Psychonomic Bulletin & Review (2025) 32:866–874
https://doi.org/10.3758/s13423-024-02593-2

BRIEF REPORT

Effect of negative emotional stimuli on working memory: Impact of voluntary and automatic attention

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Accepted: 15 September 2024 / Published online: 7 October 2024

Abstract

Emotions are known to influence cognitive performance, particularly working memory (WM) in both its aspects, processing, and maintenance. One explanatory mechanism might be that negative stimuli capture attentional resources, leaving fewer resources for attentional maintenance and processing of information in WM. However, this attentional capture was only investigated using WM tasks in which participants were explicitly asked to process negative items. The aim of this paper was to determine whether explicit processing of emotional stimuli is necessary to impair WM performance, or if their mere presence is enough to capture attention. For this purpose, participants performed a complex span task in which they alternated between memorizing a series of neutral words and processing either emotional images or neutral ones. In Experiment 1, participants were instructed to explicitly process emotional images, whereas in Experiment 2, emotional images were presented without any processing being required. In both experiments, we observed a decrease in memory performance when the images were negative compared to neutral. Whether or not voluntary processing is involved, emotional images seem to capture attentional resources, which in turn leads to a decline in memory performance. These results were discussed in relation to attentional theories and the influence of emotion on the specific mechanisms of WM.

Keywords Working memory · Emotion · Attention

Introduction

Emotional events are known to influence episodic memory (see Kensinger & Schacter, 2016; Schweizer et al., 2019; J. R. Williams et al., 2022, for reviews). Numerous studies have shown that emotional stimuli are better recalled than neutral stimuli (Cahill & McGaugh, 1998; Labar & Cabeza, 2006; Talmi & McGarry, 2012), potentially due to the attentional capture exerted by emotional stimuli. Indeed, emotional stimuli are more likely to attract attention compared with neutral ones (Dolcos et al., 2020; Fournier & Koenig, 2023). Preferential processing of emotional relative to neutral events contributes to memory enhancement by increasing processing and elaboration of the stimulus (i.e., encoding), and facilitating storage and consolidation (Mickley Steinmetz et al., 2014; Riggs et al., 2011; J. R. Williams et al., 2022).

Nevertheless, emotional stimuli can also interfere with memory. Emotional contextual information has been found to disrupt the maintenance of information in memory (Lewis et al., 2011; Schweizer & Dalgleish, 2016). This disruption is explained by the automatic capture of attention by emotional contextual information, which results in reduced resources for memory processes. In fact, numerous studies have shown that the processing of contextual emotional information is prioritized and influences memory performance (Anderson, 2005; Pessoa, 2008; Vuilleumier, 2005; Williams et al., 1996), a crucial mechanism for survival (Deweese et al., 2016; Öhman et al., 2001; Vuilleumier & Schwartz, 2001).

The present study focused on a particular system of memory—namely, working memory (WM), which can be defined as the ability to temporarily hold information while manipulating other information. In theoretical models, attention is conceptualized as playing a central role in WM.

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One of the most prominent of these models is the time-based-resource-sharing (TBRS) model (Barrouillet et al., 2004, 2011; Plancher & Barrouillet, 2020). The TBRS model assumes that processing and storage compete for a unique attentional resource shared within a unitary system, resulting in a perfect trade-off between the two functions. Because this resource is limited (Kahneman, 1973), it has to be shared between the two components, and since a central bottleneck constrains cognition, processing and maintenance take place in a sequential manner. According to the model, WM traces suffer from temporal decay and interference as soon as attention is switched away. Consequently, to avoid memory loss, attention has to be frequently redirected to memory traces. This process is called "attentional refreshing," a maintenance mechanism relying on attention to keep mental representations active (Camos & Barrouillet, 2014). The complex span task is typically used in the TBRS framework because it provides a good model of WM as memoranda alternate with processing. In this task to-be-remembered items are presented for further serial recall, each of these items being followed by a series of distractors (e.g., digits, words, or images) that must be explicitly processed concurrently to working memory maintenance. Barrouillet et al. (2004) demonstrated the existence of a processing–storage trade-off in WM, and several studies showed that this trade-off may be influenced by emotion (Chainay et al., 2023; Garrison & Schmeichel, 2018; Plancher et al., 2019; Schweizer & Dalgleish, 2011, 2016). For instance, Plancher et al. (2019) showed in two experiments that when participants tried to remember a sequence of letters while categorizing images, memory performance was lower when the images were negative rather than neutral. These authors suggested that emotional stimuli capture attentional resources, so the amount of resources available to process other stimuli is reduced, preventing the maintenance of items through attentional refreshing. Conversely, to investigate whether maintaining emotional information would affect the processing of neutral stimuli, Chainay et al. (2023) asked participants to memorize a series of images, either negative or neutral, each followed by digits to be categorized (parity judgment). They showed better memory performance for negative images than neutral ones and longer processing times for digits when series of negative stimuli were maintained. These results show that emotional processing impacts both processing and attentional maintenance in WM. These findings are consistent with the TBRS model of WM, which suggests an attentional trade-off between maintenance and processing.

In the WM literature, the effect of concurrent processing on memory has always been investigated by requiring participants to actively process stimuli (e.g., Barrouillet et al., 2011; Plancher & Barrouillet, 2013). In our previous studies (Chainay et al., 2023; Plancher et al., 2019) investigating the impact of emotion on WM, participants were explicitly asked to voluntarily focus their attention on concurrent processing. In general, in WM literature, it is assumed that there is no effect of the concurrent task when there is no explicit processing of the task stimuli. This explicit and voluntarily processing is an attentional process which is goal-driven and directed toward events or stimuli consciously decided by the individual to be the targets of processing. Therefore, it is unclear whether the detrimental effect of negative images on memory performance would be observed with the mere exposure of negative images without voluntary processing. In parallel, it has been shown that emotional stimuli automatically capture attention in order to prioritize their processing (e.g., Fournier & Koenig, 2023; Pessoa, 2008; Vuilleumier, 2005; Williams et al., 1996). This attentional capture corresponds to exogenous, stimulus-driven, automatic attention (Carretié, 2014). By enabling the rapid detection of salient events, this capture would be indispensable to the individual's survival. This would thus be implemented even when the individual is engaged in a resource-consuming task, to deal with it when necessary. It would then be expected that the mere presence of negative items captures attention in WM, and that impacts memory performance. However, the effect of the mere presence of distractors, whether emotional or not, in complex span task had not been studied yet. Testing this impact would make it possible to extend the predictions of the TBRS model to a situation of involuntary processing, one that occurs very often in everyday life. To answer this original question, we carried out a study in which the two cases were dissociated. In one case, participants had to carry out explicit voluntary processing on emotional or neutral stimuli; in the other, the stimuli were presented but no explicit processing was required.

In two experiments, participants had to perform a WM task akin to a complex span task, in which they had to maintain neutral words interspersed by neutral or negative images. In the first experiment, participants were required to categorize the images, inducing a controlled orientation of attention on them. In the second experiment, no explicit processing was required, thus, we expected no involvement of voluntary attention. In line with the literature and our previous results (Chainay et al., 2023; Plancher et al., 2019), we expect the processing of negative images to decrease memory performance compared with processing neutral images when voluntary attention is engaged (Experiment 1). In addition, if the capture due to emotion is automatic in nature (i.e., linked to an early and exogenous attention; Carretié, 2014), in the second experiment, we should also observe a decrease in recall performance after a simple, rapid presentation of negative images (vs. neutral images).

Experiment 1

Method

Participants

Twenty-eight students from the Université Lyon 2 (15 women, 13 men), between ages 18 and 30 years (mean = 23.21 years, $SD = 1.14$) were included in the final analyses. Ten additional participants were excluded from data analysis because they were unable to complete the task correctly. To ensure that the participants were really involved in the processing task, we kept, for statistical analysis, only the participants with scores equal or higher than 75% of correct responses in categorization task, as is frequently done in the literature (e.g., Barrouillet et al., 2004). The participants had normal or corrected-to-normal vision and did not declare any history of psychiatric or neurological disease. All participants signed informed consent in accordance with the standard of the 1964 Helsinki Declaration. They were not paid and did not receive course credit for their participation.

The target sample size was determined on the basis of the effect size, Cohen's $d = -0.58$, reported in Experiment 1 in Chainay et al. (2023). An a priori power analysis (G*Power; Faul et al., 2007) for a design with one repeated factor (valence condition) showed that 27 participants were necessary to achieve 90% power with an alpha = 0.05.

Stimuli

The same 180 color pictures (5.5 cm wide × 5.5 cm high) as in Plancher et al. (2019) and Chainay et al. (2023) were used in this experiment. These pictures were selected from a 988 images database, rated on 1–7-point scales for valence (1 = *very negative*, 7 = *very positive*) and arousal (1 = *not at all exciting*, 7 = *very exciting*) in our laboratory by 30 young adults between 18 and 30 years of age (mean = 22.46 years, $SD = 2.28$). The evaluators were instructed to rate on the above scales the degree of negativity or positivity they felt when looking at each picture for the valence scale, and the degree of excitement they felt for the arousal scale. They were informed that the middle of each scale corresponded to neither a negative nor a positive feeling for the valence scale, and neither calm nor exited for the arousal scale. The selected pictures represented, shown on a white background, isolated elements of living (e.g., plants, fruits, vegetables, animals, human body parts) and nonliving (e.g., utensils, vehicles, furniture, tools) categories. Half of these pictures were negative (mean valence = 2.1, $SD = 0.98$; mean arousal = 4.6, $SD = 1.6$) and the other half were neutral (mean valence = 4.2, $SD = 0.67$; mean arousal = 1.7, $SD = 1.1$). These two sets of pictures were significantly different on valence, $t(89) = 2.12$, $p < 0.0001$, and arousal, $t(89) = 2.91$, $p < 0.0001$. There were 50 living items in the 90 negative pictures and 21 in the 90 neutral pictures. The pictures can be viewed on the Open Science Framework (https://osf.io/39f5b/).

In addition, 120 French words, common names, one to three syllables, with frequency in films superior to 1/million and were of neutral valence (varying from −0.5 to 0.5 on the scale −3 to 3) were selected based on Lexique3 (New et al., 2004) and EMA (Gobin et al., 2017) databases. The words were divided into two lists. These lists were equivalent in word frequency, valence, arousal, and number of words of one, two, and three syllables. Within each list, 12 series of five words were created. These series were counterbalanced in such a way that the series presented with negative pictures for one participant were presented with neutral pictures for another participant. The words were written in lowercase, black size 60 Mono font and corresponded to the stimuli to be memorized.

Before the experiment, we also used the Brief Mood Introspection Scale (BMIS; Mayer & Gaschke, 1988), which allowed us to evaluate participants' current mood on four subscales: Pleasant-Unpleasant Mood, Aroused-Calm Mood, Positive-Tired Mood, and Negative-Relaxed Mood.

Procedure

A complex span WM task was used in which participants had to alternate between storage and processing. They had to categorize pictures into living and nonliving categories using a computer keyboard, keys *S* and *L*, and to read aloud and memorize words in a serial order. Three pictures were presented after each word, and each trial contained five words 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 that were presented in a random order. Each picture and word were presented for, respectively, 150 ms and 800 ms, with interstimulus interval of 1,850 ms (see Fig. 1). This short time frame of the pictures' presentation and long interstimuli interval was chosen to respect both experiments' constraints. First, interstimuli interval was chosen to allow sufficient time for processing in Experiment 1, and the time of pictures' presentation was chosen based on the time course of attentional capture. The 150 ms allowed sufficient time for attention to be captured automatically, without leaving time for attention to be intentionally maintained on the images (Müller & Findley, 1988; Santangelo et al., 2011). At the end of each trial, signaled by question mark, participants had 30 s to

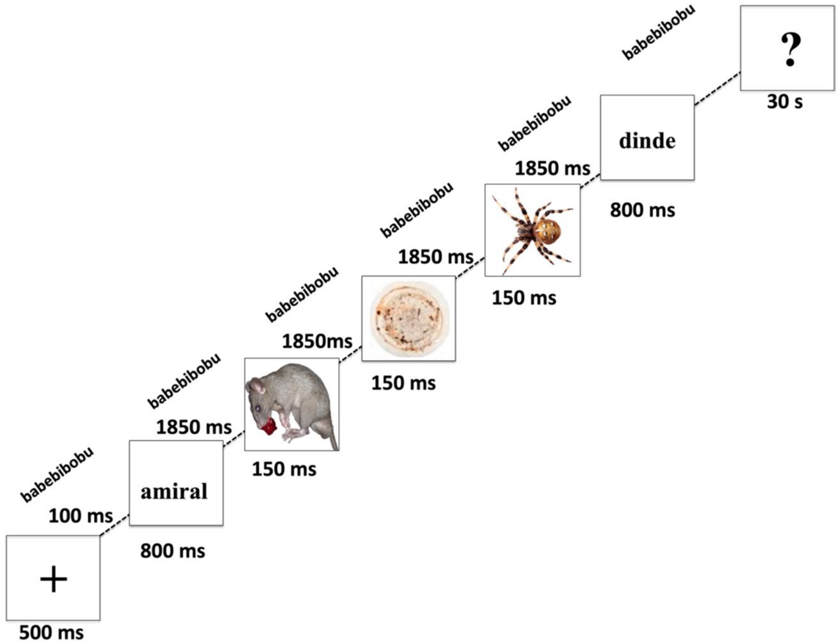

Fig. 1 Working memory task used in Experiment 1. Words are the stimuli to be maintained, and pictures are the stimuli to be processed (living/nonliving categorization). The example illustrates a part of a negative trial. One trial is composed of fine words and 15 pictures

recall orally, in serial order, the presented words. Each trial started by a fixation cross displayed for 500 ms. In addition, throughout the trial, except when reading aloud the words, participants were asked to continuously repeat "babebibobu" aloud. This was done to prevent participants from repeating the words subvocally. The experiment was programmed and run with the OpenSesame (Mathôt et al., 2012) software on an ASUS 17-in. computer. The participants were placed about 60 cm from the computer screen. Before starting the experimental task, each participant completed the BMIS.

Results

Pairwise Student's t tests were used to analyze the recall and time of categorization performance after having checked for the normality of the distribution. The serial recall of words was significantly lower, $t(27) = -2.88$, $p < 0.008$; Cohen's $d = -0.54$; 95% CI [$-0.938, -0.143$], for series presented with negative pictures (mean = 2.10, $SD = 0.81$) than for series presented with neutral pictures (mean = 2.40, $SD = 0.95$; see Fig. 2). In addition, the

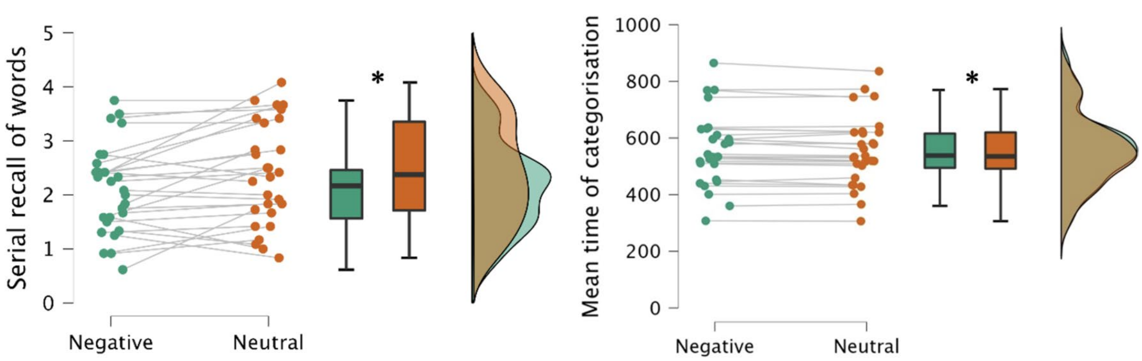

Fig. 2 Correct serial word recall in the negative and neutral picture conditions (left panel) and mean categorization time of negative and neutral pictures into living/nonliving categories (right panel) in Experiment 1. *Note*. Within each of the two panels: on the left, the colored dots and connected lines depict the mean data of each participant as a function of the two conditions. In the middle, the center line, the hinges, and the whiskers of the box plots illustrate the median, the first and third quartiles, and the 1.5 interquartile ranges of the distributions for the two conditions, respectively. On the right, the density for each measure condition is reported. Mean time of categorization is expressed in ms. *The differences between the neutral and negative image conditions are significant ($p < .05$). (Color figure online)

negative pictures (mean = 559 ms, *SD* = 126) were categorized more slowly than neutral pictures (mean = 554 ms, *SD* = 123), $t(27) = 2.23$, $p = 0.034$; Cohen's $d = 0.42$; 95% CI [0.03, 0.80] (see Fig. 2). Because of the different number of living and nonliving items among negative and neutral pictures (see Stimuli section), we conducted a supplementary analysis to exclude the possibility that the significantly slower categorization of negative pictures was due to this disbalance rather than to the emotional nature of the stimuli. An analysis of variance (ANOVA) on RT for correct categorizations, with two within-subject factors of category (living vs. nonliving) and valence (neutral vs. negative) showed an effect of valence, $F(1,27) = 8.7$, $p = 0.006$, $\eta_p^2 = 0.24$, with negative pictures being more slowly categorized than neutral ones, and the effect of category, $F(1,27) = 5.2$, $p = 0.032$, $\eta_p^2 = 0.16$, with living items being more slowly categorized (mean = 570 ms, *SD* = 122) than nonliving items (mean = 550 ms, *SD* = 123). However, there was no significant interaction between these two factors, $F(1,27) = 1.19$, $p = 0.29$ $\eta_p^2 = 0.04$.

A correlation analysis was also performed between the recall scores and the scores obtained for the four subscales of the BMIS to see if the participants mood could influence their memory performance. There was no significant correlation observed between serial recall and each of the four BMIS subscales: Pleasant-Unpleasant Mood ($r = -0.24$, $p = 0.24$), Aroused-Calm Mood ($r = 0.09$, $p = 0.66$), Positive-Tired Mood ($r = -0.17$, $p = 0.41$), and Negative-Relaxed Mood ($r = 0.20$, $p = 0.32$). These results can be viewed on the Open Science Framework (https://osf.io/39f5b/).

Experiment 2

Method

Participants

Twenty-eight students from the Université Lyon 2 (12 women, 16 men) between 18 and 30 years of age (mean = 22.96 years, *SD* = 1.8) participated in this study. The target sample size of 26 participants was determined on the same bases as in Experiment 1, and two additional participants were included in a case it was necessary to exclude some participants from the study. The participants had normal or corrected-to-normal vision and did not declare any history of psychiatric or neurological disease. All participants signed informed consent in accordance with the standard of the 1964 Helsinki Declaration. They were not paid and did not receive course credit for their participation.

Stimuli and procedure

The stimuli and procedure used were the same as in Experiment 1, except for one point. During the task, we simply presented the pictures after each word without any processing instructions. By doing this, we did not expect participants to engage voluntary attention on the pictures.

Results

A pairwise Student's *t* test was used to analyze the recall performance after having checked for the normality of the distribution. The serial recall of words was significantly lower, $t(27) = -2.35$, $p = 0.026$; Cohen's $d = -0.44$; 95% CI [-0.830, −0.052]) for series presented with negative pictures (mean = 2.98, *SD* = 0.75) than for series presented with neutral pictures (mean = 3.25, *SD* = 0.76; see Fig. 3).

The correlation analysis was also performed between the recall scores and the scores obtained for the four subscales of the BMIS to see if the participants mood could influence their memory performance. There was no significant correlation observed between serial recall and each of the four BMIS subscales: Pleasant-Unpleasant Mood ($r = 0.36$, $p = 0.056$), Aroused-Calm Mood ($r = 0.10$, $p = 0.61$), Positive-Tired Mood ($r = 0.31$, $p = 0.11$), and Negative-Relaxed Mood (neutral $r = -0.27$, $p = 0.17$). In order to strengthen the correlation analyses, we combined the data from Experiment 1 and Experiment 2. No significant correlation was observed between recall and scores of the four BMIS subscales: ($r = 0.11$, $p = 0.46$), aroused-calm mood ($r = 0.13$, $p = 0.35$), positive-tired mood ($r = 0.17$, $p = 0.22$),

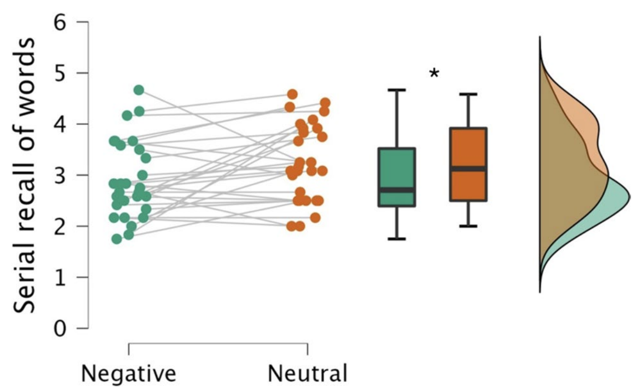

Fig. 3 Mean correct serial word recall in the negative and neutral picture conditions in Experiment 2. *Note.* On the left, the colored dots and connected lines depict the mean data of each participant as a function of the two conditions. In the middle, the center line, the hinges, and the whiskers of the box plots illustrate the median, the first and third quartiles, and the 1.5 interquartile ranges of the distributions for the two conditions, respectively. On the right, the density for each measure condition is reported. *The differences between the neutral and negative image conditions are significant ($p < .05$). (Color figure online)

and negative-relaxed mood (rho = −0.06, p = 0.67). These results can be viewed in the Open Science Framework (https://osf.io/39f5b/).

Discussion

Emotions are known to influence cognitive performance, especially memory, by inducing either a beneficial effect (emotional stimuli are better remembered than neutral stimuli) or a deleterious effect (emotional stimuli not relevant to a given task-induce distraction) (Williams et al., 2022). Previous WM studies have shown that processing negative stimuli decreases short-term recall performance (Chainay et al., 2023; Plancher et al., 2019). The purpose of the present study was to determine whether explicit processing is required to induce an emotional effect on WM performance, or whether the mere presence of emotional stimuli, without explicit processing, is sufficient to automatically capture attention and induce a deleterious effect on WM. For this purpose, in two experiments, participants had to perform a complex span task in which neutral words to memorize were presented and interspersed by negative or neutral images. In Experiment 1, participants had to carry out explicit voluntary processing of the images by categorizing them into living and nonliving categories, while in Experiment 2, no explicit processing was required on these stimuli.

In line with the literature and our previous results (Chainay et al., 2023; Plancher et al., 2019), in Experiment 1 we showed that WM performance was lower when the voluntary processing was engaged with negative valence images compared with neutral ones. In addition, processing of the emotional images was slower than that of neutral ones. Thus, emotional stimuli appear to capture attentional resources, so that the amount of resources available to process other stimuli was reduced, which impaired the maintenance of words through attentional refreshing. In Experiment 2, results showed that even when no processing was required, presenting emotional stimuli also produced lower serial recall. This suggests that the mere presentation of emotional images automatically captures attention, which has a deleterious impact on memory performance. Thus, regardless of whether voluntary processing is involved, attending emotional stimuli leads to a drop in WM performance. Given the attentional trade-off between WM maintenance and processing, this reduction in memory performance suggests that emotional stimuli automatically capture attention, consuming resources that are therefore no longer available to maintain the information in WM. Interestingly, we previously observed a detrimental effect of maintaining emotional information on the processing of neutral information (Chainay et al., 2023). Taken together, all these results suggest that attention is a limited resource that has to be shared between maintenance and processing in WM, regardless of whether the processing was made explicitly or not.

In the WM literature, the effect of concurrent processing on memory was observed mainly when participants were explicitly required to process stimuli (e.g., Barrouillet et al., 2011; Plancher & Barrouillet, 2013), thus involving top-down controlled attention. In our study, we showed that the mere exposure of negative images in a complex span task had a detrimental effect on WM performance. This result is consistent with previous studies on a variety of cognitive tasks showing that the processing of task-relevant stimuli is impaired when emotional distractors that do not require any processing are presented before (Pereira et al., 2006, 2010) or during the task (Erthal et al., 2005; Fernandes et al., 2013; Vuilleumier & Schwartz, 2001). Here, we confirm this interference effect in a WM task.

Our results are in line with the literature on attention and theories of WM. In the attention literature, Kahneman (1973), proposed that individuals would have a unique reservoir of attentional resources from which we can draw for our various activities. The more complex an activity is, in terms of processing and number of stimuli to be processed, the more resources it consumes, and the more difficult it will be to carry out another activity simultaneously. This is no doubt why, if we compare the magnitude of the effects of emotional stimuli on WM performance in our two experiments, we find a greater effect in Experiment 1, where voluntary processing semantic categorization task was required on the images, than in Experiment 2, where the images appeared only as distractors, without processing. The more costly processing in Experiment 1 consumed additional resources and therefore had an even greater effect on word recall in WM. Consistent with the idea that cognition and emotion share the same attentional resources, it has been reported that in a letter classification task presented with low or high perceptual load, fear-conditioned angry face distractors captured attention and interfered with task performance only under conditions of low perceptual load (Yates et al., 2010). Similarly, with subliminal emotional stimuli presented during a WM task (n-back), Uher et al. (2014) showed that when cognitive load (CL) of the main task was low (1-back), attention could be partly captured by subliminal emotional stimuli, whereas when CL was higher (2-back), capture could be lower and emotional stimuli could interfere less. According to the authors, there is a kind of top-down regulation of goal-directed attention.

Our results can also be discussed in relation to theories of WM. Attention is a central component in several WM models (Barrouillet et al., 2011; Cowan et al., 2005). The TBRS model, a specific attention-based model of WM, suggests that memory traces deteriorate when attention is divided between the maintenance and processing functions of WM due to limited and general attentional resources (Barrouillet et al., 2011). Refreshing, which involves placing memory traces into the focus of attention, prevents forgetting. Our results have implications for the TBRS model, as we observed that the mere presence of negative items, without explicit processing, captures attention in WM and impacts memory performance. We can thus generalize the predictions of the TBRS model to a situation of involuntary processing i.e. the processing–storage trade-off is implemented whatever the processing is voluntary or not. It would be important in the future to test whether this is restrictive to emotional stimuli or whether it can be generalized to any stimuli that automatically capture attention.

Within the TBRS framework the mechanism of attentional refreshing has been distinguished from verbal rehearsal (Barrouillet & Camos, 2014; Camos, 2015). Importantly in our study, verbal rehearsal was prevented by the continuous articulatory suppression, as our participants had to continually repeat "babebibobu" aloud. Even though both mechanisms, attentional refreshing and verbal rehearsal, 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 (for a review, see Camos, 2015). For instance, the phonological similarity effect or word length effect (which both are assumed to rely on verbal rehearsal) were observed on memory performance even when the attentional refreshing was impeded by an attentional task with a high CL. Contrary to attentional refreshing, it has been demonstrated that verbal rehearsal is a mechanism with low attentional demand (Atkinson & Shiffrin, 1968; Baddeley et al., 1975; Belleville et al., 1992; Naveh-Benjamin & Jonides, 1984). In our study, given that we assume that emotional stimuli capture attentional resources, emotional content of stimuli is supposed to impact the attentional refreshing only, and not the verbal rehearsal. We would have predicted the same effect of emotion on memory performance without articulatory suppression, but with higher overall memory performance because both mechanisms would have been available for word maintenance.

One method to examine refreshing is by varying the CL of a secondary task, typically done in complex span tasks. CL refers to the proportion of time attention is occupied by processing items from the concurrent task relative to the total available processing time (Barrouillet et al., 2011). Adjusting cognitive load alters this proportion: When more time is devoted to processing items, less time is available for refreshing. Consequently, memory traces decay more rapidly, leading to impaired memory performance. In a complex span task, this can be classically done by varying the complexity or the pace of the processing component of the task. In the context of the present study, we could assume that the CL is higher with emotional stimuli. Indeed, emotional stimuli are likely to capture attention for too long (as evidenced by slower processing times in negative compared with neutral trials), resulting in poorer memory performance. In complex span task, the CL effect has often been taken as evidence for active maintenance in WM (e.g., Fanuel et al., 2018; Plancher et al., 2017). If negative emotional stimuli impair the use of attentional refreshing, the joint manipulation of CL and the emotional nature of stimuli should result in an interaction between the two factors. In the present study, we did not manipulate the cognitive load, but in the future studies it would be interesting to investigate the effect of CL on the impact of emotions in a WM task to better understand their competition for attentional resources. As mentioned earlier, we have in the past examined the impact of emotional storage on processing, showing a detrimental effect of negative memoranda on processing (Chainay et al., 2023). It would also be interesting to test whether attentional resources overflow to the processing of negative stimuli only when the storage load is low or whether it generalizes to high storage.

Until now, models of WM have paid little attention to the emotional nature of the processing carried out during the proposed tasks. However, as our results suggest, the fact that involuntary, highly automatic processing can influence performance may also call into question the role of uncontrolled emotional mechanisms, such as an individual's emotional state. In the present study, we assessed participants' mood using BMIS (Mayer & Gaschke, 1988) before they performed the experimental task. We observed no significant correlations between serial recall of words and any of the four subscales of the BMIS in either Experiment 1 or Experiment 2. This was also the case when the data from both experiments were analyzed together. However, these data should be taken with caution, as it has been suggested in the literature that the emotional state can influence cognitive processes. For example, there is evidence that an unpleasant emotional state is associated with impaired cognitive functioning. Indeed, in a memory task, Lee & Sternthal (1999) showed that after inducing a positive or negative emotional state in participants by listening to music, neutral word recall performance was better after positive than negative induction. In addition, depression has been linked to a variety of neuropsychological deficits, including in the areas of processing speed, memory, and executive functioning (Rock et al., 2014). This raises the question of whether an individual's emotional state alone can impact WM performance. Recently, Songco et al. (2023) showed in a complex span test that individuals with a lifetime history of depression (individuals with current depression and individuals remitted from depression) performed worse on the WM task, compared with healthy controls. Such disturbances may contribute to the impairments in daily functioning often experienced by people suffering from depression.

In the future, it would be important to better understand the interaction between emotion, attention, and WM in order to offer patients appropriate care.

Acknowledgements We thank Adele Generet, Lobdna Wadii, Omar Chabak, and Christel Ramialiarison for help in testing participants.

Funding No funding was received for conducting this study.

Availability of data and materials The data and materials for all experiments can be viewed on the Open Science Framework: https://osf.io/39f5b/

Code availability The experiment was programmed and run using OpenSesame software. The script is available (without code) on the Open Science Framework: https://osf.io/39f5b/

Declarations

Conflicts of interest The authors have no relevant financial or non-financial interests to disclose.

Ethics approval No ethical approval is required. The study was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments.

Consent to participate All participants signed informed consent in accordance with the standard of the 1964 Helsinki Declaration.

Consent for publication Patients signed informed consent regarding publishing their data.

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