Following

artefact rejection, the EEG waveforms were averaged, taking into account the different conditions. The CDA was computed by subtracting the ipsilateral activity from the contralateral activity of analogous electrodes as a function of the cue direction. We obtained a measure of CDA for the two- and four-square arrays for both the neutral and unpleasant emotional states, which resulted in four CDA waveforms for each pair of electrode sites.

Segments containing horizontal eye movements, as well as incorrect trials, were excluded from further analysis. The baseline corresponded to the 200 ms period preceding the onset of the arrow cue. Epochs containing deviations larger than 100  $\mu$ V were rejected. The epoch rejection rate per subject did not exceed 20%. The mean peak amplitude of the parietal and occipital (P3/P4, O1/O2) electrode pairs (Vogel and Machizawa, 2004) was computed over a 500–1000 ms time window.

## Statistical analysis

### Behavioural analysis

**Error.** Incorrect responses included anticipation (reaction time (RT) < 150 ms), slow responses (RT > 2000 ms), and incorrect key-press responses. The total number of incorrect responses was submitted to a repeated-measures analysis of variance (ANOVA) that included the factors number of squares (2 vs 4 squares) and emotional state (neutral vs unpleasant).

**Formula K.** We estimated visual memory capacity for each set size using Pashler's formula:  $K = Sx(H-FA)/(1-FA)$  (Pashler, 1988), where  $K$  corresponds to the number of items maintained in visual WM,  $S$  is the size of the array (2 or 4 coloured squares),  $H$  is the hit rate and  $FA$  is the false alarm rate. We used Pashler's  $K$  because it was developed for whole-display probes such as those used in the change detection task (Rouder et al., 2011).

To determine whether the  $K$  value increased with a larger number of squares, the  $K$  values estimated for the different numbers of squares (2 vs 4) were compared. We also compared the highest  $K$  value derived from any of the set sizes between the unpleasant and neutral blocks. We used the highest  $K$  value across the set sizes to better capture the participant's visual WM capacity (Diamantopoulou et al., 2011; Kundu et al., 2013). For both comparisons, we applied the Wilcoxon matched pairs test because the data presented a non-normal distribution as assessed by the Shapiro-Wilks  $W$ -test.

### EEG data

The mean peak CDA amplitudes for correct responses were submitted to repeated-measures ANOVA with the following within-subject factors: site (P3/P4 vs O1/O2), number of squares (2 vs 4) and emotional state (neutral vs unpleasant). The Newman-Keuls procedure was used to test for post hoc differences when necessary. Because the CDA is a negative wave, the data were multiplied by  $(-1)$  to obtain positive values for better visualization.

To investigate the  $K$ -CDA relationship, we conducted Spearman's rank correlations between the individual's WM capacity  $K$ -estimate and the increase in the CDA amplitude between the 2 and 4 squares conditions during the unpleasant and neutral emotional states.

We also correlated the individual's WM capacity  $K$ -estimate obtained during the neutral emotional state with the increase

in the CDA amplitude between the 2 and 4 squares conditions during the unpleasant emotional state. This analysis was conducted to assess whether individual differences in WM capacity in the absence of stress moderate the impact of unpleasant emotion on the increase in CDA amplitude between the 2 and 4 squares conditions (Beilock and Carr, 2005).

### Anxiety and intrusive thoughts measures

Anxiety was assessed using the STAI-T (Biaggio et al., 1977; Spielberger et al., 1983). Additionally, we specifically investigated the ability to control intrusive thoughts using the TCAQ (Luciano et al., 2005).

Because the CDA data showed a normal distribution as assessed by the Shapiro-Wilks  $W$ -test, we conducted Pearson's correlations to investigate the association between the increase in the CDA amplitude between the 2 and 4 squares conditions in the different emotional states (neutral and unpleasant) and the STAI-T and TCAQ scores. Because the CDA has a negative amplitude, the values of delta 4–2 are negative; therefore, the data were multiplied by  $(-1)$ . Accordingly, larger values represent a higher increase in the CDA amplitude between the 2 and 4 squares conditions.

We also conducted Spearman's rank correlations between these measures and the estimated WM capacity  $K$  for each emotional state.

### Emotional state manipulation check

The induced emotional state was measured in a separate behavioural experiment by applying the task previously described for the EEG data collection. First, the participants ( $n = 20$ ) completed a pre-induction emotional state questionnaire (Watson et al., 1988; de Carvalho et al., 2013). Then, they performed the Change Detection task (Vogel and Machizawa, 2004) preceded by viewing unpleasant or neutral images in a blocked fashion. To ascertain that the blocked design induced a sustained emotional state, the participants completed the Positive and Negative Affect Schedule (PANAS) (Watson et al., 1988; de Carvalho et al., 2013) immediately after the unpleasant and neutral blocks (post-induction questionnaire). The order of the blocks was counterbalanced across the participants with respect to the emotional state.

## Results

### Behavioural analysis

**Error.** The interaction between the factors number of squares and emotional state did not approach significance,  $F(1,25) = 1.01$ ,  $P = 0.32$ . The main effect of number of squares approached significance,  $F(1,25) = 204.60$ ,  $P < 0.01$ . The participants committed more errors during the 4 squares condition ( $M = 30.62$ ,  $SD = 7.84$ ) than during the 2 squares condition ( $M = 7.64$ ,  $SD = 7.88$ ). The main effect of emotional state did not approach significance,  $F(1,25) = 0.14$ ,  $P = 0.71$ . The number of errors committed during the unpleasant emotional state condition ( $M = 20.27$ ,  $SD = 10.78$ ) did not differ from the number committed during the neutral emotional state condition ( $M = 18.00$ ,  $SD = 6.32$ ).

**Formula K.** As expected, Pashler's  $K$  for the 4 squares condition ( $M = 2.28$ ,  $SD = .51$ ) was larger than that for the 2 squares condition ( $M = 1.86$ ,  $SD = 0.17$ )  $Z = 3.14$ ;  $P < 0.01$ . This result is consistent with previous findings (Vogel and Machizawa, 2004; Vogel



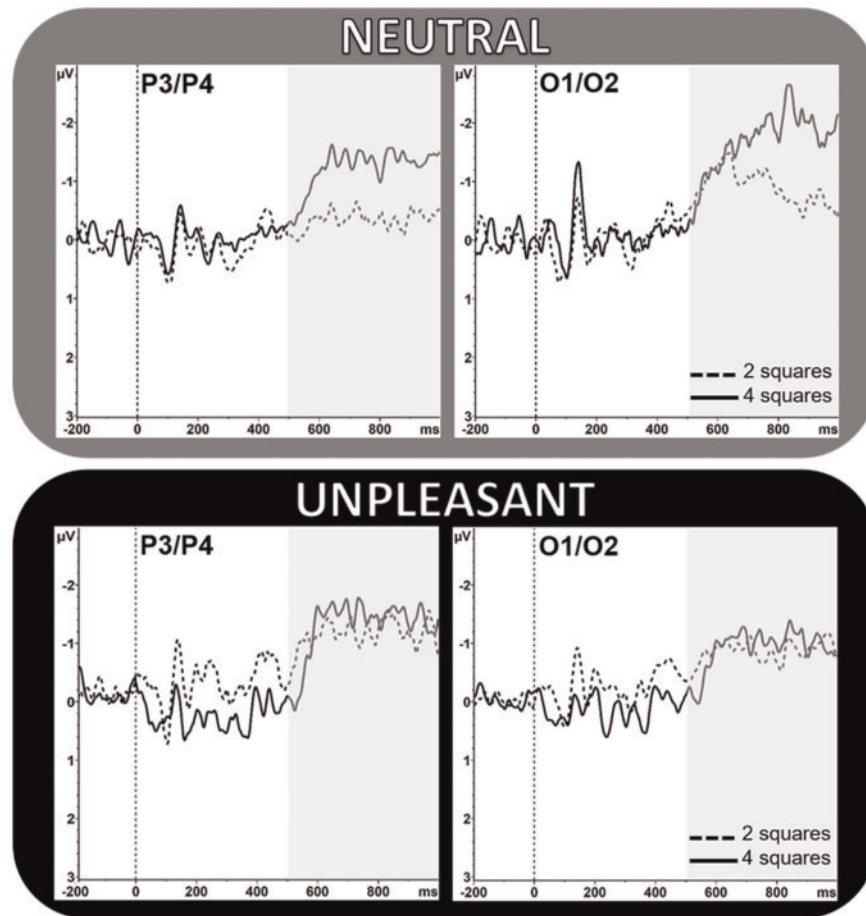


Fig. 2. Contralateral delay activity (CDA) waveforms on parietal and occipital (P3/P4 and O1/O2) electrode pairs upon presentation of the change detection task during the neutral (top, grey contour) and unpleasant (bottom, black contour) emotional states. Note that potentials are plotted with negative voltages upward, corresponding to an increase in CDA amplitude. The figure depicts the increase in CDA amplitude from 2 (dashed lines) to 4 (filled lines) to-be-remembered items. The CDA was measured in the 500–1000 ms time window after the onset of the arrow (grey shaded rectangle).

et al., 2005; Qi et al., 2014). The difference between the K-estimates during the neutral ( $M = 2.43$ ,  $SD = 0.56$ ) and the unpleasant ( $M = 2.30$ ,  $SD = 0.55$ ) emotional states was not significant,  $Z = 0.11$ ;  $P = 0.91$ .

### EEG data

We looked at the CDA, which is an electrophysiological index of the representations actively maintained in visual WM (Vogel and Machizawa, 2004), to test our hypothesis that an unpleasant emotional state can modulate WM capacity.

The repeated-measures ANOVA revealed a significant interaction effect between the number of squares and the emotional state,  $F(1,25) = 5.96$ ,  $P < 0.02$ . The main effect of the number of squares was also significant,  $F(1,25) = 5.30$ ,  $P < 0.03$ ; however, the main effects of the emotional state and site did not approach significance,  $F(1,25) = 0.19$ ,  $P = 0.67$  and  $F(1,25) = 2.28$ ,  $P = 0.14$ , respectively.

To better understand the differences in CDA for each emotional state (Figure 2), post hoc tests were conducted. For the unpleasant emotional state, the CDA amplitude did not differ between the 2 ( $M = -0.91$ ,  $SD = 1.05$ ) and 4 ( $M = -0.99$ ,  $SD = 1.36$ ) squares ( $P = 0.69$ ) conditions, which showed that an unpleasant emotional state can affect the usual CDA increase that occurs from 2 to 4 squares (Vogel and Machizawa, 2004; Vogel et al.,

2005; Qi et al., 2014). As expected, for the neutral emotional state, the CDA amplitude increased from the 2 ( $M = -0.62$ ,  $SD = 0.97$ ) to 4 ( $M = -1.44$ ,  $SD = 0.93$ ) squares conditions,  $P < 0.01$ . The CDA amplitudes for the unpleasant and neutral emotional states did not differ during the 2 squares condition,  $P = 0.18$ . During the 4 squares condition, the difference in the CDA amplitude between the emotional states was significant,  $P < 0.05$  (see Figure 3). It is important to highlight that the number of usable epochs did not differ across the neutral emotional state ( $M = 93.35$ ,  $SD = 7.05$ ) and the unpleasant emotional state ( $M = 90.38$ ,  $SD = 9.36$ ),  $t(25) = -1.27$ ,  $P = 0.21$ .

The correlations between the individual's WM capacity K-estimate and the increase in the CDA amplitude between the 2 and 4 squares conditions was not significant during the unpleasant ( $\rho = 0.12$ ,  $P = 0.55$ ) and neutral ( $\rho = -0.07$ ,  $P = 0.73$ ) emotional states. The correlation between the individual's WM capacity K-estimate during the neutral emotional state and the increase in the CDA amplitude between the 2 and 4 squares conditions during the unpleasant emotional state was also not significant ( $\rho = -0.19$ ,  $P = 0.33$ ).

### Anxiety and intrusive thoughts measures

During the unpleasant emotional state, there was a correlation between the trait of anxiety (STAI-T) and the CDA amplitude

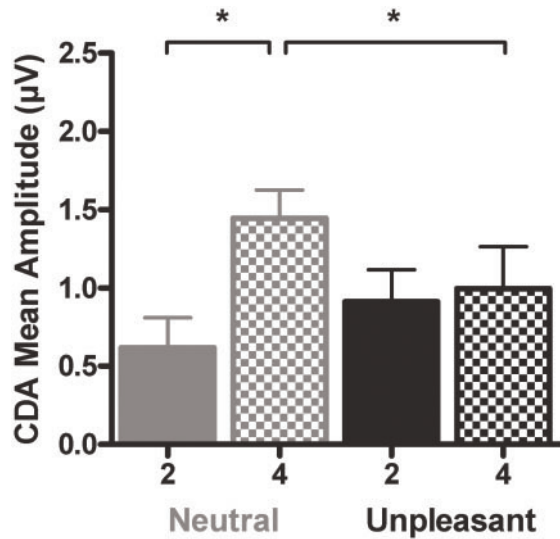


Fig. 3. Effect of the emotional state (neutral and unpleasant) on the mean CDA amplitude ( $\mu\text{V}$ ) when the participants were required to remember 2 or 4 squares. The increase in CDA amplitude between 2 and 4 squares only occurred during the neutral emotional state. The mean CDA amplitude during the neutral and unpleasant emotional states differed when the participants were required to remember 4 coloured squares. The error bars indicate the standard error of the mean. Asterisks indicate significant differences ( $P < 0.05$ ).

increase from 2 to 4 squares,  $r = -0.57$ ,  $P < 0.01$ . During the neutral emotional state, this correlation was not significant,  $r = -0.07$ ,  $P = 0.75$  (Figure 4). In other words, the higher the volunteers' measure of anxiety, the lower the WM capacity in face of an unpleasant emotional state.

During the unpleasant emotional state, the lower the ability to control intrusive thoughts, as revealed by the TCAQ score, the lower the WM capacity (Figure 5),  $r = 0.45$ ,  $P < 0.05$ . This correlation did not reach significance for the neutral emotional state,  $r = 0.06$ ,  $P = 0.77$ .

The correlation between the trait of anxiety and the WM capacity K-estimate did not reach significance for the neutral emotional state ( $\rho = -0.11$ ,  $P = 0.61$ ) or for the unpleasant emotional state ( $\rho = -0.18$ ,  $P = 0.37$ ). Likewise, the correlation between the TCAQ scores and the WM capacity K-estimate did not reach significance for both the neutral ( $\rho = 0.27$ ,  $P = 0.18$ ) and unpleasant ( $\rho = -0.06$ ,  $P = 0.77$ ) emotional states.

### Emotional state manipulation check

Given that the data did not show a normal distribution as assessed by the Shapiro-Wilks  $W$ -test, we conducted the Wilcoxon matched pairs test for the analysis. Post-induction negative affect was significantly greater after the unpleasant block ( $M = 15.6$ ,  $SD = 4.80$ ) than after the neutral block ( $M = 13.6$ ,  $SD = 4.21$ ),  $Z = 2.92$ ;  $P < 0.01$ . After the subtraction of the pre-induction negative affect ratings, the difference in the ratings after the neutral ( $M = -3.65$ ,  $SD = 5.03$ ) and unpleasant blocks ( $M = -1.60$ ,  $SD = 5.27$ ) remained significant ( $Z = 2.92$ ,  $P < 0.01$ ). The post-induction positive affect after the unpleasant block ( $M = 28.80$ ,  $SD = 6.69$ ) and neutral block ( $M = 28.15$ ,  $DP = 6.23$ ) did not differ,  $Z = 0.57$ ;  $P = 0.57$ .

### Discussion

We used the CDA, an electrophysiological index of the representation of items maintained in WM, to assess if an unpleasant

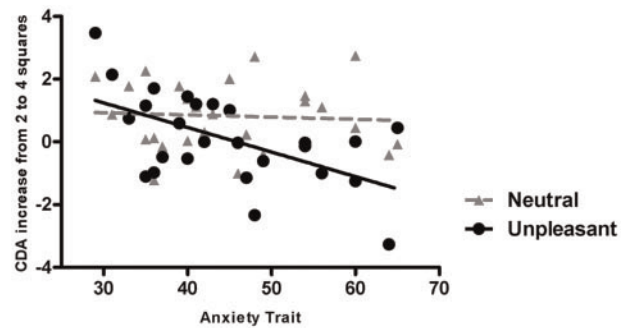


Fig. 4. Correlation between the participants' CDA mean amplitude ( $\mu\text{V}$ ) increase from 2 to 4 coloured squares and the anxiety trait scores during the unpleasant (black filled line and circles) and neutral (grey dashed lines and triangles) emotional states.

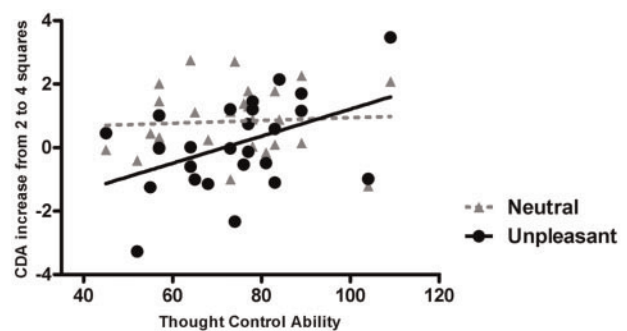


Fig. 5. Correlation between individual participants' working memory capacity (CDA mean amplitude ( $\mu\text{V}$ ) increase from 2 to 4 coloured squares) and scores of the ability to control intrusive thoughts during the unpleasant (black filled line and circles) and neutral (grey dashed lines and triangles) emotional states.

emotional state would disrupt the efficiency of the maintenance of goal-relevant information in WM. During the neutral emotional state, the participants were capable of holding 4 coloured squares in WM. However, during the unpleasant emotional state, the CDA amplitude became asymptotic for only 2 coloured squares, indicating that the expected increase in CDA amplitude from 2 to 4 was disrupted when an unpleasant emotional state was induced. Remarkably, the participants were unable to minimize the intrusive effect of the unpleasant stimuli even though the unpleasant stimuli were presented several milliseconds before the WM task, suggesting a long-lasting effect of emotional state. In addition, presenting the picture separately from the memory array enabled exactly the same experimental array to be compared between both the unpleasant and neutral emotional states. Employing this experimental design eliminated any confound of CDA activity produced by physical differences in the memory array.

In addition, the unpleasant emotional state differentially affected the participants. High-anxiety trait participants and those who experienced more intrusive thoughts were more affected. The greater the anxiety trait scores and the lower the ability to control intrusive thoughts, the smaller the CDA amplitude increased in response to an increase in the number of squares to be held in WM during the unpleasant emotional state, suggesting a reduction in WM capacity. Taken together, the present results provide new evidence that WM capacity is limited by an unpleasant emotional state and that high levels of anxiety and a lower ability to control intrusive thoughts are

associated with greater WM impairment during an unpleasant state.

Studies have shown that the unnecessary storage of unpleasant distracters may reduce the representation of task-relevant information, indicating competition for the limited representation capacity. For instance, Stout *et al.* (2013) adapted the change detection task described by Vogel and Machizawa (2004) by substituting the to-be-remembered coloured squares with emotionally neutral or threat-related faces. The participants were asked to retain one or more faces while ignoring others. The mean CDA amplitude for the trials that contained one to-be-remembered neutral face was smaller than that for the trials that contained one to-be-remembered neutral face and one to-be-ignored threat-related face. That is, an emotional stimulus that was irrelevant to the main task occupied the WM, and this occupation was reflected in the CDA amplitude.

Along the same vein, a previous neuroimaging study showed that WM performance could be impaired in the presence of emotional distracters (Dolcos and McCarthy, 2006). This impairment was associated with disrupted activity in brain regions responsible for the active maintenance of goal-relevant information in WM. Interestingly, the studies described above showed concomitant competition for representation in WM because the emotional stimulus was presented in a randomized manner during the experimental session. However, emotion-cognition interaction has also been investigated across longer timescales in studies that induced a sustained emotional state (Bradley *et al.*, 1996; Smith *et al.*, 2005; Pereira *et al.*, 2006; Brouwer *et al.*, 2013; Ben-Haim *et al.*, 2014), and this approach may be related to enhanced modulation of cognitive control by emotional stimuli (Cohen *et al.*, 2016).

Cohen *et al.* (2016) showed that sustained, but not transient, positive and unpleasant emotional states are associated with changes in performance and altered neural activation and connectivity in healthy adults. They did so by demonstrating that the brief presentation of emotional cues less efficiently modulates cognitive control capacity. Furthermore, a previous study showed that when a sustained unpleasant state is induced by the visualization of unpleasant arousing pictures in a blocked manner, participants' ability to perform a subsequent non-emotional task is impaired (Pereira *et al.*, 2006).

In the present study, the presentation of unpleasant stimuli in a blocked manner induced a sustained unpleasant state (Bradley *et al.*, 1996; Pereira *et al.*, 2006), and this emotional state biased the representation of unpleasant information in WM (Grant *et al.*, 2001; Siemer, 2005; Hammar and Årdal, 2009; Brose *et al.*, 2012; Delgado *et al.*, 2012; Charpentier *et al.*, 2016). Accordingly, individuals in unpleasant mood states exhibit an attentional bias towards unpleasant stimuli (Joormann and Gotlib, 2008) and impaired cognitive flexibility, resulting in a cost of maintaining task-relevant items in WM (Gasper, 2003). In summary, sustained unpleasant states limit one's ability to remove irrelevant unpleasant information and update WM space.

We demonstrated that susceptible participants were more affected by and more often experienced increased interference from the unpleasant information when trying to update the content in WM. The results of the present study indicate that the participants with the trait of high anxiety experienced a greater impact of the unpleasant emotional state on WM capacity, as indexed by CDA. These results are in agreement with those of Qi *et al.* (2014), who also suggested that the trait of high anxiety is related to a reduced representation of task-relevant items in WM.

Regarding the control of intrusive thoughts, we observed that this ability was positively correlated with WM capacity. This result suggests that individuals who adequately regulate their thoughts more efficiently updated the content of WM and more effectively controlled the access of the unpleasant information into WM. Thus, it is necessary to take into account the capacity to rapidly update information in WM based on demand. This capacity is also known as cognitive flexibility and relies on the maintenance of goal-relevant information over time and on shielding the goal-relevant information from intrusive information in order to adjust behaviour to changing demands (O'Reilly *et al.*, 1999, 2006). Individuals with a high ability to control intrusive thoughts may not actually suppress them; instead, they exhibit a higher capacity to avoid unpleasant information when it is appropriate to do so (Luciano *et al.*, 2005). On the other hand, sustained unpleasant states may have a global effect that enhances the likelihood of intrusive thoughts, most likely due to decreased cognitive flexibility (Brewin and Smart, 2005).

Finally, as expected, we found an increase in the WM capacity using *K*-estimates as more items were required to be maintained in WM. However, we did not find any significant association between the CDA and the WM capacity using *K*-estimates. One explanation is that, in the present study, we underestimated the WM capacity using *K*-estimates by applying a task with only 4 items in the memory array. In fact, in other studies in which the association between *K*-estimates and CDA was described (Vogel and Machizawa, 2004; Jost *et al.*, 2011; Kundu *et al.*, 2013; Tsubomi *et al.*, 2013), a larger number of squares were applied, varying from 1 to 10 squares. Taking into consideration that the average WM capacity is approximately three to four items, it is expected that more than four items are necessary to better capture individual differences in WM capacity using *K*-estimates. Therefore, applying a task with up to 4 items would avoid an underestimation of the WM capacity using *K*-estimates. In addition, the small sample size and number of trials may also account for the null behavioural effects. We acknowledge that these limitations probably prevent observing significant behavioural results. Future studies are needed to clarify these issues.

In summary, we provide strong evidence that an unpleasant emotional state is associated with impaired cognitive functioning, including reduced WM capacity. Our study is the first to measure the neural correlate of WM's vulnerability to an unpleasant emotional state. Under an unpleasant emotional state, susceptible individuals are quick to allow unpleasant information to unduly control their thoughts and guide their behaviour. These findings open new avenues for future research aimed at further clarifying the circuits involved in this detrimental effect of emotion on WM, uncovering the overall processing that confers the risk for the development of mental disorders.

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