Emotion

Relationship Between Emotion and Forgetting

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A major determinant of forgetting in memory is the presence of interference in the retrieval context. Previous research has shown that proactive interference has less impact for emotional than neutral study material (Levens & Phelps, 2008). However, it is unclear how emotional content affects the impact of interference in memory. Emotional content could directly affect the buildup of interference, leading to reduced levels of interference. Alternatively, emotional content could affect the controlled processes that resolve interference. The present study employed the response deadline speed–accuracy trade-off procedure to independently test these hypotheses. Participants studied 3-item lists consisting of emotional or neutral images, immediately followed by a recognition probe. Results indicated a slower rate of accrual for interfering material (lures from previous study list) and lower levels of interference for emotional than neutral stimuli, suggesting a direct impact of emotion on the buildup of interference. In contrast to this beneficiary effect, resolution of interference for emotional material was less effective than neutral material. These findings can provide insight into the interactions of emotion and memory processes.

Keywords: proactive interference, emotion, memory retrieval, forgetting, speed–accuracy trade-off procedure

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Memory enhancement for emotional material is a well-studied phenomenon (see Buchanan, 2007; Doerksen & Shimamura, 2001; Hamann, 2001, for reviews). Research on emotion−memory interactions has suggested that emotional information may be more likely to be remembered and persist longer in memory than neutral material (Buchanan, Etzel, Adolphs, & Tranel, 2006). Emotional content has influence on the quantity and quality of events remembered as well as the total amount of correctly remembered details of the events (Kensinger & Schacter, 2008). Additionally, emotional memories are remembered with a greater sense of recollective experience (Sharot & Yonelinas, 2008) that is strengthened over time (Ritchey, Dolcos, & Cabeza, 2008).

Although effects of emotional content on remembering are well documented, the exact nature of this relationship is not as clear. Here we attempted to provide a better understanding of the interactions between emotion and memory processing using an in-depth investigation of the impact of emotion on forgetting. A mechanistic explanation of the relationship between emotion and forgetting could provide insight into the underlying mechanisms that modulate the interactions between emotion and memory processes.

A major cause of forgetting over the short and the long term is the presence of interference in the retrieval context. When faced with proactive interference (PI), prelearned yet irrelevant material interferes with the subsequent encoding and/or retrieval of newer information (Gardiner, Craik, & Birtwistle, 1972; Keppel & Underwood, 1962; Tehan & Humphreys, 1996; Watkins & Watkins, 1975; Wickens, 1970). Because PI affects the efficient use of working memory (WM) resources, it can drastically limit ongoing cognitive processes. Hence control of PI is a critical determinant of successful performance for many cognitive tasks that depend on WM resources. Although PI is a well-studied phenomenon, the majority of the literature has focused on the effects of PI with nonemotional stimuli (Badre & Wagner, 2005; D'Esposito, Postle, Jonides, & Smith, 1999; Jonides & Nee, 2006; Jonides, Smith, Marshuetz, Koeppe, & Reuter-Lorenz, 1998; Öztekin, Güngör, & Badre, 2012; Öztekin & McElree, 2007, 2010). Given its well-established interactions with memory processes, it is quite conceivable that study material with emotional content might impact forgetting due to PI. For instance, emotion could directly modulate the buildup of interference in memory, resulting in lower levels of interference to resolve. Alternatively, emotion could affect the memory operations that aid the successful resolution of interference.

WM is a dynamic memory system that allows us to maintain a limited amount of information available for processing while processing upcoming information. WM can be described as the cognitive system that acts as a mediator of the encountered information for its short-term maintenance as well as its manipulation to be used while executing a task. Because maintaining information in WM might be an important factor that contributes to the retention of information in the long term, it is expected that emotional information might be treated differently in WM as well.

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Studies examining the differences between emotional and neutral stimuli in WM tasks, however, have not capitulated enhancing effects emotion has in long-term memory (Kensinger & Corkin, 2003). For instance, Mather et al. (2006) showed that the source memory (i.e., remembering the relative locations of items) for highly arousing images were poorer than low arousing images, indicating that the arousal component of the stimuli disrupted the interitem binding in WM.

More recently, the impact of emotion on WM has been investigated by presenting emotional stimuli as a task-irrelevant distractor to induce cognitive interference (Denkova et al., 2010; Dolcos & McCarthy, 2006). Because emotional information benefits from prioritized processing and tends to capture our attention in a fast and automatic way, presenting it as a distractor might lead to impairments in task-relevant performance (see Dolcos & Denkova, 2014, for a review). When emotional distraction was presented during the delay between to-be-remembered items and test probes in a WM task, specific patterns of brain activity were observed in response to the emotional distractors (Dolcos, Diaz-Granados, Wang, & McCarthy, 2008; Dolcos & McCarthy, 2006). Impaired WM performance in the presence of emotional distractors was associated with enhanced activity in hot emotional systems, such as the amygdala, and reduced activity in cold executive systems, such as the dorsolateral prefrontal cortex. Research has further shown that when emotional content is task-irrelevant, it can have detrimental effects on memory performance (Dolcos, Denkova, & Dolcos, 2012; Dolcos, Iordan, & Dolcos, 2011; Iordan, Dolcos, & Dolcos, 2013).

Interference of task-irrelevant material impedes our ongoing cognitive functioning. However, forgetting can be overcome if PI is successfully resolved. Accordingly, how we handle PI with emotional material is important in our understanding of the interactions between emotion and memory processes. A common way of inducing interference in experimental settings is using the recent probes (RP) task (Jonides & Nee, 2006; Monsell, 1978). The RP task is an item recognition memory paradigm, where the task demands are the same as a standard item recognition tasks for target test probes. PI is manipulated by changing the recency of the lures. Specifically, presenting a lure from the previous study list induces PI by putting familiarity and source information in conflict. Namely, the recently encountered probe has high residual familiarity and thus is a strong competitor among target representations. To correctly resolve PI, one needs to retrieve detailed episodic information (e.g., list-specific or source information that the item belonged to the preceding trial) in order to correctly reject the recognition probe. Noninterference trials, on the other hand, test a new probe or a probe that was not recently presented, which have low residual familiarity and thus are easy to reject. The detrimental effects of PI on memory performance have been measured by comparing the reaction times (RTs) and false-alarm (FA) rates on interference and noninterference trials (D'Esposito et al., 1999; Jonides & Nee, 2006; Jonides et al., 1998; Öztekin et al., 2012; Öztekin & McElree, 2010). Typically, due to its high residual familiarity, participants are more likely to mistakenly endorse this item, leading to high FA rates on interference trials compared with noninterference trials. Alternatively, participants could successfully resolve PI by engaging in controlled operations that access diagnostic information from memory (e.g., source memory), which leads to slower RTs for interference compared with noninterference trials (Jonides & Nee, 2006; Öztekin et al., 2012; Öztekin & McElree, 2007, 2010).

Levens and Phelps (2008) employed the RP task to investigate how emotion affects memory performance in the presence of PI. Their results indicated lower RT differences between interference and noninterference trials for emotional (E) trials compared with neutral (N) trials, indicating that emotionally arousing stimuli were less affected by PI. Accordingly, they suggested that highly arousing emotional content might act as a facilitator for interference resolution in memory (Levens & Phelps, 2008, 2010). There may be two mechanisms underlying this effect: One possibility is that emotion could impact directly on the buildup of interference in memory, by altering the early/automatic familiarity-based responses, and thus leading to lower levels interference to resolve. Alternatively, emotion could impact on the resolution of PI, via modulating the controlled processes that access detailed episodic information from memory. More specifically, there might have been a decrease in the familiarity signal, which would be reflected in the amount of interference created, or an enhancement for the source memory of emotional items that would facilitate the resolution of interference. Unfortunately, RT measures do not allow disentangling the effects on the buildup from resolution of PI. The present study aimed to independently assess the two hypotheses by providing a time-course investigation of how emotion impacts on the buildup and resolution of PI. To do so, we employed a response signal speed−accuracy trade-off (SAT) procedure to the RP paradigm consisting of neutral and highly arousing negative images from the International Affective Picture System (Lang, Bradley, & Cuthbert, 2005), which allowed us to trace the impact of emotion on memory processes that are operative across the full time-course of retrieval (see Figure 1). This allowed us to keep track of the impact of emotion in the presence and in the absence of PI, which enabled us to evaluate the use of emotional stimuli when it is task-relevant and task-irrelevant.

SAT Procedure

SAT is a variation of a deadline method in which subjects are signaled to respond at variable intervals after the onset of each test item, allowing a time-course function that measures the growth of retrieval as a function of processing time (McElree & Dosher, 1989). An important advantage of the SAT over traditional paradigms is that it provides conjoint measures of the accuracy and speed of processing, independent of each other. This is in contrast to RT measures derived from traditional tasks, which cannot provide pure measures of processing speed because they are subject to speed−accuracy trade-offs (McElree, 2006). Sampling the full time-course of retrieval also allows independently probing automatic versus controlled operations, because the output of automatic operations have typically been observed to be available before the output of controlled operations across a wide range of tasks (Hintzman & Curran, 1994; McElree, Dolan, & Jacoby, 1999; Öztekin & McElree, 2007, 2010; Yonelinas, 2002). Accordingly, the SAT procedure enables independent estimation of both the timing and the magnitude of the output of these processes via quantitative modeling routines (see Figure 2 for illustration and description of a hypothetical SAT function).

Previous studies investigating nonemotional PI with SAT (Hintzman & Curran, 1994; McElree & Dosher, 1989; Öztekin et

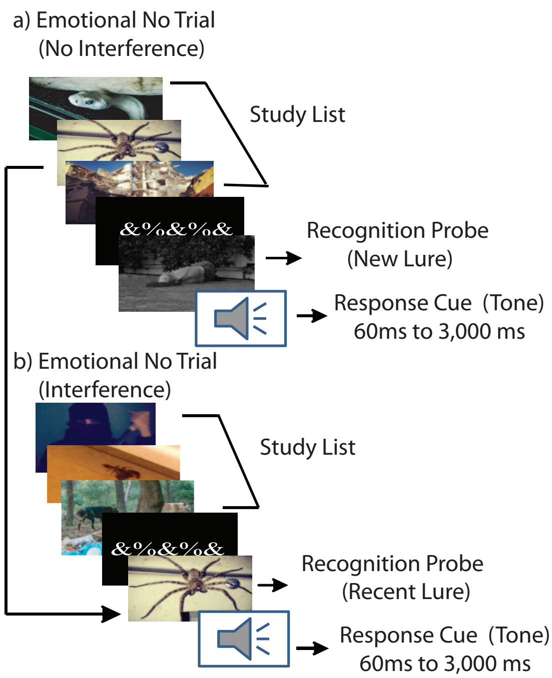

Figure 1. Illustration of noninterference (a) and interference (b) trials for emotional stimuli. For each trial, three study images were presented, followed by a visual mask. Participants indicated whether or not the recognition probe was presented in the study list. They were trained to respond within 300 ms of the response signal. *Note.* Images are representative of emotional stimuli driven from IAPS database. Original images are not presented due to copyright reasons. See the online article for the color version of this figure.

al., 2012; Öztekin & McElree, 2007, 2010) have shown that recent negative (RN) probes induce high FA rates early in retrieval compared with nonrecent or unstudied lures. However, crucially, the elevated FA rates diminish later in retrieval when participants are able to recover more detailed episodic information (i.e., either that the probe was not a member of current study list or that it was studied on previous trial). This nonmonotonic FA function for RNs is consistent with two operations in opposition: Automatic assessments of familiarity engender high FA rates early in retrieval, which are then subsequently countered by controlled, strategic retrieval operations that serve to recover detailed episodic information.

Figure 3 illustrates a hypothetical two-phase retrieval function that characterizes the buildup and resolution of PI. Buildup of PI starts at the point in time when item familiarity becomes available (see Point A in Figure 3). During this time, performance shows an exponential increase in FA rates reaching an asymptote until the time when diagnostic information (e.g., source or list-specific information) becomes available. When given enough time, participants can engage in controlled retrieval operations and access the relevant source information (i.e., that the RN probe was not in the current study list). After this breakpoint (see Point B in Figure 3), PI can be resolved and FA rates diminish. Accordingly, evaluating how the buildup and resolution of PI unfolds across the full time-course of retrieval allowed us to assess whether emotional content of the material directly affects the early/automatic period where interference builds up, or the controlled memory operations that successfully resolve PI. As such, this fine-grain analysis has the potential to identify the underlying mechanisms that modulate the relationship between emotion and forgetting in memory.

Method

Participants

Twenty students (14 undergraduates and 6 graduate students) from Koç University participated in the experiment. All participants gave written informed consent before participation. Two participants were members of the lab and volunteered their time. The remaining participants were compensated for their time. Data from four participants who failed to comply with the SAT procedure were excluded from analyses, leaving 16 participants. SAT procedure employs within-subject comparisons across experimental conditions with intensive data collection from each participant (e.g., the present study consisted of over 2,000 experimental trials per participant). Accordingly, consistent with previous investigations (McElree & Dosher, 1989; Öztekin et al., 2012; Öztekin & McElree, 2007, 2010), the present study aimed for a conservative sample size of 16 participants.

Design and Stimuli

The experiment consisted of twelve 20-min sessions, completed over several weeks. Each session contained 84 emotional and 84 neutral experimental trials in which participants studied a three-item list consisting of images. Next, participants were cued to respond to a recognition probe following a brief visual mask and indicated whether the test probe was a member of the study list

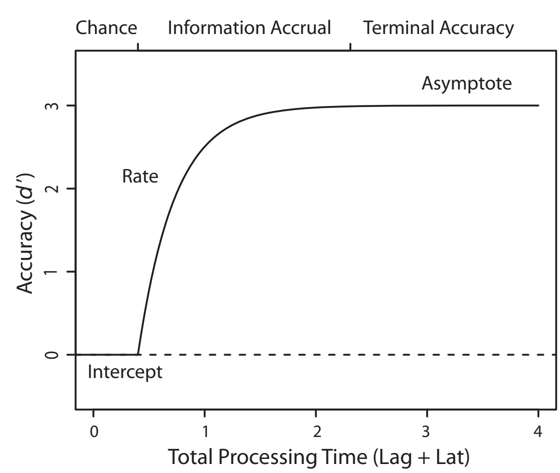

Figure 2. Illustration of a hypothetical SAT function that shows how accuracy (in d' units) grows over processing time (in seconds). The SAT curve reflects three phases: a period where performance is at chance (the departing point in time from chance is marked by the intercept parameter), followed by a period of information accrual (the rise of this information accumulation is reflected by the rate parameter of the SAT function), and, following this period, the maximum level of accuracy is reached, where performance does not improve (the asymptote parameter of the SAT function). Lag = duration of the response deadline; Lat = response latency; SAT = speed−accuracy trade-off.

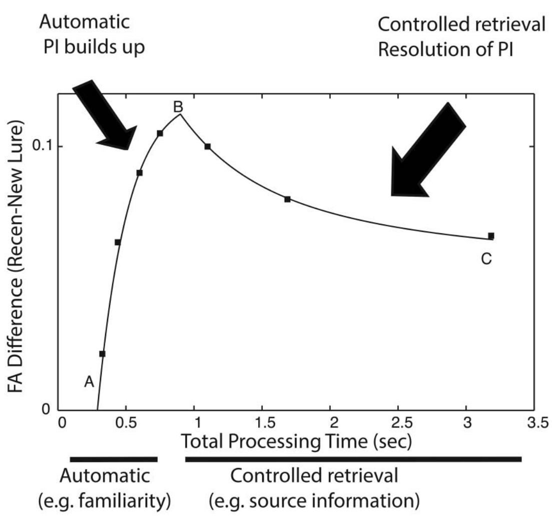

Figure 3. Illustration of a hypothetical two-phase retrieval function that shows the behavior of FA difference between interference and noninterference trials. The function reflects: (a) the time point when participants start to make FAs (familiarity intercept; Point A), (b) the speed of interference buildup (rate parameter), (c) the terminal level the FA difference reaches before participants engage in controlled processes and correct their judgments (familiarity asymptote; Point B), (d) the time point when participants start to recover the detailed/contextual information and correct their judgments (recollective intercept; Point B), and (e) the terminal level of FAs after the retrieval of source information (recollective asymptote; point C). FA = false alarm; PI = proactive interference.

using a "yes" or "no" recognition response. Participants completed a 20-min practice session with nonemotional stimuli to train for the SAT procedure.

Study design adapted a response-deadline version (McElree & Dosher, 1989; Öztekin et al., 2012; Öztekin & McElree, 2010) of the RP task, a widely used paradigm to induce PI by presenting lures from previous study list. The stimuli were chosen from the International Affective Picture System (Lang et al., 2005), according to the standardized scores of valence and arousal levels. For the emotional stimuli set, 273 highly arousing ($M = 5.80$, $SD = 0.69$) and negatively valenced ($M = 2.85$, $SD = 0.69$) images were selected. The neutral stimuli set consisted of 273 low arousing stimuli ($M = 3.5$, $SD = 0.63$), with medium valence levels ($M = 5.26$, $SD = 0.76$). The emotional stimuli set was significantly more arousing, $t(272) = 40.673$, $p < .001$, and more negatively valenced, $t(272) = -38.792$, $p < .001$, than the neutral stimuli set. Each image was presented once per session.

There were equal numbers of targets; probes that required a "Yes" response and lures; probes that required a "No" response for both (E) and (N) trials. Targets were chosen equally from the three serial positions (SPs) of the current study list. Half of the lures consisted of recently presented lures selected from the study list of previous trial (recent lures), and half consisted of lures that had not been presented in the current session (new lures).

Procedure

Figure 1 illustrates the sequence of events in a single trial: (a) Study images were presented sequentially for 1,200 ms each. (b) The study list was followed by a visual mask, consisting of nonletter symbols for 1,200 ms. (c) After the mask, the test image was presented for the duration of the response deadline. (d) At 60, 200, 300, 500, 800, 1,500, or 3,000 ms after the onset of the recognition probe, a 50-ms tone sounded to cue participants to respond. (e) Participants indicated provided a yes−no recognition response as quickly as possible after the onset of the tone by pressing a key. (f) After providing a response, participants were given feedback on their latency to respond. Participants were trained to respond within 300 ms of the tone. They were informed that responses longer than 300 ms were too slow and responses less than 100 ms were anticipations, and that both should be avoided. (g) After the latency feedback, participants were asked to give a confidence rating ranging from 1 (*low confidence*) to 3 (*high confidence*). The confidence ratings primarily served to enable participants to self-pace themselves through trials and were not analyzed. Participants initiated the next trial by pressing a key.

Results

For targets, each participant's hit rates were scaled against the FA rates to new lures to obtain (equal-variance Gaussian) d' measures. To ensure measurable d' values, we adapted a minimal correction procedure, as suggested by Snodgrass and Corwin (1988).

General Effects of Emotion on the Dynamics of Memory Retrieval in the Absence of Interference

Asymptotic accuracy. Consistent with previous research, we averaged d' values for the last two response deadlines to obtain empirical measures of asymptotic accuracy (see Figure 4). This measure reflects the terminal accuracy level reached, indicating the probability of successful retrieval (McElree, 2001; McElree & Dosher, 1989, 1993; Öztekin & McElree, 2007).

A 2 × 3 (Stimuli type [emotion vs. neutral] × Serial Position of Positive Test Probes) analysis of variance, conducted on asymptotic d' values indicated a main effect of SP for both E and N trials: asymptotic accuracy increased as a function of SP of the test probe, E trials: $F(2, 15) = 12.037$, $p < .005$, $\eta_p^2 = 0.445$; N trails: $F(2, 15) = 9.177$, $p < .005$, $\eta_p^2 = 0.380$. Post hoc comparisons indicated that the mean scores for the asymptotic accuracy of later SPs were significantly higher for both emotional (SP1: $M = 3.58$, $SD = 0.43$; SP2: $M = 3.81$, $SD = 0.21$; SP3: $M = 3.96$, $SD =$

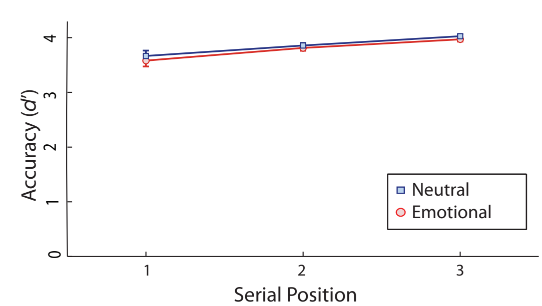

Figure 4. Asymptotic accuracy levels (averaged d' over the last two response deadlines) across the three study positions. Error bars denote *SEM*. See the online article for the color version of this figure.

0.17) and neutral (SP1: $M = 3.66$, $SD = 0.4$; SP2: $M = 3.85$, $SD = 0.19$; SP3: $M = 4.02$, $SD = 0.14$) material. On the other hand, there was no measurable impact of emotion on asymptotic accuracy ($P > 0.315$, $\eta_p^2 = 0.067$); participants performed comparably across E and N trials. We also did not observe a Reliable Stimuli Type × SP interaction ($p > .915$, $\eta_p^2 = 0.006$).

Retrieval dynamics. We estimated the retrieval dynamics by fitting individual participant's data and the average data (derived by averaging d' values for each condition across participants) with an exponential approach to a limit:

$$d'(t) = \lambda(1 - e^{-\beta(t-\delta)}), \quad t > \delta, \text{ or else } 0. \qquad \text{(Equation 1)}$$

In Equation 1, $d'(t)$ is the predicted d' at time t; λ is the asymptotic accuracy level reflecting the overall probability of recognition; δ is the intercept reflecting the discrete point in time when accuracy departs from chance ($d' = 0$); β is the rate parameter, which indexes the speed at which accuracy grows from chance to asymptote. Previous studies have indicated that this equation provides a good quantitative summary of the shape of the SAT functions (Dosher, 1981; McElree, 2001; McElree & Dosher, 1989; Wickelgren & Corbett, 1977; Wickelgren, Corbett, & Dosher, 1980).

The quality of the model fits were assessed by: (a) the value of an adjusted R^2 statistic (Reed, 1973); (b) the consistency of parameter estimates across participants; and (c) evaluation of whether the fit yielded systematic deviations that could be accounted for by additional parameters. These latter two metrics were assessed using statistical tests conducted on the parameter estimates derived from the model fits across participants.

Within and composite list dynamics. We first evaluated whether SAT functions for E and N trials exhibited the same patterns observed in previous studies (McElree, 2006). To do so, SAT functions for the three SPs were fit with sets of nested models that systematically varied the three parameters in Equation 1. Our results indicated that the most recent item benefits from a privileged state in the focus of attention (McElree & Dosher, 1993; Öztekin et al., 2012; Öztekin & McElree, 2007, 2010; Wickelgren et al., 1980) and extends this phenomenon to emotional study material (see supplemental materials for these results in more detail).

We next evaluated overall differences in terminal accuracy and retrieval speed across neutral and emotional stimuli. To do so, we averaged individual participants' d' values as well as average (over participants) d' values across the three SPs. These composite list functions were then fit with Equations 1 as described above. Figure 5 illustrates the SAT functions for the average emotional and neutral data, with smooth curves indicating the fitted exponential functions.

Consistent with the pattern observed for within-list dynamics for E and N trials, analyses of the retrieval dynamics across emotional and neutral composite SAT functions revealed a reliable difference between E and N trials in retrieval speed measures. Specifically, the intercept parameter, which marks the point in time when performance departs from chance, was slower for E than N trials, $t(15) = -2.50$, $p < .025$, $d = 0.631$. The average (across participants) intercept parameter was 296 ms and 308 ms for E and N trials, respectively (see supplemental material Tables S3A and S3B

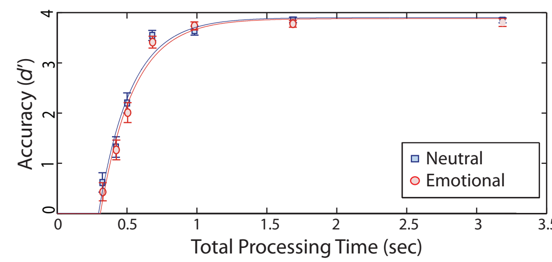

Figure 5. Illustration of the composite list SAT functions and model fits. Accuracy (in d' units) for the composite list (averaged over serial position of the test probe) SAT functions plotted against the total processing time (duration of the response deadline plus latency in seconds) for the average (over participants) emotional and neutral trials. Symbols indicate empirical data points; smooth lines indicate the model fits derived from Equation 1. SAT = speed−accuracy trade-off. Error bars denote *SEM*. See the online article for the color version of this figure.

for the parameter estimates for individual participants and the average data).

In contrast to retrieval dynamics measures, terminal accuracy levels, as assessed by the asymptote parameter, were comparable across E and N trials ($p > .85$, $d = 0.051$). Thus, the impact of emotion was prominent on retrieval speed measures, with no measurable impact on probability of successful retrieval for positive trials, in the absence of interference.

Effects of Emotion on the Dynamics of Memory Retrieval in the Presence of Interference

FA analyses: Effects of emotion on the buildup and resolution of interference. We now turn to our analyses of the FAs to recent and distant lures to determine whether and how participants' response patterns to reject lures differ across E and N trials. A comparison of the response patterns across the whole time-course allowed us to independently investigate the differential impact of emotion on the buildup and resolution of PI. To do so, we analyzed the differences in FA rates between our RNs, lures that were studied in the preceding study list, and distant negatives (DNs), lures that had not been studied in the current session. This measure provided an unbiased measure of performance by factoring out participants' bias to endorse a test item as member of the study list (e.g., the tendency to respond yes more often than no, regardless of the type of probe).

Figure 6 plots the FA difference scores for the average E and N trials. Note that due to the FA scaling difference, higher scores indicate a higher tendency to FAs to RNs. Figure 6 shows that for both emotional and neutral stimuli, the FA difference scores increase early in retrieval and then diminish later in retrieval. This nonmonotonic pattern indicates that the information basis for the recognition memory judgments shifted across retrieval and is consistent with previous research (Öztekin et al., 2012; Öztekin & McElree, 2010). The early high FA rates presumably indicate the contribution of familiarity (because the RN has been studied in the previous trial, it has high residual familiarity compared with the DN). The observed reduction in FA rates later in retrieval suggests the accrual of new information that contributes to the recognition judgments, presumably reflecting source or list-

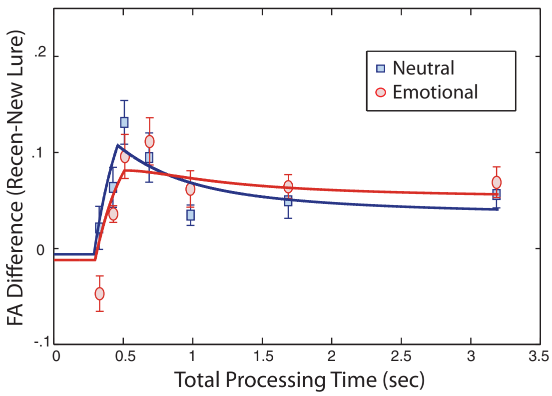

Figure 6. Difference in FA rates across the recent and distant negative probes plotted against the total processing time (duration of the response deadline plus latency in seconds) for the average (across participants) of emotional and neutral trials. Symbols indicate empirical data points; smooth lines indicate the model fit derived from Equation 2. Error bars denote *SEM*. FA = false alarm. See the online article for the color version of this figure.

specific information recovered by a recollective process (e.g., the fact that the RN probe was studied in a previous trial or that it was not a member of the current study list). Below, we statistically assessed these differences with a modified version of the quantitative two-process SAT model originally suggested by Ratcliff (1980) and adapted to the exponential form by McElree and Dosher (1989).

$$FA_{diff}(t) = \begin{cases} [\lambda(1 - e^{-\beta(t-\delta_1)})] + \gamma, & \text{for } \delta_1 < t < \delta_2 \\ [\lambda_2 + (\lambda_1 - \lambda_2)(\delta_2 - \delta_1)/(t - \delta_1) \\ \times (1 - e^{-\beta(t-\delta_1)})] + \gamma, & \text{for } t \geq \delta_2 \end{cases}$$

(Equation 2)

Equation 2 states that, during the initial retrieval period ($\delta_1 < t < \delta_2$), accuracy depends on accrual of one type of information, presumably familiarity information. During this initial period, accuracy is modeled by the top portion of Equation 2, a simple exponential approach to an asymptote (λ_1). At time δ_2, a second source of information starts to contribute to the recognition memory judgments. This source of information could arise from the output from a second process; for example, a recollective operation that accesses detailed episodic information. The accrual of this second type of information leads to the change in retrieval, shifting the asymptote from λ_1 to λ_2.The bottom portion of Equation 2 states that response accuracy gradually shifts to the new asymptote (λ_2) starting at time δ_2. In addition, a shifting parameter (γ) was added to the model to account for negative scores.[1]

We should state that the two processes mentioned in the model presented in Equation 2 contemplate the recovery of information through an automatic versus controlled retrieval operation. These processes need not be equivalent to familiarity versus recollection. Although the notion of a fast/automatic familiarity assessment (or a component of stimulus/item identification that could lead to an increase in FA rates) is consistent with dual-process theories of recognition (e.g., see Yonelinas, 2002, for review), the slower controlled component might not necessarily equal general recollection, but could also reflect the independent accrual of diagnostic episodic information (e.g., source information) that can aid the successful resolution of interference. The slower accrual of this diagnostic episodic information can overrule the contribution of the fast/automatic assessments (independent of whether the automatic process has reached completion), leading to the nonmonotonic pattern observed in the data.

To test the effects of emotion on the familiarity-based responses that reflect the buildup of PI versus the controlled processes that reflect the resolution of PI, we fit each participants' and average data for E and N trials with Equation 2 and compared the parameter estimates derived from each phase. Namely, if emotion directly impact the buildup of PI, we should see differences early in retrieval, either on the magnitude or timing of familiarity-based judgments. If, on the other hand, emotion impact the controlled operations that aid successful resolution of PI, then we should observe differences later in retrieval. These effects can be observed either on the magnitude or timing of responses based on controlled responses that access detailed episodic information and aid resolution of PI.

A paired *t* test comparison across the parameter estimates for E and N trials indicated that the familiarity asymptote (λ_1; 0.154 for average E trials and 0.22 for average N trials) was marginally lower ($p < .91$, $d = 0.470$) for emotional than neutral material. Crucially, the recollective asymptote (λ_2; 0.075 for average E trials and 0.032 for average N trials) was marginally higher ($p < .056$, $d = 0.69$) for emotional than neutral material. Notably, this crossover Asymptote (λ_1 vs. λ_2) × Condition (emotional vs. neutral) interaction was significant ($F = 4.71$, $p < .046$). Additionally, there was a speed difference for the information accrual, reflected by the rate parameter estimate, $t(15) = 2.77$, $p < .014$, $d = 0.918$ (163 ms in $1/\beta$ units for average E trials and 116 ms in $1/\beta$ units for average N trials), indicating that the buildup of interference was *slower* for emotional study material. The two intercept estimates, however, (δ_1 and δ_2) were comparable across emotional and neutral stimuli (δ_1; E trials = 330 ms, N trials = 344 ms, $p >$ .17, $d = 0.11$; δ_2; E trials = 650 ms, N trials = 494 ms, $p > .094$, $d = 0.62$). Tables S4A and S4B in the supplemental materials present the parameter estimates for individual participant's data and average data for E and N trials.

These data suggest that early in retrieval, when processing is largely automatic, emotion has a beneficiary effect on memory performance by slowing the buildup of interference. However, in contrast, our data indicate that, despite leading to a slower buildup of PI, emotion leads to less effective resolution of PI later in retrieval when retrieval is more based on controlled retrieval operations that access diagnostic information from memory. Thus, the data point to the conclusion that emotion differentially impacts the buildup and the resolution of interference in memory.

Discussion

The present study aimed to provide an in-depth investigation of the relationship between emotion and forgetting. To do so, we tracked the impact of emotion on memory performance in the

[1] Due to the observed negative scores in the emotional data, future research would provide additional insight as to whether a revised two-process retrieval model would be more appropriate for emotional material.

absence and presence of interference across the full time course of retrieval, allowing us to independently examine its impact on the buildup and resolution of interference, as well as its general effects on the dynamics of memory retrieval in the absence of interference. Prior work on the effects of emotion on interference resolution has suggested that there might be a facilitatory effect of having an emotional component (Levens & Phelps, 2008, 2010). In the current investigation, we endeavored to uncover the exact mechanisms behind this effect emotion has on PI and its resolution in memory in order to provide new insights on how emotion impacts forgetting.

General Effects of Emotion on Retrieval Dynamics in the Absence of Interference: Distinct Impact on Retrieval Success and Retrieval Speed

In the absence of interference, both the composite list and the SP analyses indicated comparable asymptotic accuracy levels for neutral and emotional study material. However, crucially, retrieval dynamics estimates indicated a slower intercept, that is, the point in time when information first becomes available, for emotional compared with neutral study material.

Recognition memory judgments are thought to be based on the accrual of two types of information: a fast assessment on the quality of the match of a probe to representations in memory (often referred to as familiarity) and a rather detailed contextual information recovery of information (such as source information). Recovery of source information, often viewed as recollection, is usually led by effortful retrieval operations and, as a consequence, accumulate slower than familiarity based assessments that are thought to be fast and more automatic (Yonelinas, 2002). Although it is not possible to separate the contributions of familiarity and source information for positive trials, previous time-course investigations have shown that familiarity information becomes available earlier than detailed episodic information (McElree et al., 1999; Öztekin & McElree, 2007). Hence, the intercept difference between emotional and neutral stimuli observed in our study presumably reflects the effect of emotional content on fast/automatic familiarity assessments.

Relationship Between Emotion and Forgetting: Differential Impact of Emotion on the Buildup and Resolution of Interference in Memory

Manipulating the presence of interference in the retrieval context allowed us to investigate the relationship between emotion and forgetting. Specifically, comparison of responses to RN probes, lures studied on the previous study list, and hence with high residual familiarity, with DNs, lures that had not been studied in an experimental session, allowed us to track the differential impact of emotion on the time-course of responses early and later in retrieval; that is, responses based on familiarity that are dominant early in retrieval and reflect the buildup PI, and those based on recovery of detailed information that are dominant later in retrieval and aid in successful resolution of interference in memory.

Emotional information is treated differently due to its survival value, hence, the importance of how a task-irrelevant emotional memory representation could interfere with recognition memory judgments. Our FA analysis showed that: (a) the buildup of PI for emotional material was slower (indicated by a slower rate parameter in the modeling estimates) compared with neutral material; (b) emotional material did not lead to as many FA difference as neutral material did (reflected as a lower familiarity asymptote); and (c) however later in retrieval, the resolution of PI was less effective for emotional (observed as a higher recollective asymptote) than neutral material.

Our findings indicating a slower buildup and a lower amount of PI for emotional material are consistent with the delayed onset of information accrual for positive trials. Taken together, the data indicate that the impact of emotion on memory processing is largely dominant early in retrieval during automatic processing, presumably reflecting the contribution of familiarity-based judgments. On the other hand, we also observed an effect of emotion on the controlled memory operations that aid successful resolution of PI. However, this effect was not in favor of emotional stimuli. Conclusively, our FA analysis revealed that while once goal-relevant but yet irrelevant emotional stimuli reduce the effects of PI early in retrieval, its resolution is not as effective later in retrieval. We further discuss these findings below.

Effects of emotion on automatic processes early in retrieval (buildup of PI). Our time-course investigation revealed that the previously observed (Levens & Phelps, 2008) facilitatory effect emotion has on the control of PI emerges early in retrieval as a slower rate of accrual for distracting material, leading to a reduced amount of PI to resolve. Previous work, which investigated the neural circuitry behind this facilitatory effect, has shown that although resolution of interference is associated with enhanced activation in the inferior frontal gyrus for both emotional and neutral items, interference resolution of emotional items recruited additional regions such as anterior insula and orbital frontal cortex (Levens & Phelps, 2010). Most importantly, the left amygdala showed differential activity for emotional stimuli. Previous work has also shown that effects of emotion have relatively earlier traces in special limbic areas such as the amygdala, acting as a gating mechanism for sensory processing, projecting to distant regions at later latencies (see Pourtois, Schettino, & Vuilleumier, 2013, for a review). As such, the amygdala is seen as a mediator for emotional effects along with its interactions with frontal and temporal brain structures (LaBar & Cabeza, 2006). Consistent with an early effect of emotion led by the amygdala, Düzel and colleagues (Fenker, Schott, Richardson-Klavehn, Heinze, & Düzel, 2005) observed right amygdala activation for know (subjective basis of judgments related to familiarity) but not for remember (subjective basis of judgments related to recollection of specific details) responses during recognition of emotional faces. Consistent with prior work that has indicated the impact of the amygdala to be dominant early in processing, it is possible that, in the current investigation, amygdala activity might have delayed the accrual of familiarity information, the dominant source of information early in retrieval.

Additionally, previous research (e.g., Denkova et al., 2010; Dolcos et al., 2008; Dolcos & McCarthy, 2006) has indicated a distinct pattern of activity in the systems specific to emotion processing and to executive processes. Specifically, when emotional distraction was presented during the delay between to-be-remembered items and probes in a WM task, an increased pattern of activity was observed in the amygdala, while activity in the dorsolateral prefrontal cortex decreased for emotional material. The differential activity pattern in the emotion-related and executive systems might also be prominent in the control of PI of emotional material. Studies investigating the effects of emotional interference on cognitive functioning have indicated that task performance depends on the dynamic interactions between neural networks that supports emotion processing and the brain regions that assist the efficient use of task-relevant information (Dolcos et al., 2012). One might speculate that heightened amygdala activity early in retrieval interferes with the automatic processing of item information (i.e., lowered or delayed perirhinal cortex activity) resulting in reduced availability, hence, less interference. This pattern, however, might be specific to the projections early in retrieval, which might change later in retrieval. Consistent with this notion, several studies (e.g., Pitkänen, Pikkarainen, Nurminen, & Ylinen, 2000; von Bohlen und Halbach & Albrecht, 2002) have provided evidence for strong projections between the amygdala and the perirhinal cortex. Future neuroimaging studies focusing on early amygdala and hippocampal structure interactions could provide further insight into the effects of emotion on memory processing early in retrieval.

Effects of emotion on the controlled processes later in retrieval (resolution of PI). When resolving the conflict in the presence of PI, one needs to rely on the relevant information in the competing memory representations, namely, the familiarity of the item encountered with an item from the preceding trial, and more specific episodic information that determines the item belongs to the previous study list. The successful resolution of PI requires accessing and selecting the diagnostic source information that the probe belongs to the previous trial and discounting the familiarity information. During this phase, our data showed that, for emotional study material, PI was not resolved as successfully as neutral material. That is, the asymptote reached after the resolution of PI has been completed was higher for emotional items, presumably indicating a reduced availability of recollective/detailed episodic information.

Although this finding might seem at odds with the facilitative effects of emotion on PI noted earlier (e.g., Levens & Phelps, 2008, 2010), it is important to note that, in traditional RT experiments where processing time is not controlled, it is not possible to capture the entire retrieval process: Most typically, participants will respond fast, thus allowing capture mostly of the buildup of PI, but not allowing capture of its complete resolution. However, our time-course investigation provided the retrieval pattern in which the two phases of PI can be fully observed. We next discuss possible explanations for the distinct pattern observed during the resolution of PI.

The RP task is a manipulation of an item recognition task in which participants are asked to indicate whether a probe was presented in the current study list. Participants are not informed about the recency manipulation, hence, the sole aim of the task for them is to correctly recognize the encounter of the item in a trial. Accordingly, contextual information about the item (i.e., the item belonging to the trial n or trial $n - 1$) is not central to the task requirements. In the case of emotional material, because the contextual information is not the main focus of the task, there might be a trade-off between central and peripheral details of the item. Previous work has suggested that such a trade-off (i.e., emotion induced memory trade-off) arises due to the fact that processing of emotion narrows attention, and that the mnemonic signal for the emotional components of the item is strengthened, leaving nonemotional details unattended (Murray & Kensinger, 2012; see Phelps & Sharot, 2008, for a review). However, although strengthened emotional details can have a boosting effect on the subjective sense of remembering, it does not guarantee a general enhancement of recollection (Rimmele, Davachi, Petrov, Dougal, & Phelps, 2011; Sharot & Yonelinas, 2008). In general, vivid and enhanced recollective experience is accompanied by successful recovery of contextual details of the event, which reflects the recollection component of recognition (Yonelinas, 2002). It is important to state that although emotion is expected to have an enhancing effect on memory in general, in this case, there appears to be a discrepancy between the enhanced subjective sense of recollection and memory for contextual details of emotional material.

When emotion's effect on contextual and relational information are examined, a specific pattern emerges: emotion enhances source memory for the features that are perceptually bound to the item while it impairs contextual/relational details that are not inherent to the item (see Chiu, Dolcos, Gonsalves, & Cohen, 2013, on opposing effects of emotion on contextual or relational memory; see Kensinger, 2009, for a review on emotion's effects on remembering the details). For instance, it has been shown that the font color or spatial location information of emotional items are remembered better than neutral items (D'Argembeau & Van der Linden, 2005; Doerksen & Shimamura, 2001; Mather & Nesmith, 2008). On the other hand, a group of studies has found impaired detailed memory of a scene/context in which emotional items have been embedded and presented (see Kensinger, Garoff-Eaton, & Schacter, 2007). Additionally, other investigations have shown that relational binding of the emotional item pairs is worse than neutral items (Knight & Mather, 2009; Nashiro & Mather, 2011; Pierce & Kensinger, 2011). Findings from a recent study conducted by Bisby and Burgess (2014) supported this differential impact of emotion on item and associative memory; contextual memory of emotional items were impaired compared with neutral items while memory for individual emotional items were enhanced or unaffected under certain conditions. Conclusively, it has been suggested that the emotional element of an object induces enhanced focused attention that alters within-object binding (i.e., features related to the object such as color or location) while this narrowing of attention might not favor the object−object bindings or the binding of contextual features (Mather, 2007). The pattern we observed in our study is consistent with this recent work, and indicates that there might be a cost to having an emotionally arousing component that reduces availability of nonprioritized episodic information, such as source or contextual memory, which, in our case, was list-specific episodic information required to successfully resolve PI.

Conclusion

The present study provides an in-depth investigation of the relationship between emotion and forgetting via tracking the full time-course of how the impact of emotion on memory unfolds in the presence of interference. Our findings suggest that emotion has a differential impact on the buildup and resolution of PI in memory: Emotion aids memory by slowing down the buildup of interference and leads to less interference early in retrieval when memory judgments are largely automatic. This finding provides an explanation for the previously observed facilitating effect of emotion during PI. However, this facilitating effect should be interpreted cautiously. In contrast to the pattern observed during the buildup of PI, our data indicate that emotion has a negative impact later in retrieval when PI is resolved via controlled memory operations that access detailed episodic information from memory.

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