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Effect of Negative Emotional Content on Working Memory and Long-Term Memory

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In long-term memory, negative information is better remembered than neutral information. Differences in processes important to working memory may contribute to this emotional memory enhancement. To examine the effect that the emotional content of stimuli has on working memory performance, the authors asked participants to perform working memory tasks with negative and neutral stimuli. Task accuracy was unaffected by the emotional content of the stimuli. Reaction times also did not differ for negative relative to neutral words, but on an *n*-back task using faces, participants were slower to respond to fearful faces than to neutral faces. These results suggest that although emotional content does not have a robust effect on working memory, in some instances emotional salience can impede working memory performance.

Memory is often divided into the ability to retain information over short delays (*working memory*) and long delays (*long-term memory*). A critical question for understanding the relation between emotion and memory is the extent to which the emotional content of the to-be-retained information influences these forms of memory. Abundant evidence suggests that emotional content increases the likelihood that individuals retain information over long delays. This emotional memory enhancement effect has been demonstrated in numerous studies, using stimuli that have included pictures, words, stories, and narrated slide shows (see Buchanan & Adolphs, 2003; Dolan, 2002; Hamann, 2001, for reviews). The effect of emotional content on working memory processes remains unknown.

Working memory is a limited capacity system required for the ability to maintain and manipulate information over short periods of time (e.g., a few seconds) in the service of other cognitive tasks (e.g., problem solving; see Baddeley & Hitch, 1974; Cowan, 1988, 1995; Engle, Kane, & Tuhulski, 1999; Engle & Oransky, 1999; Jonides & Smith, 1997). The specifics of the system continue to be debated. In an influential model, Baddeley and colleagues (Baddeley & Hitch, 1974) proposed that working memory consisted of two storage buffers (the phonological loop for verbal information and the visuospatial sketchpad for nonverbal information). The coordination of these buffers was proposed to be elicited by a central executive (modeled as the Supervisory Attentional System; Norman & Shallice, 1980). It has since been suggested that no single "central executive" exists, but rather a host of functions of the central executive that focus attention on task-relevant details and inhibit processing of task-irrelevant information (e.g., Baddeley, 1998). In contrast to the model of Baddeley and colleagues, others conceptualize working memory as the activated component of long-term memory stores (Cowan, 1995; Engle et al., 1999; Engle & Oransky, 1999). As in Baddeley and colleagues' working memory model, processes of selective attention are critical to the operation of working memory: They determine what information is selected from long-

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term memory, thereby controlling what information is contained within the working memory system.

Emotion and Working Memory

The vast majority of studies examining the link between emotion and working memory have focused on emotional state. In the typical experiment, participants are induced into a positive or negative mood and then are administered the experimental task. Most studies have found that mood induction results in a change in cognitive task performance (Darke, 1988; Elliman, Greene, Rogers, & Finch, 1997; Gray, 2001; Spies, Hesse, & Hummitzsch, 1996). For example, negative mood has been shown to impede performance on tests of problem solving, working memory, and attention (Cheng & Holyoak, 1985; Spies et al., 1996). This adverse effect of negative mood on working memory may result because of intrusive thoughts and worries that distract the individual from the task at hand (Eysenck & Calvo, 1992; Seibert & Ellis, 1991). In support of this hypothesis, anxiety has been shown to have a disproportionate effect on verbal working memory as compared with visuospatial working memory performance (Ikeda, Iwanaga, & Seiwa, 1996). This pattern would be expected if verbalization of task-irrelevant information were interfering with the articulatory loop (implicated in verbal working memory) while leaving the visuospatial sketchpad (implicated in nonverbal working memory) unaffected (see Nitschke, Heller, Palmieri, & Miller, 1999, for further discussion) Other negative mood states (e.g., sadness) could impede working memory for a similar reason (i.e., intrusion of task-irrelevant thoughts).

It is currently an open question as to whether this modulation of working memory by emotion occurs when the emotional content of the stimuli is manipulated, rather than the emotional mood of the participant. Emotional content could affect what information is attended (e.g., the particular stimuli or stimulus attribute). The emotional content of stimuli is known to affect the distribution of attention, such that emotional stimuli are likely to “grab” attention, (Bargh, Chaiken, Govender, & Pratto, 1992; Pratto & John, 1991; Reimann & McNally, 1995; Williams, Mathews, & MacLeod, 1996) and to gain prioritized processing (Anderson & Phelps, 2001; Dolan, 2000; Tabert et al., 2001). Multiple lines of evidence suggest that emotional stimuli can be processed relatively automatically: At least in some circumstances, individuals appear able to process fear-related visual stimuli in the absence of attention (Stenberg, Wilking, & Dahl, 1998) or conscious awareness (Öhman, 2002). Emotional stimuli have been found to activate the amygdala, even when individuals are unaware that the information has been presented (Morris, Öhman, & Dolan, 1998; Vuilleumier et al., 2002; Whalen et al., 1998, but see Pessoa, Kastner, & Ungerleider, 2002), and patients with neglect are more likely to recognize an emotional stimulus than a neutral stimulus presented in the contralesional field (Vuilleumier & Schwartz, 2001). This biasing of attention toward emotional stimuli could result in an enhanced likelihood of processing emotional, as compared with nonemotional, information in working memory. The prioritized or relatively automatic processing of emotional content could also facilitate the holding online of emotional information as compared with nonemotional information. Thus, in this respect, emotional content could be expected to enhance performance on working memory tasks via effects on attention.

The story, however, may not be so straightforward: Attentional biasing toward emotional content could also have a detrimental effect on working memory performance, depending on task requirements. Emotional content may result not only in attending to emotional stimuli over nonemotional stimuli but also in a specific focusing of attention on the stimulus dimensions that convey the emotion salience. In other words, attention is likely focused on the emotion-relevant stimulus dimensions and diverted from the other stimulus dimensions. This biasing of attention is proposed to account for a number of experimental observations, including the exaggerated Stroop phenomenon, in which individuals are particularly slow to name the color of ink in which an emotional word is written, as compared with a neutral word (reviewed by Williams et al., 1996). Thus, to the extent that performance on working memory tasks requires focusing of attention on nonemotional stimulus dimensions, emotional content could actually impede task performance.

In addition to these relatively automatic effects of emotion on attention, the emotional content of stimuli may also influence controlled processing of the information. Individuals may be more likely to direct attention consciously toward emotional stimuli or to elaborate on emotional information because of its personal relevance (Doerksen & Shimamura, 2001; Heuer & Reisberg, 1990) or distinctiveness (Christianson & Engelberg, 1999; Pesta, Murphy, & Sanders, 2001). These intentional processes could affect working memory performance, although, as with the more automatic processes discussed above, the direction of the modulation is not without question. Depending on the specific task characteristics, having additional processing of emotional stimuli could facilitate (if task-relevant information is attended) or impair (if task-irrelevant details are processed) working memory performance.

To our knowledge, only one study has asked whether emotional content affects processes supporting working memory (Perlstein, Elbert, & Stenger, 2002). The authors, who used a modified delayed match-to-sample task, found evidence that emotional content of stimuli modulates working memory processes: Negative emotional content (negative photographs) reduced working memory related brain activation. This result would suggest that emotional content might hinder performance on working memory tasks. The primary goal of the present study was to examine whether there is a consistent effect of emotional content on working memory performance, and if so, whether emotional content enhances or impairs performance.

Emotion and Long-Term Memory

Another goal of the present study was to examine whether emotional content had similar effects on working memory and long-term memory performance (e.g., enhancing effects on both types of memory) or whether there are instances in which emotional content might have distinct effects on working memory as compared with long-term memory.

Many of the processes discussed in relation to working memory (e.g., biasing of attention, prioritization of processing) would also be expected to influence long-term memory. The direction of the modulation, however, would not necessarily be anticipated to be identical. As discussed, biasing of attention toward the emotional content of stimuli could actually have a hindering effect on working memory performance if emotional aspects of a stimulus were attended to rather than nonemotional aspects that may be critical for task performance. In contrast, attention to any stimulus characteristics at encoding would likely be beneficial to long-term retention of that stimulus.

Controlled processing would also likely have an effect on long-term memory as well as working memory. If individuals are more likely to elaborate on semantic or autobiographical features of emotional stimuli (Christianson & Engelberg, 1999; Doerksen & Shimamura, 2001; Kensinger & Corkin, in press; Phelps, LaBar, & Spencer, 1997), or if they show increased rehearsal of emotional information (Christianson & Engelberg, 1999), these factors could increase the likelihood that emotional information is encoded into long-term memory. Another possibility is that emotional events are more distinct and unique, and this characteristic contributes to their being better remembered over the long term (Christianson & Engelberg, 1999; Pesta et al., 2001).

Additional effects of emotional content may be orthogonal to these processes, and some of these interactions between emotion and memory processes are likely to be unique to long-term memory. For example, part of the long-term memory enhancement for emotional information is thought to result from a modulation of consolidation processes (see Cahill & McGaugh, 1998; McGaugh, 2000, for review): Information that is emotional may be more frequently consolidated than information that is not emotional. In support of this idea, comparisons across studies suggest that emotional enhancement increases as retention interval increases (Cahill et al., 1996; Canli, Zhao, Desmond, Glover, & Gabrieli, 1999; Canli, Zhao, Brewer, Gabrieli, & Cahill, 2000; Tabert et al., 2001). One plausible neuroanatomical explanation for this finding is that emotional stimuli activate the amygdala, which in turn modulates hippocampal function, thereby modulating consolidation (Cahill, 1999; McGaugh, 2000; McGaugh, Cahill, & Roozendaal, 1996).

Another factor that may explain the long-term memory enhancement for emotional information concerns retrieval processes: Emotion may serve as a cue at retrieval, thereby making retrieval of emotional information easier than retrieval of neutral information because of the additional contextual support.[1] Some evidence that individuals may retrieve the emotional context in which information was encoded comes from neuroimaging studies (Maratos, Dolan, Morris, Henson, & Rugg, 2001; Maratos & Rugg, 2001) that found different patterns of brain activity at retrieval as a function of whether the neutral word being retrieved was studied in an emotional context (i.e., a negative sentence) or a neutral context. These effects of emotion on consolidation or retrieval would be expected to impact long-term retention but not the ability to

[1] We thank an anonymous reviewer for bringing this possibility to our attention.

maintain or manipulation information over short intervals.

Present Study

As discussed above, some effects of emotional content (e.g., biasing of attention, prioritization of processing) could be expected to influence both working memory and long-term memory performance. In contrast, other effects of emotion (e.g., modulation of consolidation processes) could have specific effects on long-term retention. The goal of the present study was to examine whether emotional content affects performance on working memory tasks as well as influencing long-term retention. Although prior studies suggest that emotional state can influence working memory performance, it is unclear whether the affective content of information maintained in working memory can also influence performance. Additional factors, such as intrusive thoughts (Seibert & Ellis, 1991), focus of attention on internal stimuli (Carver, Peterson, Follansbee, & Scheier, 1983; Ingram, 1990), and emotional load (Mackie & Worth, 1989) may occur with mood induction procedures but not with tasks that manipulate emotional content.

To our knowledge, no study has looked at the effect of emotional content on behavioral performance across a range of working memory tasks. It therefore remains unclear whether emotional content benefits, hinders, or has no effect on the ability to maintain or manipulate information over short periods of time. To answer this open question, we examined participants' performance on working memory tasks (self-ordered pointing, *n*-back, backward word span, and alphabetical word span) with emotional and neutral stimuli. The critical question was whether participants' working memory performance would be affected by the emotional content of the stimuli (e.g., decreased accuracy or increased reaction time for emotional items as compared with neutral items or vice versa). We also included a long-term retention component: Following a delay of at least 24 hr, participants took a free recall test in which they were asked to write descriptions of all the stimuli they remembered from the previous day's experiment.

Task 1: Self-Ordered Pointing

Method

Participants

The participants comprised 46 young adults (25 men, 21 women; mean age = 23.7). All participants were native English speakers; they were screened to exclude those who were depressed or who had a history of depression. No participant was taking centrally acting medications. Completion of the task required 10–15 min, and participants were remunerated at $10/hr. Testing materials and procedures were approved by the Massachusetts Institute of Technology (MIT) Committee on the Use of Humans as Experimental Subjects, and all participants gave informed consent.

Working Memory Task (Adapted From Petrides & Milner, 1982)

Participants viewed a series of 15 slides, 1 at a time. Slides were presented on an iMac,G3, Macintosh computer. The 15 slides each contained the same 15 pictures, arranged in a different, random order on each slide. Pictures were arranged in a grid that was five columns by three rows in size. The order of the slides was pseudorandomized across participants. Participants were instructed that they should point to all the stimuli, one at a time and in any order they wished, but that they should not point to any stimulus more than once. Thus, on each of the 15 slides, participants were to select a picture (by pointing to it) that was different from any picture that they had previously chosen. Successful performance required participants to monitor the total pool of pictures and to update, trial by trial, the pictures that they had selected. If a participant made an error and pointed to a picture already selected, he or she was told that picture had already been selected and was asked to pick another picture on the same slide. The next slide was shown as soon as the participant had selected a picture that differed from those selected on prior slides. The experimenter recorded all responses of the participant. Participants were instructed to avoid using spatial or semantic strategies, and a participant's data was eliminated if he or she was judged by the experimenter to be using such a strategy.

Two error types were relevant when scoring the performance (Petrides & Milner, 1982): between-trial errors (when a participant selected a picture that had been chosen previously on a different slide) and the number of trials with an error (e.g., if a person made two between-trial errors on a slide—selecting an already-chosen picture and then, when told that picture had already been selected, selecting another already-chosen picture—we would record that as one trial with an error).

The six different versions of the test each incorporated a different kind of stimulus material: (a) negative animals (e.g., snakes), (b) neutral animals (e.g., camel), (c) positive animals (e.g., puppies), (d) negative people (e.g., injured), (e) neutral people, and (f) positive people (e.g., very attractive people; nudes were not included). Pictures were selected from the International Affective Picture Rating System (Lang, Bradley, & Cuthbert, 1999). The order of test versions was pseudorandomized across participants, and all participants first performed a practice task with a set of common household objects.

Negative pictures were selected to be relatively high in arousal and low in valence, positive pictures were relatively high in arousal and high in valence, and neutral pictures were rated as nonarousing and were neither high nor low in valence. As the means and standard deviations given below indicate, negative and positive pictures were matched in absolute valence (i.e., distance from neutral), negative pictures were higher in arousal than the positive pictures (for people images: negative valence = 2.06 [*SD* = 0.53]; negative arousal = 6.11 [*SD* = 0.53]; neutral valence = 4.21 [*SD* = 0.27], neutral arousal = 4.1 [*SD* = 0.60]; positive valence = 6.06 [*SD* = 0.38], positive arousal = 5.76 [*SD* = 0.51]; for animal images: negative valence = 2.62 [*SD* = 1.54], negative arousal = 6.02 [*SD* = 0.83]; neutral valence = 4.45 [*SD* = 0.72], neutral arousal = 4.46 [*SD* = 0.83]; positive valence = 6.16 [*SD* = 0.33], positive arousal = 5.65 [*SD* = 0.51]).

Long-Term Memory Task

After a delay of approximately 1 day, participants were given a free recall task in which they were asked to write a brief description of all of the pictures they remembered from the previous day's experiment.

Results and Discussion

Working Memory Performance

We obtained two error scores: (a) total number of between-trial errors for a set of 15 pictures and (b) total number of trials with an error (Table 1).

Between-Trial Errors

We conducted a repeated-measures analysis of variance (ANOVA) on the number of between-trial errors with emotion (positive, negative, neutral) and stimulus type (animals, people) as within-subject factors. The ANOVA revealed no main effects (and critically no effect of emotion, $F[2, 88] < 1.8$; $\eta^2 = .002$) and no significant interactions.

Table 1
Self-Ordered Pointing: Errors as a Function of Picture Category and Item (Emotion) Type

Picture category and item type	Between-trial errors		Trials with an error	
	M	*SE*	*M*	*SE*
People				
Positive	2.00	0.41	0.96	0.16
Negative	1.74	0.36	1.07	0.18
Neutral	1.56	0.27	1.07	0.16
Animals				
Positive	1.51	0.25	0.95	0.15
Negative	1.86	0.35	1.02	0.16
Neutral	2.02	0.36	1.31	0.21

Trials With an Error

A repeated-measures ANOVA, conducted as above, again indicated no effect of emotion on the number of trials with an error, $F(2, 88) < 1.8$; $\eta^2 = .02$, and no other main effects or interactions.

These results indicate that participants performance on the self-ordered pointing task was unaffected by emotional content. Thus, emotional content did not alter performance on a working memory task requiring updating and monitoring of primarily nonverbal information. (The stimuli were complex pictures; however, they could be verbalized, so it is likely that verbal and nonverbal manipulation were used to perform the tasks).

Long-Term Memory Performance

A repeated-measures ANOVA indicated a significant effect of emotion, $F(2, 80) = 12.09$, $p < .01$; $\eta^2 = .41$, no effect of stimulus type, and no interaction between stimulus type and emotion type. Subsequent *t* tests indicated that recall was better for the negative animals and positive animals than neutral animals, $t(32) > 3.5$, $p < .01$, and for negative people and positive people than neutral people, $t(32) > 3.8$, $p < .01$ (see Table 2).

Thus, consistent with prior studies (see Hamann, 2001; Buchanan & Adolphs, 2003, for reviews), delayed recall was superior for the emotional pictures (positive or negative) than for the neutral pictures. The next task examined the effect of emotion on a working memory task, using verbal stimuli.

Table 2
Delayed Recall of Stimuli Used on the Self-Ordered Pointing Task as a Function of Picture Category and Item Type

Picture category and item type	Number recalled[a]	
	M	*SE*
People		
Positive	3.69	0.40
Negative	4.16	0.43
Neutral	2.29	0.41
Animals		
Positive	3.47	0.46
Negative	3.63	0.48
Neutral	1.72	0.29

[a] The number of pictures recalled was out of a total of 15.

Task 2: Backward and Alphabetical Word Span With Blocked Stimuli

Method

Participants

The participants comprised 41 young adults (23 men, 18 women; mean age = 23.7) meeting the criteria outlined for Task 1.

Backward Word Span

The participants heard a series of words at a rate of approximately one word per second. They were then asked to repeat the words in reverse order. Participants were given two attempts at each list length; if they missed both of the trials, the task was discontinued. The first administered word string consisted of 2 words, and the maximum word string length that could be achieved was 10 words.

There were two versions of the task. One version used arousing words (taboo words, selected to be high in arousal, e.g., *bitch, shit*). The other version used neutral words, matched in word length and frequency to the arousing words (Coltheart, 1981). To control for the fact that taboo words were also in some way semantically related (i.e., taboo is a category), all neutral words were semantic associates of the words *think* or *mind*. The order of the versions was counterbalanced across participants.

We scored the backward word span task in three ways. First, we scored the span as the highest word string length at which participants had correctly repeated (in reverse order) at least one of the two strings of words (e.g., if one of two attempts at Length 4 was successful, and neither attempt at Length 5 was successful, the span score would be 4). Second, we allotted 1 point for each string that the participant repeated correctly. Thus, if participants correctly repeated both strings of Length 2 and one string of Length 3, their score would be 3. Third, we calculated a weighted sum whereby a correct string of Length 2 received 2 points, a correct string of Length 3 received 3 points, and so forth.

Alphabetical Word Span

Task administration was identical to that of the backward word span task except that participants were instructed to repeat the words in alphabetical order.

Long-Term Retention

A pilot study indicated that long-term recall of words from the word span task was near floor (less than 1% of words were recalled). Participants from this study, therefore, returned on a separate day, at least 2 weeks from the time of the completion of the word span task, to participate in a different long-term retention study. In this study, participants viewed 168 words (84 neutral, 84 arousing) and were asked to rate the frequency of the words. Participants were unaware that a memory test would follow. After a 1-day delay, they were asked to recall all of the words from the list.

Results and Discussion

Backward Word Span

We scored the word span task in three ways: (a) the highest number of words correctly repeated, (b) assigning 1 point for every word string repeated correctly, and (c) as a weighted sum (e.g., two word strings correct at Length 2 equals 4 points, and so forth; see Table 3). We conducted a repeated-measures ANOVA for each score and found no effect of word type (emotional, neutral) on span length, $F(1, 40) = 0.96$, $p > .30$; $\eta^2 = .02$, on the summed score, $F(1, 40) = 1.5$, $p > .20$; $\eta^2 = .03$, or on the weighted score, $F(1, 40) = 2.20$, $p > .15$; $\eta^2 = .06$.

Alphabetical Word Span

We conducted repeated-measures ANOVA for each score and found no effect of word type (emotional, neutral) on span length, $F(1, 40) < 2.10$, $p > .15$; $\eta^2 = .05$, summed score, $F(1, 40) < 0.96$, $p > .33$; $\eta^2 = 0.2$, or weighted score, $F(1, 40) < 1.37$, $p > .20$; $\eta^2 = .03$.

Consistent with the results from the self-ordered pointing task, the emotional content of the stimuli did not affect working memory performance on the back-

Table 3
Word Span Scores as a Function of the Emotion Type of the Words Included in the Task

Task	Span		No. of words repeated		Weighted sum of words	
	M	*SE*	*M*	*SE*	*M*	*SE*
Backward word span						
Emotional	4.88	0.16	5.89	0.40	22.02	1.44
Neutral	5.05	0.19	6.20	0.43	24.39	1.82
Alphabetical word span						
Emotional	4.73	0.15	5.91	0.39	22.17	3.01
Neutral	4.93	0.17	6.13	0.42	23.66	1.58

ward word span or alphabetical word span tasks. These tasks are believed to place high demands on verbal storage and manipulation; thus, the results suggest that emotional content does not have a robust effect on a person's accuracy in holding verbal information online or in manipulating that information.

Long-Term Recall

A repeated measures ANOVA with word type (arousing, neutral) as a within-subject factor indicated a significant effect of item type, $F(1, 39) = 7.24$, $p < .01$. Subsequent *t* tests confirmed that participants recalled significantly more arousing words ($M = 26.5$, $SE = 2.1$) than neutral words ($M = 15.5$, $SE = 2.3$), $t(40) = 8.13$, $p < .01$. Thus, the results from the word span tasks converge with those of the self-ordered pointing task, suggesting that although emotional content modulates long-term memory, it does not have an effect on working memory task performance.

One plausible reason why the self-ordered pointing and word span tasks may not have shown effects of emotional content is because the stimulus types were blocked (i.e., participants performed a version with all emotional and then all neutral stimuli, or vice versa). Participants may have noticed this consistency and may have adopted strategies that resulted in similar performance on versions with the different stimulus types. In the next task, therefore, we intermixed emotional and neutral words within the same task version.

Task 3: Backward and Alphabetical Word Span With Interleaved Stimuli

Method

Participants

The participants were 25 young adults (12 men, 13 women; mean age = 24.1), meeting the criteria outlined for Task 1.

Span Task

Task materials and design were identical to those described above for the word span tasks, except that neutral and emotional words were intermixed. Thus, participants heard a series of emotional and neutral words and repeated the words in reverse alphabetical order. The critical question was whether participants would be more or less likely to omit an emotional word as compared with a neutral word when repeating back the word strings.

Results and Discussion

A repeated-measures ANOVA indicated no effect of word type (emotional, neutral), $F(1, 24) = 0.92$, $p > .30$; $\eta^2 = .04$, on the total number of words repeated. Participants were just as likely to omit an emotional word as they were to omit a neutral word. We also conducted an ANOVA to examine whether there was an effect of the prior word (e.g., if people were more likely to omit a word that immediately followed an emotional word). This analysis indicated no effect of item type or preceding item type on performance or an interaction (Table 4).

Even with emotional and neutral stimuli intermixed on the word span tasks, participants' accuracy was

Table 4
Performance on the Word Span Task With Interleaved Stimuli as a Function of Item Type and Preceding Item Type

Word type and preceding word type	No. of words omitted	
	M	*SE*
Emotional		
Emotional	2.08	0.75
Neutral	2.21	0.73
Neutral		
Emotional	2.11	0.67
Neutral	2.05	0.79

unaffected by the emotional content of the words. Taken together with the results from the self-ordered pointing and word span tasks with blocked stimuli, these results suggest that emotional content may not have an effect (or at least not a robust effect) on the accuracy with which individuals maintain or manipulate verbal information held online.

A dimension not addressed in the prior tasks, however, was speed: All of the previous tasks were self-paced, and therefore differences in speed of information processing might not have affected performance. The next task, therefore, measured reaction times as well as accuracy.

Task 4: *n*-Back With Blocked Stimuli

Method

Participants

The participants comprised 30 young adults (15 men, 15 women; mean age = 21.8), meeting the criteria outlined for Task 1.

Working Memory Task

The participants viewed 50 frames of stimuli, consisting of six unique faces or six unique words. Participants were instructed to press a button marked "S" if the stimulus was the same as the stimulus that had occurred *n* stimuli before. In the first run, $n = 2$ (i.e., participants pressed a button every time the current stimulus matched the one that had occurred two before, with one intervening stimulus). The *n* continued to increase by 1 until participants received a corrected score (percentage of hits percentage of false alarms) of less than 25%. On each run, 40% of the items required a button press.

There were four versions of this task. In the first version, there were six faces, three men and three women, each displaying a facial expression of fear. In the second version, there were six faces, three men and three women, each displaying a neutral expression. Faces were taken from Ekman (Ekman & Friesen, 1976). In the third version, there were six arousing (taboo) words (e.g., *slut, penis*). In the fourth version, there were six neutral words, matched in length and frequency to the arousing words (Coltheart, 1981). The order of the versions was pseudorandomized across participants.

We scored this task for accuracy in two ways. First, we calculated the corrected recognition rate (hits false alarms) separately as a function of the number of intervening stimuli (i.e., at each gap length). Second, from these percentages, we calculated a corrected *n*-back score at each gap length and summed the percentages attained by each participant (e.g., 100% at Gap Length 2, 50% at Gap Length 3, and 20% at Gap Length 4 would result in a score of $1 + 0.5 + 0.2 = 1.7$). Only gap lengths at which the corrected recognition score was at or above 25% were included in these analyses. Third, we calculated a weighted score. Thus, in the above example, the score would be $(1 \times 2) + (0.5 \times 3) + (0.2 \times 4) = 4.1$. We also tabulated the reaction times to identify the targets.

Long-Term Retention

Following a delay of approximately 24 hr, participants were asked to write all of the words they remembered as being words on the *n*-back task. We could not assess long-term memory for the faces because recall descriptions were usually not sufficient to differentiate the faces, and recognition performance was at ceiling for all participants.

Results and Discussion

Working Memory Performance

Corrected recognition rates. A repeated-measures ANOVA indicated an effect of memory load (whether the task was 2-back, 3-back, and so forth), $F(4, 112) = 268.03$, $p < .01$; $\eta^2 = .87$, but indicated no effect of emotion type, $F(1, 28) = 1.44$, $p > .25$; $\eta^2 = .03$, and no interaction between emotion type and memory load.

Sum of scores. A repeated-measures ANOVA with emotion type (emotional, neutral) and stimulus type (faces, words) as within-subject factors indicated no effect of stimulus type, $F(1, 29) = 0.33$, $p > .40$; $\eta^2 = .02$, no effect of emotion type, $F(1, 29) = 1.88$, $p > .18$; $\eta^2 = .06$, and no interaction (see Table 5).

Weighted sum of scores. A repeated-measures ANOVA with emotion type (emotional, neutral) and stimulus type (faces, words) as within-subject factors indicated no effect of stimulus type, $F(1, 29) = 0.76$, $p > .35$; $\eta^2 = .03$, no effect of emotion type, $F(1, 29) = 0.21$, $p > .35$; $\eta^2 = .01$, and no significant interactions (see Table 5).

Reaction time. A repeated-measures ANOVA indicated no effect of emotion type, $F(1, 29) = 0.82$, $p > .35$; $\eta^2 = .02$ (see Table 5).

Recall

A repeated-measures ANOVA conducted on the words recalled indicated a significant effect of emotion type, $F(1, 29) = 77.87$, $p < .01$; $\eta^2 = .15$, with

Table 5
Scores and Reaction Time on the n-Back Task With Blocked Stimuli as a Function of Stimulus Type and Emotion Type

	Sum of scores		Weighted sum of scores		Reaction time[a]	
Stimulus	*M*	*SE*	*M*	*SE*	*Mdn*	*SE*
Faces						
Emotional	1.65	0.13	4.82	0.48	0.793	0.19
Neutral	1.77	0.13	5.07	0.48	0.801	0.08
Words						
Emotional	1.58	0.13	4.61	0.51	0.779	0.16
Neutral	1.68	0.12	4.88	0.47	0.772	0.18

[a] Reaction time was measured in seconds.

participants recalling significantly more emotional ($M = 4.31$, $SE = 0.41$) than neutral ($M = 2.77$, $SE = 0.32$) words.

As in the prior tasks, emotional content had a robust effect on long-term retention but no effect on working memory accuracy. There was also no evidence of an effect of emotional content on speed or efficiency of processing: Participants responded with similar reaction times on the *n*-back task with emotional and neutral faces. This task, however, included stimuli blocked by emotion; therefore, the critical comparisons occurred across task versions rather than within a version. It is possible that variability in response times across the two versions obscured any effect of emotion. It is also possible that any effects of emotional content were attenuated if participants expected emotional stimuli to appear. To address the possible confounds introduced by blocking stimuli, the next experiment again used the *n*-back design, but with emotional and neutral stimuli intermixed.

Task 5: *n*-Back With Interleaved Stimuli

Method

Participants

The participants comprised 36 young adults (18 men, 18 women; mean age = 22.6), meeting the criteria outlined for Task 1.

Working Memory Task

The materials were identical to those described above, except that emotional and neutral stimuli were interleaved within the same task. Thus, there were six stimuli used in each task (6 words, 3 taboo, 3 neutral, or 6 faces, 3 angry, 3 neutral). Two different task versions were created, with different faces and words, so that all 12 faces and 12 words used in the blocked-stimulus task were used in this design. The task version and order of the tasks (faces–words or words–faces) were pseudorandomized across participants.

We introduced several methodological changes from the prior task version: Participants were asked to respond both to target matches (by pressing “M” for match) and nonmatches (by pressing “N” for nonmatch). Speed of response was also emphasized: Participants were told that it was critical to respond as quickly as possible (whereas in the prior version, speed had not been emphasized). The 2-back and 3-back tasks were administered; however, because of the emphasis on speed, participants’ accuracies were much lower than in the prior task version with blocked stimuli. Thus, performance on the 3-back task was near chance (many participants’ accuracy rates were below 20%). We, therefore, present only the results for the 2-back task.

Long-Term Retention

Following a delay of approximately 24 hr, participants were asked to write all of the words they remembered as being words on the *n*-back task. We could not assess long-term memory for the faces because recall descriptions were not sufficient to differentiate the faces, and recognition performance was at ceiling for all participants.

Results

Working Memory Accuracy

A repeated-measures ANOVA with item type (match, nonmatch), emotion type (emotional, neutral), and stimulus type (face, word) as within-subject factors indicated no significant main effect of stimulus type ($\eta^2 = .002$), item type ($\eta^2 = .01$), or emotion type ($\eta^2 = .03$), and no significant interactions (see Table 6).

Table 6
Reaction Time and Accuracy on the n-Back Task as a Function of Stimulus Type, Item Type, and Preceding Item Type

Stimulus, item type, and preceding item type	Reaction time[a]		% Correct	
	Mdn	*SE*	*M*	*SE*
Faces				
Emotional				
Emotional	1.01	0.04	65	5
Neutral	0.85	0.03	65	5
Neutral				
Emotional	0.88	0.03	68	5
Neutral	0.79	0.03	66	5
Words				
Emotional				
Emotional	0.95	0.05	67	4
Neutral	0.95	0.04	68	4
Neutral				
Emotional	0.91	0.03	68	4
Neutral	0.92	0.03	68	4

[a] Reaction time was measured in seconds.

Reaction Time

A repeated-measures ANOVA with item type (match, nonmatch), emotion type (emotional, neutral), and stimulus type (face, word) as within-subject factors indicated no effect of item type ($\eta^2 = .01$), no effect of stimulus type ($\eta^2 = .004$), a marginal effect of emotion type, $F(1, 35) = 2.93$, $p < .10$; $\eta^2 = .08$, and a significant interaction between stimulus type and emotion type, $F(1, 35) = 8.00$, $p < .01$; $\eta^2 = .186$).

An ANOVA conducted only for the faces 2-back task indicated a significant effect of emotion, $F(1, 35) = 9.05$, $p < .01$; $\eta^2 = .205$), whereas an ANOVA conducted only for the word 2-back did not, $F(1, 35) = 0.65$, $p > .40$; $\eta^2 = .02$. Subsequent *t* tests indicated that individuals responded faster to neutral faces than to emotional faces, $t(35) = 3.01$, $p < .01$, but that reaction times were similar for neutral and emotional words, $t(35) = 0.81$, $p > .30$.

We next asked whether the reaction times differed as a function of the preceding stimulus (i.e., whether reaction times were faster or slower if they followed an emotional face than a neutral face). An ANOVA with item type (emotional, neutral), preceding item type (emotional, neutral), and stimulus type (face, word) as within-subject factors indicated a significant effect of item type, $F(1, 35) = 4.44$, $p < .05$; $\eta^2 = .13$, a significant effect of preceding item type, $F(1, 35) = 14.2$, $p < .01$; $\eta^2 = .33$, no effect of stimulus type, a significant interaction between item type and preceding item type, $F(1, 35) = 6.12$, $p < .05$; $\eta^2 = .17$, a marginal interaction between item type and stimulus type, $F(1, 35) = 4.03$, $p < .07$; $\eta^2 = .03$, and a significant three-way interaction between item type, preceding item type, and stimulus type, $F(1, 35) = 4.21$, $p < .05$; $\eta^2 = .13$.

An ANOVA conducted only for the words indicated no effect of item type, no effect of preceding item type, $F(1, 35) = 2.68$, $p > .15$, and no interaction. In contrast, ANOVA conducted only for the faces indicated a significant effect of item type, $F(1, 35) = 28.23$, $p < .01$; $\eta^2 = .49$, preceding item type, $F(1, 35) = 20.89$, $p < .01$; $\eta^2 = .42$, and a significant interaction between item type and preceding item type, $F(1, 35) = 31.91$, $p < .01$; $\eta^2 = .52$. Participants were slowest to respond to an emotional face that followed an emotional face and were fastest to respond to a neutral face that followed a neutral face (see Table 6).

Recall

A repeated-measures ANOVA conducted on the recall for the words indicated a significant effect of emotion type, $F(1, 35) = 80.01$, $p < .01$; $\eta^2 = .18$. Participants recalled more emotional words ($M = 4.7$) than neutral words ($M = 2.9$).

As in all prior tasks, emotional content had a robust effect on long-term retention. In addition, consistent with the prior tasks, emotional content did not alter the accuracy of information maintained or manipulated: Participants were just as accurate at noting matches or nonmatches when the faces or words were emotional as compared with when they were neutral. In contrast, reaction times on the faces version of this task were affected by emotional content: Participants were slower to respond to emotional faces than neutral faces. We also found an interaction with the preceding stimulus, such that individuals were slowest to respond when the face was emotional and the preceding face had also been emotional and were fastest when the face was neutral and the preceding face had also been neutral. No such effect was present for the verbal stimuli.

General Discussion

By altering the emotional content of stimuli used in a series of working memory tasks and by assessing delayed free recall of those stimuli, this study compared the effects of negative emotional content on (a) the ability to maintain information online and to manipulate that information and (b) to recall the information after a delay. Consistent with prior studies, emotional content had a large effect on delayed free recall: After a delay interval of 1–2 days, participants recalled significantly more negative stimuli than neutral stimuli used in the working memory tasks. Thus, even with incidental encoding (i.e., participants did not realize their memories would later be tested), differences at encoding, consolidation, or retrieval enhanced participants' long-term memory for the negative relative to the neutral information.

In contrast to the enhancing effects on long-term memory, emotional content did not have a robust or consistent effect on working memory performance. Emotional content did not modulate the accuracy with which participants performed any of the working memory tasks. The efficiency or speed of performance, however, was affected on one task: Participants' reaction times on the 2-back task were slower for fearful faces than neutral faces. The effect was highly specific, such that it occurred only when stimuli were faces (not words) and occurred most strongly when an emotional face followed another emotional stimulus.

These findings raise a number of questions. First, why might we have found an effect of emotional content only for a test measuring speed and not on tasks measuring accuracy? Test sensitivity may have been a contributor, that is, reaction times may be more sensitive to small modulations by emotional content than is accuracy. It is interesting to note that although accuracy measures for emotional and neutral stimuli did not differ significantly, in nearly every task, performance was numerically poorer for emotional as compared with neutral items.

Nevertheless, statistical sensitivity may not be the only explanation. Emotional content may be more likely to modulate the efficiency with which information is processed, as compared with the accuracy with which it is held online. When emotional processing systems are activated (e.g., by viewing a fearful stimulus), additional inputs would likely be received by the working memory system (e.g., those dealing with emotion, arousal, physiological response; see LeDoux, 2002, for further discussion). It may be, therefore, that there are many additional facets of information that must be inhibited to allow for processing of only the task-relevant information (in the 2-back task, whether the face is identical to that seen two before). This increased demand on inhibition may slow the response times of individuals presented with stimuli that represent a fearful state (i.e., the fearful faces).

This explanation also fits with the finding that the preceding item type influenced speed of responding on the 2-back task. Specifically, when emotional stimuli were presented back-to-back, the required inhibitory processes were likely much greater, given that emotional processing would have been particularly strong. Thus, it would follow that individuals would be slowest in that instance and fastest when a neutral stimulus preceded another neutral stimulus (i.e., when emotional processing, and thus perhaps demands on inhibitory processes, were at a minimum).

The direction of the modulation on the working memory task (i.e., slower performance with fearful vs. neutral faces) is consistent with much of the literature on the effect of emotional state on working memory. Negative mood has often been found to hinder performance on working memory tasks or other problem-solving tasks (Darke, 1988; Elliman et al., 1997; Hartlage, Alloy, Vazquez, & Dykman, 1993). The fact that similar modulation occurred on a task with interleaved stimuli suggests that a state effect is not necessary; rather, a modulatory effect of emotion appears to occur even on an item-by-item basis.

Another question raised by the results of this study is why reaction times on the *n*-back task were modulated by emotional content when the stimuli were faces but not when they were words. This specificity of the effect for faces as compared with words can be thought of in a few ways: Perhaps there is something special about faces (or even specifically fearful faces) that allows emotional content to have a greater modulatory effect on these stimuli as compared with other emotional stimuli. There is evidence that specific neural processes are recruited for the processing of faces (see Kanwisher, 2000, for review), and further evidence suggests that fearful faces receive prioritized processing (Whalen et al., 1998). Perhaps the pathways implicated in processing faces are particularly likely to be modulated by emotional content.

The effect could also have to do with the use of verbal versus nonverbal stimuli. Negative emotional content could have a larger effect on the ability to maintain or manipulate nonverbal, as compared with verbal, information. This hypothesis is supported by findings that negative emotion is often associated with right-sided brain activity (Bowers, Bauer, Coslett, & Heilman, 1985; Hellige, 1993), including in regions of prefrontal cortex (R. J. Davidson, 1992) that have also been implicated in nonverbal working memory performance (e.g., Smith, Jonides, & Koeppe, 1996). Thus, there may be a stronger interaction between negative emotion and nonverbal working memory, as compared with verbal working memory (cf. Gray, 2001, for evidence that negative mood states impair verbal working memory while enhancing spatial working memory).

Another possibility is that words may have a special quality that prevents emotional content from having a modulatory effect on their maintenance or manipulation. Verbal stimuli must be read before their emotional content can be assessed. Thus, some low-level effects of emotion may not occur with emotional words because they have to be processed to a relatively high level before their threat can be determined. The present study cannot distinguish these possibilities because only fearful faces and negative words were used as emotional stimuli in the task that emphasized speed of responding. Thus, at this time, we can only suggest that the fearful faces activated emotional circuits (e.g., amygdala and orbitofrontal cortex) to a greater extent than did the emotional words, thus resulting in greater modulation of working memory performance. Future studies, using a wider range of nonverbal stimuli (e.g., fear-evoking pictures, angry faces), will be needed to distinguish the circumstances in which emotional stimuli influence working memory (e.g., whether the stimuli must be threat-related, must be faces, and so forth) and to confirm whether these stimuli do indeed result in greater modulation of emotional circuitry.

Despite these open questions, the results of the present study suggest that, at least in some instances, emotional content of stimuli can have distinct effects on working memory performance (eliciting either no effect on performance or resulting in poorer performance) and long-term memory performance (boosting the likelihood of long-term retention). At a cognitive level, the differential effects may result from the fact that a number of the processes that benefit long-term memory (e.g., orienting toward emotional aspects of stimuli, elaboration of emotional information) actually distract from staying on-task during the performance of working memory tasks, thus hindering performance. Further, the additional dimensions present during processing of emotional stimuli (e.g., emotion, arousal; see LeDoux, 2002) may be beneficial to long-term memory by providing additional distinctiveness at encoding or additional features to be used later as retrieval cues. The additional information, however, may simply increase the distraction present on working memory tasks, thereby increasing the demand for inhibitory processes and selective attention.

From a neurobiological perspective, the different effects of emotional content on working memory and long-term memory likely result from their distinct neural underpinnings. Because working memory is thought to rely predominantly on prefrontal functions (Braver et al., 1997; D'Esposito, Postle, & Rypma, 2000; Goldman-Rakic, 1987; Petrides, 1996; Smith & Jonides, 1999), examining the effect of emotional content on working memory provides a vantage point from which to probe the effects of emotional stimuli on frontal lobe processes. Thus, the results of the present study suggest that there are specific instances in which activation of regions critical for processing of emotional content (e.g., the amygdala, orbitofrontal cortex) results in modulation of prefrontal functions critical for working memory performance (likely functioning of dorsolateral prefrontal cortex). This interaction between the amygdala and prefrontal cortex is plausible because the amygdala shares reciprocal projections with ventromedial prefrontal cortex, whereas limbic prefrontal cortices (posterior orbitofrontal and medial prefrontal areas) receive rich projections from all sensory cortices via the amygdala (see Barbas, 1995, 2000, for a review). The information that reaches these areas is believed to be transmitted to other prefrontal areas via robust intrinsic connections (Morgan & LeDoux, 1995; Selemon & Goldman-Rakic, 1988).

Interactions within prefrontal cortex may also be important for interrelations between emotion and memory. Orbitofrontal cortex is believed to be critical for processing emotional information and for emotional response (e.g., reward and punishment; see O'Doherty, Kringelbach, Rolls, Hornak, & Andrews, 2001; Rolls, 2000). Via connections to ventral and dorsolateral regions critical for semantic elaboration, phonological rehearsal, and information manipulation, orbitofrontal cortex likely can modulate at least some aspects of cognitive function. Consistent with this idea, recent neuroimaging data (by Gray, Braver, & Raichle, 2002) have suggested that there is integration between prefrontal regions traditionally thought of as "affective" (ventromedial–orbitofrontal prefrontal cortex, e.g., Stuss & Benson, 1984, 1986) and those postulated to be "cognitive" regions (dorsolateral prefrontal cortex, e.g., Fuster, 1997; Goldman-Rakic, 1987). Specifically, a bilateral region of the lateral prefrontal cortex showed a cross-over interaction (i.e., an emotion induction condition influenced task-related activity in the region), indicating a functional influence of emotional state on the neural processes supporting working memory. Further, neuroimaging studies have indicated that activation in orbitofrontal cortex is inversely related to activity in dorsolateral prefrontal regions (Drevets & Raichle, 1998; Mayberg et al., 1999; Northoff et al., 2000; Perlstein, Elbert, & Stenger, 2002). Thus, activation of orbitofrontal cortex could result in a down regulation of dorsolateral activity, thereby reducing performance on working memory tasks.

In addition to these modulatory effects in prefrontal cortex, to the extent that performance on working memory tasks is modulated by changes in attention or lower level processing, the effects of emotional content on working memory performance could also be related to interactions with networks critical for allocation of attention (e.g., anterior cingulate, parietal cortex) and to regions important for lower level processing (e.g., visual cortex; LeDoux, 1995).

Although many of these interactions may also be important for modulation of long-term memory, hippocampal function is particularly critical for long-term retention. One of the critical roles of the amygdala in emotional memory is purported to arise via its connections to the hippocampal formation. Through this interaction, the amygdala is capable of modulating hippocampal activity, thereby increasing the likelihood that an event is consolidated into long-term memory stores (see McGaugh, 2000, for a review). Emotion may also have effects at retrieval, independent from those demonstrated at encoding. Thus, this dissociation in the neural processes required for working memory and long-term memory may allow emotion to have distinct effects on working memory and long-term memory.

In summary, the results of this investigation suggest that although emotional content has a robust enhancement effect on long-term memory for a range of stimuli, the effects of emotional content on working memory are more specific. Emotional content did not influence accuracy on any of the tasks. It did, however, increase reaction times (i.e., hinder performance) on an *n*-back task but only for faces (not for verbal stimuli) and only when emotional and neutral faces were interleaved (not when they were blocked). In particular, individuals were slower to respond to emotional faces when they followed an emotional stimulus (another emotional face). Future experiments will be needed to clarify the stimulus and task characteristics that give rise to a modulatory effect of emotional content on working memory.

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