Memory & Cognition (2023) 51:1774–1784
https://doi.org/10.3758/s13421-023-01428-0

Modulation of maintenance and processing in working memory by negative emotions

Hanna Chainay[1,2] · Romain Ceresetti[1] · Carl Pierre-Charles[1] · Gaën Plancher[1]

Accepted: 13 April 2023 / Published online: 1 May 2023

Abstract
Previous research has shown that working memory processes are affected by emotions. However, it is not clear if both components – maintenance and processing of information – are modulated by emotion. Since emotion is intimately related to attention, we focused on attentional maintenance in working memory. In a previous study, using a complex span task, we showed that processing emotionally negative information reduced maintenance of neutral information in working memory. The objective of the present study was first to replicate the results of our previous study and second to investigate whether maintaining emotional information would affect processing of neutral information. In Experiment 1, young adults were asked to remember a series of five letters each followed by images, either negative or neutral, to be categorized. In Experiment 2, participants were required to memorize a series of five images, either negative or neutral, each followed by digits to be categorized. In order to focus on attentional maintenance, in both experiments the tasks were performed under continuous articulatory suppression. In Experiment 1, longer processing times were observed for emotional stimuli than neutral ones, and lower recall of series of letters when negative stimuli were processed. In Experiment 2, higher memory performance was observed for negative images than neutral ones and longer processing times of digits when a series of negative stimuli was maintained. Overall, our results show that emotion impacts both processing and attentional maintenance in working memory. This is consistent with models of working memory suggesting an attentional trade-off between maintenance and processing.

Keywords Working memory · Processing · Attentional maintenance · Emotion

Introduction

Working memory (WM) is the ensemble of components of the mind that hold a limited amount of information temporarily in a heightened state of availability for use in ongoing information processing (Cowan, 1988). A typical WM task, as for example the complex span task, involves to-be-remembered items and to-be-processed distractors. In order to perform a task correctly the participants thus have to maintain the to-be-remembered items and process the distractors. The Time-Based-Resource-Sharing (TBRS) model proposes that both mechanisms – processing and maintenance – involve and share the same limited resource that is sustained attention (Barrouillet et al., 2004). According to Barrouillet et al. (2004), sharing of attention is accomplished via switching between processing and maintenance. Thus, when attention is involved in processing, the memory trace of the to-be-maintained information suffers from temporal decay. However, it can be refreshed, and thus retrieved, by refocusing attention on this information. On the other hand, when attention is involved in maintenance, the processing cannot readily occur. As a consequence, there is a trade-off between these two activities of WM that compete for a limited resource. Importantly, the TBRS model confers a central role on attentional maintenance in WM. To prevent memory decay, a specific mechanism called *attentional refreshing* aims to restore the activation level of the decayed memory traces. This mechanism has been distinguished from verbal rehearsal. Even though both mechanisms can maintain verbal information in WM, they are considered to be independent, in particular because of some specific effects of each mechanism on recall and of distinct underlying brain networks (Camos, 2015). Another

✉ Hanna Chainay
hanna.chainay@univ-lyon2.fr

1 Laboratoire d'Etude des Mécanismes Cognitifs, Université Lyon 2, Lyon, France

2 5 avenue Pierre Mendes, 69676 Bron, France

cognitive function for which attention is central is emotion. The emotional content of a stimulus does indeed influence the distribution of attention, with the result that emotional stimuli are more likely to attract attention compared to neutral information. With tasks such as detection, interference, masking, or attentional blink, many studies have illustrated how the processing of emotional stimuli is prioritized (e.g. Anderson & Shimamura, 2005; Pessoa, 2008; Vuilleumier, 2005; Williams et al., 1996). This emotional bias is probably more linked to arousal than to the emotional valence (negative vs. positive) of the stimuli (Anderson & Shimamura, 2005; Vuilleumier, 2005). If attention plays a major role in emotion, emotional content should modulate processing and maintenance in WM, two processes relying on attention. The objective of the present study was to examine how emotion modulates both processes in WM. Even if numerous of studies have reported data in favor of the TBRS model (Barrouillet et al., 2011; Plancher & Barrouillet, 2013, 2020), the majority of the studies have been conducted with emotionally neutral stimuli.

There is a large body of literature focusing on episodic memory and to a lesser extent on WM showing that emotions influence memory performance (for reviews, see Kensinger & Schacter, 2016; Schweizer et al., 2019). It was suggested that the influence of emotion on memory may be in part due to the emotion-attention interaction (for a review, see Dolcos et al., 2020). More precisely, studies on episodic memory pointed out that one of the mechanisms could be attentional narrowing, whereby the attention is almost exclusively focused on the emotional information in order to enhance its encoding and storage (Mickley Steinmetz et al., 2014; Riggs et al., 2011). Although this phenomenon has most often been shown for negative stimuli, some studies have also observed it for positive stimuli (e.g., Chipchase & Chapman, 2013). On the other hand, if the to be encoded information is neutral and presented in the context of emotional information, a reduction of memory performance may occur. The capture of attention by the emotional contextual information would divert attentional resources away from encoding and storage, and as a consequence lead to less efficient encoding and to a decrease in memory performance (Erk et al., 2005; Lewis et al., 2011).

Some studies that have been interested in the effect of emotions on WM used complex span tasks or n-back tasks (e.g., Coifman et al., 2021; Edelstein, 2006; Garrison & Schmeichel, 2019; Kensinger & Corkin, 2003; Schweizer & Dalgleish, 2016), and have shown inconsistent results. In addition, some other studies used a delay-estimation paradigm and have shown that, globally, negatively induced emotion decreases recall success but increases recall precision (i.e., recall of details) in WM, probably due to the enhancement of focal attention (see meta-analytic review by Xie et al., 2022). Kensinger and Corkin (2003), for example, have suggested that emotions do not have a robust effect on WM, as amongst several WM tasks used in their study, only an n-back task using faces as stimuli was affected by emotion, with slower responses for negative than neutral faces, but with no impact on WM capacity. On the other hand, Schweizer and Dalgleish (2016) have shown with a complex span that emotion modulates WM maintenance. In this study, the storage component consisted of retaining a series of neutral words and the processing component consisted of counting geometrical shapes, both presented at the same time against the negative or neutral images. The WM capacity was reduced when the words were presented on the negative background images as compared to the neutral ones. Similar results were observed by Coifman et al. (2021) for neutral words presented in the context of emotional or neutral sentences, while the processing task consisted of judging if the sentence was logical or not. Garrison and Schmeichel (2019) were interested in the effect of the emotional nature of the to-be-maintained stimuli on WM maintenance. Using an operation span task, the authors have shown that when the processing task concerns neutral stimuli (evaluation of mathematical operation), the WM capacity is larger for emotional than neutral words.

In the framework of the TBRS model, the interesting question is whether the attentional trade-off between maintenance and processing would be influenced by the emotional nature of the stimuli that is supposed to modulate attention deployment. Modulation of both the WM maintenance or processing may be expected depending on whether emotional information is to be maintained or processed. Only few studies have addressed this question directly by analyzing both maintenance and processing efficiency in WM tasks. In two experiments, Plancher et al. (2019) have shown that in a complex memory span task the maintenance of a series of letters was reduced when the processing task involved emotional pictures as compared to neutral pictures. To ensure that the participants maintained the information through attentional refreshing and not through verbal rehearsal, they were required to continuously repeat aloud "babebibobu." A decrease in memory performance was observed regardless of whether the processing task asked participants to judge whether the object presented on the image would enter the shoebox (Exp. 1) or to detect a specific color in the image (Exp. 2). In addition, in both experiments processing time was slower when performed on emotional than on neutral images. Overall, this suggests that processing emotional stimuli impacts the maintenance component of WM. In order to fully address the effect of emotion on the maintenance-processing trade-off in WM, it is necessary to measure the impact of emotional processing on memory performance but also the impact of emotional memoranda on the processing performance.

The objective of the present study was to fulfil this gap. To do so we conducted two experiments using complex span tasks. We decided to use a complex span task to fit with our previous study and because it is the task typically used in the theoretical framework we took as a reference (i.e., the TBRS model). In the Experiment 1 our objective was to replicate (Plancher et al., 2019) results by providing more evidence to support the hypothesis that processing of emotional stimuli impacts WM capacity for neutral stimuli. Contrary to our previous studies, in the present study the processing concerned the emotional nature of the stimuli. To this end we asked our participants to perform an emotional judgment task on pictures while memorizing a series of neutral words. This would allow us to test whether the effect of processing of emotional stimuli on memory is dependent on the fact that the processing is emotional in itself or not. In a second experiment, we tested whether the processing component of WM is modulated by the emotional nature of the to-be-maintained stimuli. We expected that if attentional resources are diverted by the emotional nature of the stimuli this would be the case for both components of WM, processing and maintenance. Thus, we should observe reduced performance in memory when processing is emotional and reduced performance in processing when the to-be-maintained stimuli are emotional as compared to when they are neutral.

Experiment 1

Method

Participants

Thirty-three adults (26 women) aged between 18 and 25 years (mean = 21.03, SD = 1.03) took part in this study. All were right-handed undergraduate students at the University of Lyon. They had normal or corrected-to-normal vision and did not declare having a history of psychiatric or neurological disease. All participants signed informed consent in accordance with the guidelines of the 1964 Helsinki Declaration. They were not paid and did not receive course credit for their participation.

Our target sample size was determined using an a priori power analysis (G*Power, Faul et al., 2007) using means, SD, and correlation between the two conditions of recall from Experiment 1 in the Plancher et al. (2019) study. According to these parameters, our study design with one repeated factor (valence condition) could achieve 80% power with 16 participants to obtain an a priori effect size of dz = 0.77. To achieve a greater power (99%), we decided to double this number (33 participants necessary).

Stimuli

One hundred and eighty color pictures (5.5 cm wide × 5.5 cm high) of living (e.g., plants, fruits, vegetables, animals, human body parts) and non-living (e.g., utensils, vehicles, furniture, tools) isolated elements on a white background were used for an emotional judgment task. The images can be viewed via the Open Science Framework at: https://osf.io/pgta7/. These stimuli were the same stimuli as those used in our previous study (Plancher et al., 2019) and included 90 negative images (mean valence = 2.1, SD = .98; mean arousal = 4.6, SD = 1.6) and 90 neutral images (mean valence = 4.2, SD = .67; mean arousal = 1.7, SD = 1.1). These two sets were significantly different in valence ($t(89) = 2.12$, $p < .0001$) and arousal ($t(89) = 2.91$, $p < .0001$). In addition, we used French consonants written in uppercase, black *Mono* font, size 60 pt as the stimuli to be memorized. The images were selected from 988 images in the database pretested for valence and arousal in our laboratory by 30 young adults aged between 18 and 30 years (mean = 22.46, SD = 2.28). The ratings were on a 1- to 7-point scale, with 1 being very negative and 7 being very positive on the valence scale, and with 1 being not arousing and 7 highly arousing on the arousal scale.

The images were purchased from Shutterstock (https://www.shutterstock.com/fr/images).

Procedure

We used a complex span WM task asking participants to alternate between storage and processing. They had to read aloud and memorize letters in a serial order, and to make emotional judgments according to a 6-point scale (very neutral, moderately neutral, neutral, negative, moderately negative, very negative) of the pictures. For half of the participants the valence scale was presented with values starting with very neutral and ending with very negative, and for the other half in a reverse order. The participants used a computer keyboard to perform the emotional judgment task. Three pictures were presented after each letter. Each trial contained five letters and 15 pictures that were all of negative or neutral valence depending on the trial. There were 12 trials with negative pictures and 12 trials with neutral pictures. The trials were presented in a random order and the series of letters were counterbalanced in such a way that the series presented with negative photographs for one participant were presented with neutral photographs for another participant. The presentation time of each picture and letter was, respectively, 2,000 ms and 800 ms, with an inter-stimulus interval of 100 ms (see Fig. 1). At the end of each trial a question mark prompted the participant to recall orally, in serial order, the presented letters. To prevent participants from repeating the letters subvocally, they were

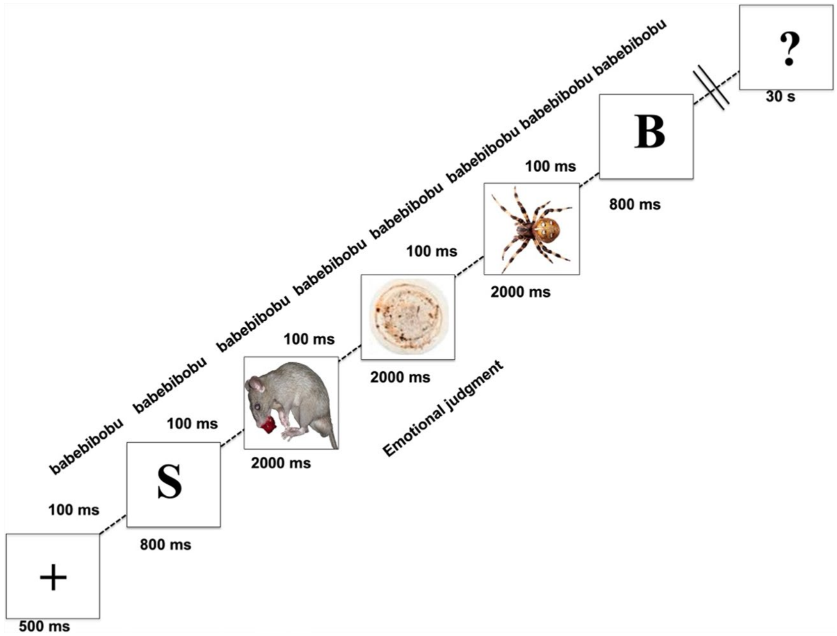

Fig. 1 Working memory task used in Experiment 1. Letters are the stimuli to be maintained and pictures are the stimuli to be processed (emotional judgment task). The example illustrates a negative trial. One trial is composed of five letters and 15 images

asked to continuously repeat "babebibobu" aloud throughout the trial except when they read the letter since they read it aloud. The experiment was programmed and run with the OpenSesame software on an ASUS 17-in. computer. The participants were placed about 60 cm from the computer screen. The full material is available from the corresponding author on a request.

Results and discussion

To ensure that the participants were really involved in the processing task (emotional judgment), we checked the distribution of participant responses. If the percentage of responses for one value of the emotional scale was higher than 90%, the participant was removed from the statistical analysis. We reasoned that if a participant almost always chose the same value, he had not paid attention to the processing task. We thus could not analyze their memory data because their attention was potentially only dedicated to the memory task. According to this criterion, the data of four participants were discarded from the analysis. Thus, the analyses were performed on the data of the 29 participants. The data that support the findings of this study are publicly available via the Open Science Framework at https://osf.io/pgta7/.

A pairwise Student's t-test showed that serial recall of letters was significantly lower (t(28) = -3.09, p < .004; Cohen's d = -.58; 95% CI = [-.965; -.177]) for series presented with negative pictures (mean = 2.13, SD = .98) than for series presented with neutral pictures (mean = 2.45, SD = .91) (see Fig. 2a). In addition, negative pictures (mean = 994 ms, SD = 140) were rated more slowly than neutral pictures (mean = 932 ms, SD = 161); t(28) = 3.31, p < .003; Cohen's d = .62; 95% CI = [.213; 1.008]) (see Fig. 2b). Finally, as expected, negative pictures (mean = 4.48, SD = .78) were rated as more negative than neutral pictures (mean = 2.04, SD = .69); t(28) = 11.15, p < .001; Cohen's d = 2.07; 95% CI = [1.41; 2.761]).

Serial recall is a measure that includes item memory and order memory. We therefore decided to measure the impact of emotions on both separately. First, we examined how emotion impacted maintenance of items independently of order. A pairwise Student's t-test showed that recall of letters without taking order into consideration was significantly lower (t(28) = 3.46, p < .002; Cohen's d = .64; 95% CI = [1.038; 0.237]) for a series of presented negative pictures (mean = 2.93, SD = .88) than for a series of presented neutral pictures (mean = 3.26, SD = .71).

Finally, we examined how emotion influenced maintenance of order independently of items. For this purpose, we computed the proportion of conditional order errors, a method typically used in short-term memory literature (e.g., Murdock, 1976; Saint-Aubin & Poirier, 1999; Roodenrys et al., 2022). In this computation, an order error is when a notification from the list is recalled in the wrong serial position. The raw number of order errors is misleading because it can vary with the overall level of recall (e.g., if three items

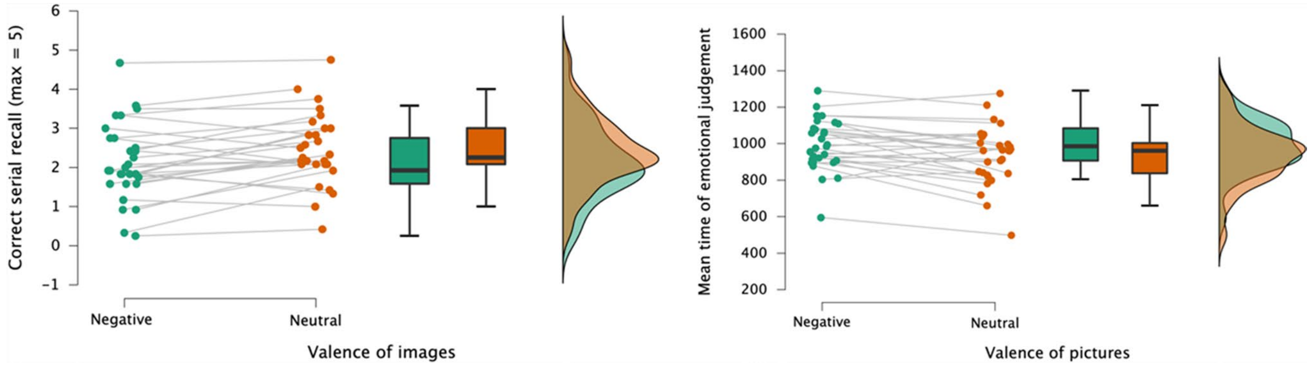

Fig. 2 The panel on the left illustrates correct serial recall of letters in the negative and neutral conditions; the panel on the right illustrates the mean time of emotional judgment for negative and neutral images. The error bars show the standard deviations

from a six-item list are recalled, the maximum number of order errors is three, whereas if five of the six items are recalled, the maximum is five). To control for different numbers of opportunities for an order error, the number of order errors is divided by the number of items recalled in any position. A pairwise Student's t-test showed that the effect of emotion on order errors was not significant ($t(28) = 0.41$, $p = .68$; Cohen's $d = .08$; 95% CI = [-.289; .440]). There was no difference between series presented with negative pictures (mean = .29, SD = .17) and series presented with neutral pictures (mean = .28, SD = .18).

In our previous work (Plancher et al., 2019) we showed that processing in trials with negative pictures (categorization task, detection task) was slower than in trials involving neutral pictures, although the participants were not explicitly asked to process the emotional aspect of the pictures. Our present experiment, involving explicit processing of the emotional aspect of the to-be-processed stimuli (emotional rating task), showed similar results. Thus, taken together our results suggest that independent of the type of processing, focused or not on the emotional aspect of the stimuli, the processing is slower when performed on the emotional stimuli.

In addition, as in our previous study, in the present experiment we showed that processing of emotional stimuli as compared with processing of neutral stimuli reduced the serial recall of letters. Thus, these results strengthen our proposition that the to-be-processed emotional stimuli direct more attentional resources into the processing component of the WM task, and thus reduce the storage capacity for the neutral stimuli. Importantly, this effect operated on item maintenance and not on order maintenance. However, it still remains unclear whether this trade-off phenomenon works in both directions. To further investigate this point in the Experiment 2 of this study, we manipulated emotional valence of the to-be-remembered stimuli and kept the stimuli to be processed neutral. We predicted that if resource allocation to processing and storage components in the WM task is interrelated and is dependent on emotional valence, we should observe reduced efficiency of processing (slower times) and increased performance in serial recall when the memoranda were emotional.

Experiment 2

Method

Participants

Twenty-nine adults (17 women) aged between 18 and 25 years (mean = 21.6, SD = 1.44) took part in this study. All were right-handed undergraduate students at the University of Lyon. They had normal or corrected-to-normal vision, and did not declare having a history of psychiatric or neurological disease. All participants signed informed consent in accordance with the guidelines of the 1964 Helsinki Declaration. They were not paid and did not receive course credit for their participation. The sample size was determined according to the same calculation as in Experiment 1. However, due to the COVID pandemic, we had to stop the inclusions before reaching the number of 33 participants.

Stimuli

We used numbers (0–9) written in black *Mono* font, size 60 pt as the stimuli for the processing task during which participants performed parity judgment. In addition, 60 color pictures (5.5 cm wide × 5.5 cm high) of living and non-living picture elements on a white background were used as the stimuli to be memorized in serial order. The pictures were selected from among the stimuli used in the Experiment 1 and included 30 negative images (mean valence = 1.9, SD = .35; mean arousal = 4.7, SD = .74) and 30 neutral images (mean valence = 4.2, SD = .18; mean arousal = 1.7, SD = 1.1). These two sets were significantly different on valence ($t(29) = -30.3$, $p < .001$) and arousal ($t(29) = 21.32$, $p < .001$). Twelve series of five negative images and 12 series of five neutral images were constructed. To do so, each image was used twice, but in different series.

Procedure

The procedure was the same as in Experiment 1, except that we used pictures for the storage task and numbers for the processing task, and we adjusted the presentation time of the stimuli (see Fig. 3). The participants were required to name aloud and memorize pictures in serial order, and to make parity judgments on numbers by using a computer keyboard. To make naming easier for the participants, before starting the WM task they were presented with the written names of the pictures and were asked to read them aloud. As for Experiment 1, the participants interrupted saying "babebibobu" as soon as a notification appeared on screen and restarted it as soon as they had named it. Each trial contained five pictures of the same valence (negative or neutral) and 15 numbers. Twelve trials contained negative pictures and the other 12 contained neutral pictures. The presentation time of each picture and number was, respectively, 1,500 ms and 1,200 ms, with an inter-stimulus interval of 100 ms. At the end of each trial a question mark prompted the participant to orally recall the pictures in serial order. The material and the data are available from the corresponding author on a request.

Results and discussion

To be sure that the participants had paid sufficient attention during the processing task (parity judgment), we only included into the analysis the data of participants with a mean correct performance of at least 75%, as is usually done in studies using complex span tasks (e.g., Barrouillet et al., 2011; Plancher & Barrouillet, 2013). One participant was excluded because of lower performance (71%). Thus, the analyses were performed on the data of the 28 participants. The recall of images was judged by two persons in order to reach agreement on the accuracy. The recall of a series was considered as correct when the name of each image was correct (i.e., both judges could identify the entities presented on the pictures) and the names of images were given in their presentation order. The data that support the findings of this study are publicly available via the Open Science Framework at https://osf.io/pgta7/.

A pairwise Student's t-test showed that serial recall was significantly higher ($t(27) = 2.50$, $p = .018$; Cohen's $d = .47$; 95% CI = [.079; .861]) for a series with negative pictures (mean = 3.65, SD = .632) than for a series with neutral pictures (mean = 3.44, SD = .74) (see Fig. 4a). In addition, the parity judgment was slower for numbers presented in series with negative pictures (mean = 651 ms, SD = 81) than those presented in series with neutral pictures (mean = 631 ms, SD = 80); $t(27) = 4.03$, $p < .001$; Cohen's $d = .76$; 95% CI = [.335; 1.179]) (see Fig. 4b).

In addition, we examined how emotion impacted maintenance of items independently of order. A pairwise student's

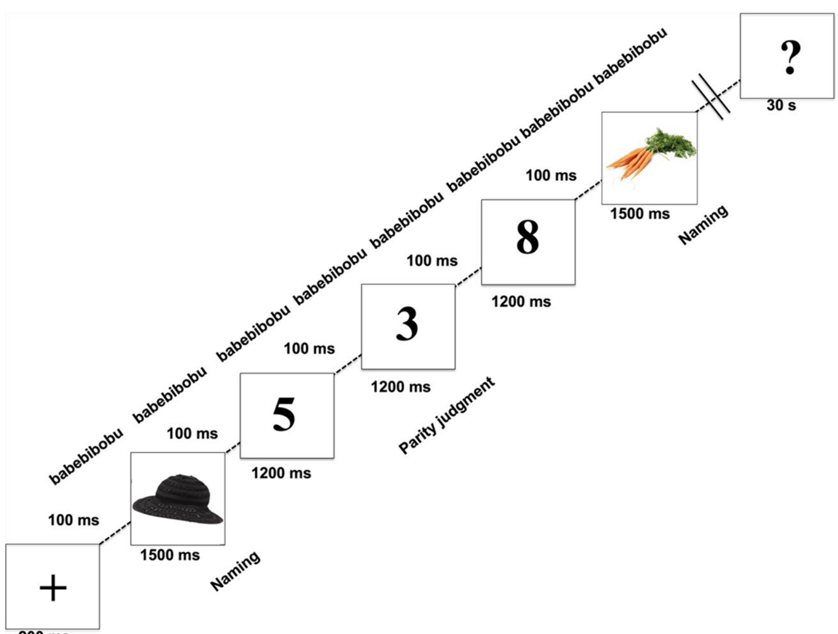

Fig. 3 Working memory task used in Experiment 2. Images are the stimuli to be maintained and letters are the stimuli to be processed (parity judgment task). The example illustrates a neutral trial. Each trial is composed of 15 numbers and five images

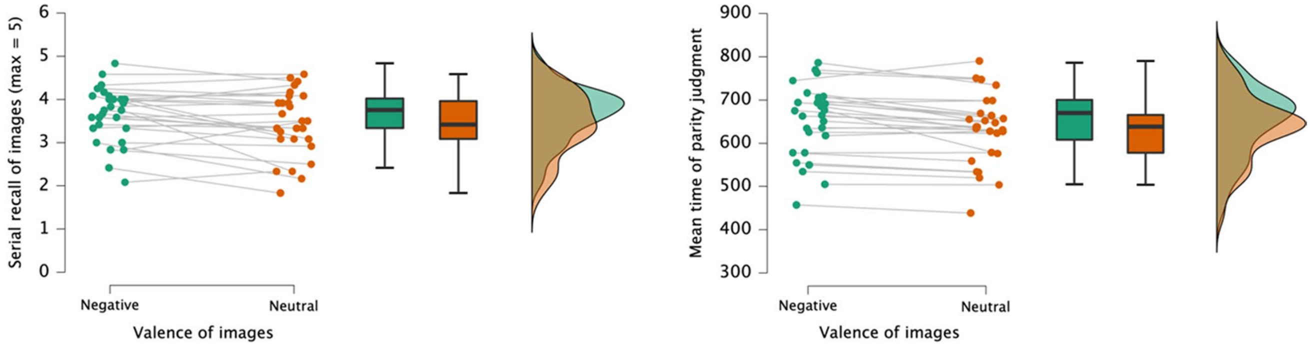

Fig. 4 The panel on the left illustrates correct serial recall of letters in negative and neutral condition, panel on the right illustrates mean time of emotional judgment for negative and neutral images. The error bars correspond to the standard deviations.

t test showed that recall of images without taking order into consideration was significantly higher (t(27) = 3.93, p < .001; Cohen's *d* = .74; 95% CI = [.317; 1.156]) for series with negative pictures (mean = 4.15, SD = .41) than for series with neutral pictures (mean = 3.90, SD = .48). Finally, we examined how emotion influenced maintenance of order independently of items. A pairwise Student's t-test showed that the effect of emotion on order errors was not significant (t(27) = - 0.06, p = .95; Cohen's *d* = -.01; 95% CI = [-.382; .359]). There was no difference between series presented with negative pictures (mean = .13, SD = .10) and series presented with neutral pictures (mean = .13, SD = .10).

These findings showed, as predicted, slower processing and increased performance in serial recall when the memoranda were emotional. First, observing better memory performance for negative images compared to neutral ones confirms the emotion-enhanced memory (EEM) effect (Cahill, L. & McGaugh, J.L., 1998; LaBar & Cabeza, 2006; Talmi & McGarry, 2012) and previous findings showing better WM performance for emotional stimuli (e.g., Coifman et al., 2021; Edelstein, 2006; Garrison & Schmeichel, 2019; Kensinger & Corkin, 2003; Schweizer & Dalgleish, 2016). Second, because we measured slower processing times when memoranda involved negative emotional content, it seems that the effect of emotion on the maintenance-processing trade-off in WM occurs in both directions. Emotional processing impacts memory performance (Experiment 1) and emotional memoranda impacts processing performance (Experiment 2). Again, this effect operated on items maintenance and not on order maintenance.

General discussion

The objective of the present study was to investigate how emotion modulates both WM functions, maintenance and processing. Taking as a framework the TBRS model, we wondered whether the attentional trade-off between maintenance and processing would be influenced by the emotional nature of the stimuli, which is supposed to modulate attention deployment. Overall, our results suggest that this is the case.

First, consistent with our previous study (Plancher et al., 2019), in Experiment 1 we showed that when the to-be-processed stimuli were emotional, their processing was slowed down and WM capacity reduced. One interpretation of our results might be that emotional stimuli direct more attentional resources into the processing component of the WM task, reducing the amount of resources necessary for maintenance. Importantly, this effect operated on items maintenance and not on order maintenance. Second, in Experiment 2 we observed that when participants were required to memorize emotional pictures compared to neutral pictures, this increased processing times of the parity task. One interpretation might be that emotional stimuli direct more attentional resources into the storage component of WM task, slowing concurrent processing. Similarly, this effect operated on items maintenance and not on order maintenance.

Interestingly, Schweizer et al. (2019) investigated in their meta-analysis the impact of moderators on the effect of emotion on WM. One of these moderators was "task-relevance of affective stimuli" (i.e. task-relevant targets vs. task-irrelevant distractors). They observed, among other things, that task-relevant affective targets improved WM performance and task-irrelevant affective distractors impaired performance. Similarly, in our study task-relevant affective targets improved WM performance (Experiment 2) and task-irrelevant affective distractors impaired WM performance (Experiment 1). Our results thus replicated the reversed effect of emotion according to the WM component targeted. From our point of view this is consistent with the fact that emotional stimuli direct more attentional resources into the targeted component of the WM task, sometimes by capturing the resources for storage, and improving it, and sometimes by capturing the resources for processing, and slowing down it.

Contrary to the assumptions of the multicomponent model developed by Baddeley and Hitch (1974), empirical work has offered support for the view that processing and maintenance activities share a common resource in WM (e.g., J. R. Anderson et al., 1996; Barrouillet & Camos, 2015; Plancher & Barrouillet, 2013, 2020; Vergauwe et al., 2014). The TBRS model (Barrouillet & Camos, 2015), one of the most prominent of these theories, assumes that processing and storage compete for a unique limited attentional resource shared within a unitary system, resulting in a perfect trade-off between the two functions. The present study suggests in addition that emotion could mean that the attention remains dedicated to one of the two processes for too long, generating negative repercussions on the other process. In Experiment 1, emotion would cause attention to remain for too long on the processing (shown by slower processing times in negative compared to neutral trials), resulting in poorer memory performance. In Experiment 2, emotion would cause attention to remain for too long on the encoding (shown by higher memory performance in negative compared to neutral trials), resulting in slower processing times. So, the present study confirms that emotion could boost certain cognitive processes, as largely documented in the literature, but this would necessarily be to the detriment of other processes. One result in particular deserves to be highlighted. In Experiment 2 we observed better memory performance for negative images compare to neutral ones; this confirms the well-known emotion-enhanced memory (EEM) effect (Cahill & McGaugh, 1998; LaBar & Cabeza, 2006; Talmi & McGarry, 2012) and previous findings showing better WM performance for emotional stimuli (e.g., Coifman et al., 2021; Edelstein, 2006; Garrison & Schmeichel, 2019; Kensinger & Corkin, 2003; Schweizer & Dalgleish, 2016). But this was the first time, as far as we know, that the impact of emotional memoranda was measured, not only on memory, but on concurrent processing. Our study suggests thus that although emotion certainly can improve memory, but this would have repercussions on parallel processing.

Another assumption of the TBRS model is that WM traces suffer from temporal decay and interference as soon as attention is moved away. Thus, when attention is occupied by processing, memory traces that can no longer be maintained decay, and when attention is occupied by maintenance activities, concurrent processing must be postponed. Our findings were consistent with this assumption, as we observed lower memory performance with slower processing times in Experiment 1. Regarding our findings in Experiment 2, we may assume that attention was heavily occupied by maintenance of emotional stimuli compared to neutral ones. As a result, processing activities were postponed, as shown by slower processing times. Eventually, according to the TBRS model, attention has to be frequently redirected to memory traces for their restoration during short pauses that would be freed while concurrent processing is running, and from maintenance to processing when items must be processed. This process is called *attentional refreshing*. In the Experiment 1 of our study, because we required participants to do a continuous articulatory suppression, the use of verbal rehearsal for maintaining the memoranda was not very plausible. Our results thus suggest that emotion impacts one mechanism of maintenance in WM in particular, namely attentional refreshing. The emotional content of the to-be-processed items, by appropriating attentional resources, would reduce the opportunities for participants to maintain information through attentional refreshing.

Our results are compatible with a general pool of attentional resources that is shared between processing and storage as postulated by the TBRS model but are also compatible with the embedded-processes model (Cowan, 1999, 2005). In this model, WM is considered as the temporarily activated portion of long-term memory. WM may hold a limited number of items in the focus of attention, making them available for treatment. This focus is controlled by an automatic orienting response to changes in the environment, but also by voluntary effort directed by the central executive toward current goals. Cowan proposed that the focus of attention is dedicated to processing and storage, thus a conflict between the two activities could arise. Based on our results, we may assume that emotional content, whatever it is, if processed or maintained should orient the focus of attention on this information, creating a conflict, and in turn causing memory loss or processing impairment. Overall, we do not believe that emotion constitutes a third task in WM that would require additional attentional resources, in the same way as maintenance or processing does. Rather, we believe that emotion prioritizes one of the processes of WM in particular, and this would be via attention.

In addition, in both experiments we observed that the effect of emotion operated on items maintenance but not on order maintenance. Our results are consistent with increasing evidence supporting the distinction between the processes involved in the use of item and order information in short-term memory (e.g., Guitard et al., 2022; Guitard & Cowan, 2022; Majerus, 2019). However, what we observed seems rather inconsistent with recent results showing larger dual-attention costs on order compared to item tests (e.g., Guitard et al., 2022; Guitard & Cowan, 2022). Indeed, if we consider capture of attention by emotion as a dual-attention cost, to be consistent with Guitard et al. (2022), we should have observed a higher effect of emotion on order rather than on items. However, our tasks and manipulations (they did not manipulate emotion) were very different. More studies in the future are needed to better understand the effect of emotion on item and order information in WM.

One last point deserves to be discussed. In our previous study (Plancher et al., 2019), the processing task did not require participants to process explicitly the emotional content of the to-be-processed stimuli. They performed categorization and detection tasks. In this previous study, we already observed that processing negative images was slower compared to neutral ones and in turn gave lower memory performance. In the present study, participants were explicitly required to do an emotional processing on distractors. Taken together, our results suggest that independent of the type of processing, explicit or implicit, the processing is slower when performed on the emotional stimuli. This suggests that the nature of the processing in itself does not matter, but the nature of the stimuli does. In the future it would be interesting to measure the impact of the mere perception of emotional images on WM performance.

One view assumes that emotional stimuli are processed automatically (Dolan & Vuilleumier, 2003; Vuilleumier et al., 2001). Our results do not seem very compatible with this as we observed that emotional stimuli compared to neutral stimuli impact concurrent processing. If emotional stimuli were processed automatically, we should have observed no increase in processing times and no reduction of WM capacity when performing emotional judgment of negative images as compared with neutral images. It seems then that the processing of the emotional aspect is not purely automatic and requires additional attentional resources. And this is the case, whether the processing of emotional aspect of stimuli is explicit or not. Our findings are more compatible with the dual competition framework (Pessoa, 2008), which assumes that resources dedicated to the processing of emotional properties become temporarily unavailable to all other relevant activities. In the same way, our findings are compatible with the emotional impairment hypothesis assuming that emotional information reduces WM capacity by interfering with attentional control (Garrison & Schmeichel, 2019; Schweizer & Dalgleish, 2011, 2016).

Conclusion

In conclusion, a large number of studies has suggested that the processing of emotional stimuli is prioritized because of their relevance to survival. In our study, we observed that emotional content impacted processing and attentional maintenance in WM. This is consistent first with the view assuming that processing of emotional stimuli is dependent on attention, and second with a unitary view of WM, where processing and storage share a common limited attentional resource. As demonstrated in the literature for decades, emotion could boost certain cognitive processes, but this would necessarily be to the detriment of other processes. WM capacity has been found to be central in cognition such as reasoning, language, mathematics, or complex learning, leading researchers to view it as the core of cognition. In addition, it has been shown that memory disruption due to processing of emotionally negative stimuli can be even greater in anxious individuals (Shi et al., 2014), those with a post-traumatic stress disorder (Schweizer & Deiglesh 2011), and those suffering from depression (Hubbard et al., 2016; Joormann et al., 2011). Consequently, it is crucial to better understand the impact of emotion on WM. It was also suggested that individual differences may modulate the effects of emotion on WM (Xie et al., 2018; Xie et al., 2022). In the present study we did not investigate this point, but future research should take it into consideration to better understand the effect of emotion on WM.

Acknowledgements Romain Ceresetti and Carl Pierre-Charles were doing their Master's research internship in the Laboratoire des Mécanismes Cognitifs when the research presented in this article was conducted.

Author's contribution Hanna Chainay and Gaën Plancher equally contributed to the conceptualization of the study, methodology, data analysis, and writing of the paper. Romain Ceresetti and Carl Pierre-Charles contributed to the methodology, data collection, data processing, and data analysis.

Funding This work was supported by the University Lyon 2.

Data availability The data that support the findings of this study are publicly available via the Open Science Framework at https://osf.io/pgta7/. The images used in the Experiment 1 and Experiment 2 can be viewed at the same space.

Declarations

Competing interests The authors declare that they have no competing interests.

References

Anderson, J. R., Reder, L. M., & Lebiere, C. (1996). Working memory : Activation limitations on retrieval. *Cognitive Psychology, 30*(3), 221–256. https://doi.org/10.1006/cogp.1996.0007

Anderson, L., & Shimamura, A. D. (2005). Influences of emotion on context memory while viewing film clips. *American Journal of Psychology, 118*(3), 323–373. https://doi.org/10.2307/30039069

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. *The Psychology of Learning and Motivation, 8*, 47–90.

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General, 133*(1), 83–100. https://doi.org/10.1037/0096-3445.133.1.83

Barrouillet, P., & Camos, V. (2015). *Working memory : Loss and reconstruction*. Psychology Press.

Barrouillet, P., Portrat, S., & Camos, V. (2011). On the law relating processing to storage in working memory. *Psychological Review, 118*(2), 175–192. https://doi.org/10.1037/a0022324

Cahill, L., & McGaugh, J. L. (1998). Mechanisms of emotional arousal and lasting declarative memory. *Trends in Neurosciences, 21*, 294–299. https://doi.org/10.1016/S0166-2236(97)01214-9

Camos, V. (2015). Storing verbal information in working memory. *Current Directions in Psychological Science, 24*(6), 440–445. https://doi.org/10.1177/0963721415606630

Chipchase, S. Y., & Chapman, P. (2013). Trade-offs in visual attention and the enhancement of memory specificity for positive and negative emotional stimuli. *Quarterly Journal of Experimental Psychology, 66*(2), 277–298. https://doi.org/10.1080/17470218.2012.707664

Coifman, K. G., Kane, M. J., Bishop, M., Matt, L. M., Nylocks, K. M., & Aurora, P. (2021). Predicting negative affect variability and spontaneous emotion regulation : Can working memory span tasks estimate emotion regulatory capacity? *Emotion, 21*(2), 297–314. https://doi.org/10.1037/emo0000585

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin, 104*(2), 163–191. https://doi.org/10.1037/0033-2909.104.2.163

Cowan, N. (1999). An embedded-processes model of working memory. In *Models of working memory : Mechanisms of active maintenance and executive control* (pp. 62–101). Cambridge University Press.

Cowan, N. (2005). *Working memory capacity*. Psychology Press.

Dolan, R. J., & Vuilleumier, P. (2003). Amygdala automaticity in emotional processing. *Annals of the New York Academy of Science, 1*, 348–355. https://doi.org/10.1111/j.1749-6632.2003.tb07093.x

Dolcos, F., Katsumi, Y., Moore, M., Berggren, N., de Gelder, B., Derakshan, N., Hamm, A. O., Koster, E. H. W., Ladouceur, C. D., Okon-Singer, H., Pegna, A. J., Richter, T., Schweizer, S., Van den Stock, J., Ventura-Bort, C., Weymar, M., & Dolcos, S. (2020). Neural correlates of emotion-attention interactions : From perception, learning, and memory to social cognition, individual differences, and training interventions. *Neuroscience & Biobehavioral Reviews, 108*, 559–601. https://doi.org/10.1016/j.neubiorev.2019.08.017

Edelstein, R. S. (2006). Attachment and emotional memory : Investigating the source and extent of avoidant memory impairments. *Emotion, 6*(2), 340–345. https://doi.org/10.1037/1528-3542.6.2.340

Erk, S., Martin, S., & Walter, H. (2005). Emotional context during encoding of neutral items modulates brain activation not only during encoding but also during recognition. *NeuroImage, 26*(3), 829–838. https://doi.org/10.1016/j.neuroimage.2005.02.045

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3 : A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175–191. https://doi.org/10.3758/BF03193146

Garrison, K. E., & Schmeichel, B. J. (2019). Effects of emotional content on working memory capacity. *Cognition and Emotion, 33*(2), 370–377. https://doi.org/10.1080/02699931.2018.1438989

Guitard, D., & Cowan, N. (2022). Attention allocation between item and order information in short-term memory. *Quarterly Journal of Experimental Psychology*. https://doi.org/10.1177/17470218221118451

Guitard, D., Saint-Aubin, J., & Cowan, N. (2022). Tradeoffs between item and order. information in short-term memory. *Journal of Memory and Language, 122*(October), 104300. https://doi.org/10.1016/j.jml.2021.104300

Hubbard, N. A., Hutchison, J. L., Turner, M., Montroy, J., Bowles, R. P., & Rypma, B. (2016). Depressive thoughts limit working memory capacity in dysphoria. *Cognition and Emotion, 30*, 193–209.

Joormann, J., Levens, S. M., & Gotlib, I. H. (2011). Sticky thoughts : Depression and rumination are associated with difficulties manipulating emotional material in working memory. *Psychological Science, 22*(8), 979–983. https://doi.org/10.1177/0956797611415539

Kensinger, E. A., & Corkin, S. (2003). Effect of negative emotional content on working memory and long-term memory. *Emotion, 3*(4), 378–393. https://doi.org/10.1037/1528-3542.3.4.378

Kensinger, E. A., & Schacter, D. L. (2016). Memory and emotion. In *Handbook of emotions* (pp. 564–578). Guilford Publications.

LaBar, K. S., & Cabeza, R. (2006). Cognitive neuroscience of emotional memory. *Nature Reviews Neuroscience, 7*(1), 54–64. https://doi.org/10.1038/nrn1825

Lewis, P. A., Cairney, S., Manning, L., & Critchley, H. D. (2011). The impact of overnight consolidation upon memory for emotional and neutral encoding contexts. *Neuropsychologia, 49*(9), 2619–2629. https://doi.org/10.1016/j.neuropsychologia.2011.05.009

Majerus, S. (2019). Verbal working memory and the phonological buffer: The question of serial order. *Cortex, 112*, 122–133. https://doi.org/10.1016/j.cortex.2018.04.016

Murdock, B. B. (1976). Item and order information in short-term serial memory. *Journal of Experimental Psychology: General, 105*, 191–216. https://doi.org/10.1037/0096-3445.105.2.191

Mickley Steinmetz, K. R., Waring, J. D., & Kensinger, E. A. (2014). The effect of divided attention on emotion-induced memory narrowing. *Cognition and Emotion, 28*(5), 881–892. https://doi.org/10.1080/02699931.2013.858616

Pessoa, L. (2008). On the relationship between emotion and cognition. *Nature Reviews Neuroscience, 9*(2), 148–158. https://doi.org/10.1038/nrn2317

Plancher, G., & Barrouillet, P. (2013). Forgetting from working memory : Does novelty encoding matter? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39*(1), 110–125. https://doi.org/10.1037/a0028475

Plancher, G., & Barrouillet, P. (2020). On some of the main criticisms of the modal model : Reappraisal from a TBRS perspective. *Memory & Cognition, 48*(3), 455–468. https://doi.org/10.3758/s13421-019-00982-w

Plancher, G., Massol, S., Dorel, T., & Chainay, H. (2019). Effect of negative emotional content on attentional maintenance in working memory. *Cognition and Emotion, 33*(7), 1489–1496. https://doi.org/10.1080/02699931.2018.1561420

Roodenrys, S., Guitard, D., Miller, L. M., Saint-Aubin, J., & Barron, J. M. (2022). Phonological similarity in the serial recall task hinders item recall, not just order. *British Journal of Psychology, 113*, 1100–1120. https://doi.org/10.1111/bjop.12575

Riggs, L., McQuiggan, D. A., Farb, N., Anderson, A. K., & Ryan, J. D. (2011). The role of overt attention in emotion-modulated memory. *Emotion, 11*(4), 776–785. https://doi.org/10.1037/a0022591

Saint-Aubin, J., & Poirier, M. (1999). Semantic similarity and immediate serial recall: Is there a detrimental effect on order information? *The Quarterly Journal of Experimental Psychology Section A, 52*, 367–394. https://doi.org/10.1080/713755814

Schweizer, S., & Dalgleish, T. (2011). Emotional working memory capacity in posttraumatic stress disorder (PTSD). *Behavior Research and Therapy, 49*, 498–504. https://doi.org/10.1016/j.brat.2011.05.007

Schweizer, S., & Dalgleish, T. (2016). The impact of affective contexts on working memory capacity in healthy populations and in individuals with PTSD. *Emotion, 16*(1), 16–23. https://doi.org/10.1037/emo0000072

Schweizer, S., Satpute, A. B., Atzil, S., Field, A. P., Hitchcock, C., Black, M., Barrett, L. F., & Dalgleish, T. (2019). The impact of affective information on working memory : A pair of meta-analytic reviews of behavioral and neuroimaging evidence. *Psychological Bulletin, 145*(6), 566–609. https://doi.org/10.1037/bul0000193

Shi, Z., Gao, X., & Zhou, R. (2014). Emotional working memory capacity in test anxiety. *Learning and Individual Differences, 32*, 178–183.

Talmi, D., & McGarry, L. M. (2012). Accounting for immediate emotional memory enhancement. *Journal of Memory and Language, 66*(1), 93–108. https://doi.org/10.1016/j.jml.2011.07.009

Vergauwe, E., Camos, V., & Barrouillet, P. (2014). The impact of storage on processing. *How Is Information Maintained in Working Memory?, 40*(4), 1072–1095. https://doi.org/10.1037/a0035779

Vuilleumier, P. (2005). How brains beware : Neural mechanisms of emotional attention. *Trends in Cognitive Sciences, 9*(12), 585–594. https://doi.org/10.1016/j.tics.2005.10.011

Vuilleumier, P., Armony, J. L., Driver, J., & Dolan, R. J. (2001). Effects of attention and emotion on face processing in the human brain : An event-related fMRI study. *Neuron, 30*, 829–841. https://doi.org/10.1016/S0896-6273(01)00328-2

Williams, J. M. G., Mathews, A., & MacLoad, C. (1996). *The Emotional Stroop Task and Psychopathology., 120*(1), 3–24. https://doi.org/10.1037/0033-2909.120.1.3

Xie, W., Cappiello, M., Meng, M., Rosenthal, R., & Zhang, W. (2018). ADRA2B deletion variant and enhanced cognitive processing of emotional information : A meta-analytical review. *Neuroscience and Biobehavioral Reviews, 92*, 402–416. https://doi.org/10.1016/j.neubiorev.2018.05.010

Xie, W., Ye, C., & Zhang, W. (2022). Negative emotion reduces visual working memory recall variability: A meta-analytical review. *Emotion, Advance online publication.* https://doi.org/10.1037/emo0001139