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Emotional dissociations in temporal associations: opposing effects of arousal on memory for details surrounding unpleasant events

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ABSTRACT

Research targeting emotion's impact on relational episodic memory has largely focused on spatial aspects, but less is known about emotion's impact on memory for an event's temporal associations. The present research investigated this topic. Participants viewed a series of interspersed negative and neutral images with instructions to create stories linking successive images. Later, participants performed a surprise memory test, which measured temporal associations between pairs of consecutive pictures where one picture was negative and one was neutral. Analyses focused on how the order of negative and neutral images during encoding influenced retrieval accuracy. Converging results from a discovery study ($N = 72$) and pre-registered replication study ($N = 150$) revealed a "forward-favouring" effect of emotion in temporal memory encoding: Participants encoded associations between negative stimuli and subsequent neutral stimuli more strongly than associations between negative stimuli and preceding neutral stimuli. This finding may reflect a novel trade-off regarding emotion's effects on memory and is relevant for understanding affective disorders, as key clinical symptoms can be conceptualised as maladaptive memory retrieval of temporal details.

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Arousal; associative/relational memory; temporal; ordering; source memory

1. Introduction

Emotion's impacts on memory are characterised by biases and trade-offs. For instance, negative emotion is thought to enhance memory for gists while impairing memory for details (Adolphs et al., 2001), enhance memory for central features of a scene at the expense of memory for peripheral features (Kensinger et al., 2007), and enhance memory for items at the expense of memory for associations (Bisby & Burgess, 2017; but see Bogdan et al., 2023). Understanding the circumstances in which emotion enhances or impairs aspects of memory is a key question in this literature. Here, we focus on the impact of negative arousal on temporal episodic memory, which is among the least examined forms of associative memory.

Early studies on this topic examined how negative arousal influences temporal source memory, asking participants about which block a stimulus was originally shown in (Rimmele et al., 2012; Schmidt et al., 2011). More recent studies have investigated how emotion influences temporal associations between consecutive stimuli, asking participants to re-order lists of items based on the original presentation sequence (Dev et al., 2021; Huntjens et al., 2015; Makowski et al., 2017; Schmidt et al., 2011). This work has yielded mixed results, with some studies showing enhancing effects of emotion on temporal memory and others showing impairing effects. In contrast, the present research probes whether negative arousal differentially impacts temporal associations

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based on the order of stimulus pairs during encoding. Specifically, we sought to clarify how unpleasant stimuli influence memory associations with preceding compared to following neutral stimuli, referred to here as Neutral-to-Negative and Negative-to-Neutral pairs, respectively. Clarification of this issue is important for understanding how emotion impacts temporal aspects of relational memory.

Of the re-ordering studies mentioned above, several point to possible beneficial effects of emotion on memory for temporal associations (Dev et al., 2021; Makowski et al., 2017; Schmidt et al., 2011). For each encoding trial of these designs, participants viewed a sequence of emotional (positive/negative) stimuli or a sequence of neutral stimuli. During retrieval, participants were presented the stimuli in a scrambled temporal arrangement and asked to re-order them to match the original encoding sequence. These studies suggest that emotion enhances re-ordering accuracy when stimuli are semantically related to one another. However, these designs carry some ambiguity. Retrieving an accurate four-stimuli sequence, A-B-C-D, may be facilitated by a diverse range of memory processes. For example, participants may retrieve one stimulus' position via associations with its temporal context (e.g. "D came last") or via a paired association (e.g. "D came after C"). Therefore, measuring retrieval in terms of re-ordering accuracy leaves it ambiguous as to *which* associations were most relevant for reconstructing the sequences. It is also ambiguous *how* the associations were retrieved (e.g. a participant may use stimulus A as a cue and retrieve that stimulus B came next or vice versa). From this earlier evidence, it is further unclear how emotion influences the retrieval of temporal order for sequences involving both emotional and neutral events. Examining temporal associations at a finer-grained level may reveal possible arousal-related biases in the temporal encoding that are similar to the trade-offs identified in other aspects of memory.

The impact of negative arousal on temporal associations with neutral information could possibly be influenced by their succession – whether the neutral information appears before or after the arousing stimulus. In other words, arousal may elicit directional temporal biases. For example, suppose you find yourself in a conversation where your partner unexpectedly insults you and then returns to an otherwise neutral discussion. Later, when you are trying to make sense of the encounter and the surrounding conversation points, will you more accurately retrieve what happened before or after the insult? More accurately retrieving what you discussed *after* the insult would be consistent with a *forward-favouring* effect of negative emotion, whereas better retrieving what you discussed *before* the insult would be consistent with a *backward-favouring* effect.

Note that comparing these two potential biases specifically concerns how the *sequence* of negative and neutral stimuli during encoding influences memory. The question is not about whether negative arousal enhances or impairs memory in general, but instead about how arousal's effects may depend on stimulus order (Neutral-to-Negative vs. Negative-to-Neutral). Either directional bias would bear resemblance to established emotional memory trade-offs. For instance, in the spatial domain, emotion seems to upregulate encoding of information at the center of a scene while downregulating encoding of peripheral neutral information (Kensinger et al., 2007; Riggs et al., 2011; Steinmetz & Kensinger, 2013). Hence, for spatial memory, emotion elicits diverging effects based on the information's position, which may also occur when considering temporal positions. Investigation of possible emotional biases in the temporal domain would lay the groundwork for future research integrating spatiotemporal aspects in emotional memory, which is even less investigated (but see Palombo et al., 2021).

The existing literature does not make clear predictions about whether emotion elicits a forward-favouring effect, backward-favouring effect, or no direction-specific effect. Indeed, there is support for each of these possibilities. Supporting a forward-favouring bias, arousal can upregulate alertness and attention towards upcoming information, which could enhance forward encoding at the expense of processing preceding information (Easterbrook, 1959; Sussman et al., 2013). Also supporting forward-favouring, the Retrieved Context Model argues that, during encoding, arousal creates a strong source context that is imbued into the memory traces of upcoming neutral stimuli (Talmi et al., 2019). During retrieval, cuing with an arousing stimulus brings its context into mind, which may ease retrieval of neutral stimuli encoded just after (i.e. a more transient form of state-dependent memory; Lewis et al., 2005; Lewis & Critchley, 2003). Conversely, emotion-attention arguments can be made for backward-favouring, as negative distractors narrow attention and can impair processing of upcoming information

(Easterbrook, 1959; Most et al., 2007; Sussman et al., 2013). Also consistent with a backward-favouring account, fear conditioning research shows that upon experiencing a distressing event, people become highly sensitive to the stimuli leading up to the event (Maren, 2001; Meulders, 2020).

Yet, other evidence suggests that no directional favouring occurs. Studies on mood induction, which is a temporal effect over a longer timescale, suggest that emotion (positive/negative) enhances retrieval of neutral stimuli that came both before and after mood induction (Nielson et al., 2005; Nielson & Powless, 2007; Tambini et al., 2017). Targeting shorter timescales, emotional oddball research suggests that negative stimuli impair free recall of neutral items encoded just before or after the oddball (Schlüter et al., 2019). Finally, Arousal-Biased Competition theory puts forth that directional favouring could occur, but it depends on other factors that may modulate that modulates the prioritisation of preceding or following associations (Mather & Sutherland, 2011).

In sum, the diversity of available evidence supporting and refuting various forms of directional favouring biases limits the ability to generate *a priori* hypothesis regarding temporal biases in the impact of emotion on memory. Accordingly, the present research used a discovery study to generate predictions and then involved a pre-registered replication study to confirm the predictions.

1.1. The present studies

For both the discovery and replication studies, participants viewed a series of negative and neutral pictures during an incidental encoding task, in which they were instructed to create stories connecting consecutive pictures. The stories promoted the formation of associations (Schmidt et al., 2011). Later, participants completed a surprise retrieval test. The test included a temporal association question, where participants were shown one picture (the *cue*), then asked whether a second picture (the *target*) originally appeared immediately before or immediately after the cue. The cue-target pairs primarily included one negative image and one neutral image, and analyses examined how the order of the two images during encoding influenced accuracy on the temporal association question.

We considered two candidate hypotheses, which are illustrated in Figure 1: (A) Consistent with a *forward-favouring* effect of arousal, participants would better encode associations between negative images and subsequent neutral images (Negative-to-Neutral ordered pairs). Thus, when cued with a negative image, participants would better retrieve the neutral image originally shown right after than the neutral image shown right before. Analogously, when cued with a neutral image, participants would better retrieve the negative image that was shown right before than the one shown right after. (B) Consistent with a *backward-favouring* effect of arousal, participants would better encode associations between negative images and preceding neutral images (Neutral-to-Negative ordered pairs). Thus, when cued with a negative image, participants would better retrieve the neutral image that was shown right before than the neutral image shown right after. Likewise, when cued with a neutral image, participants would better retrieve what negative image was shown right after than the one shown right before. Notably, it is also possible that neither hypothesis is correct, and negative arousal does not bias either direction of temporal associations. This is the null hypothesis and, if true, would give rise to insignificant differences between the experimental conditions.

2. Study 1: discovery study

2.1. Methods

2.1.1. Participants

Seventy-two participants were recruited from the local university (68% female, 32% male; $M_{age} = 18.8$; $SD_{age} = 1.04$) and completed the encoding and retrieval tasks for this study (16 participants completed the study in person, and 56 participants completed the study online). Sixteen participants were excluded for low response rates on the temporal association question (gave no response or selected "I don't know" in over 33% of trials). All participants provided informed consent under a protocol approved by the Institutional Review Board and received course credit for participation.

2.1.2. Encoding task

The present protocols, screens, and timings were designed to facilitate the encoding of temporal associations. The design builds upon earlier task protocols used by our group (Dolcos et al., 2020a, 2020b, 2022) and was developed based on pilot

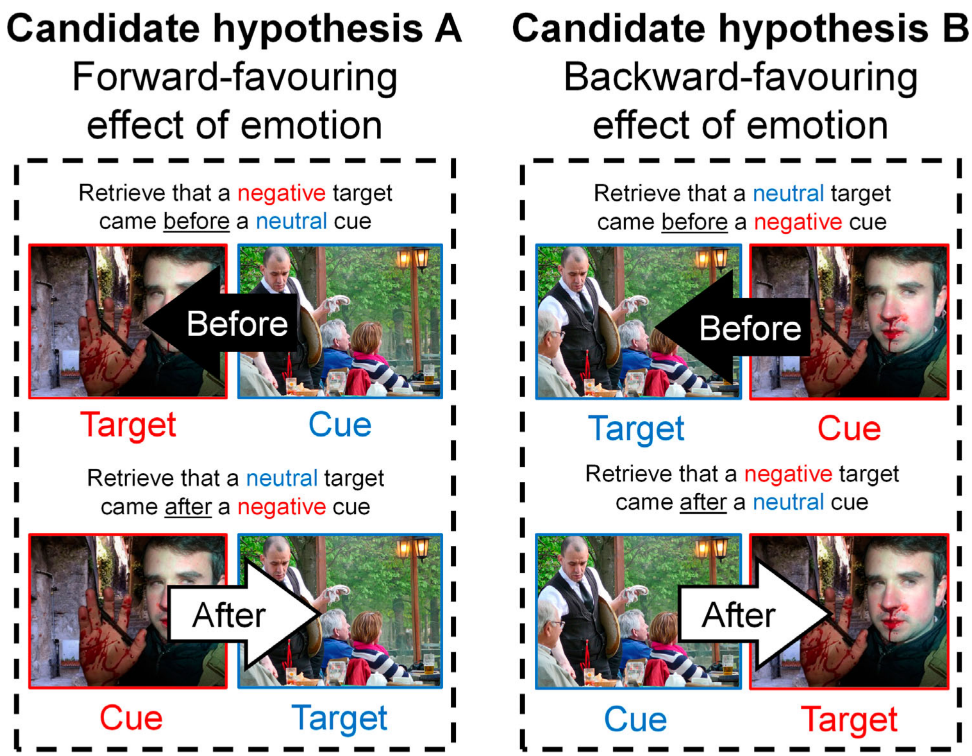

Figure 1. Illustration of two hypotheses on arousal's impact on temporal associations. Candidate Hypothesis A. The possible forward-favouring effect of emotion entails strong associations when encoding arousing stimuli followed by neutral stimuli (Negative-to-Neutral ordered pairs). During retrieval, forward-favouring would lead to better memory for both retrieving that a negative target came before a neutral cue (top left) and retrieving that a neutral target came after a negative cue (bottom left). This hypothesis conceptualises forward-favouring as an encoding-based mechanism because Negative-to-Neutral ordered pairs would yield heightened accuracy regardless of the retrieval question. **Candidate Hypothesis B.** The possible backward-favouring effect of emotion would entail the opposite patterns.

studies showing that temporal associations are difficult to retrieve. Participants viewed a series of images (120 negative images & 120 neutral images), organised into five blocks (Figure 2 left). To encourage the formation of temporal associations between sequential images, participants were instructed to imagine that they are travelling and interpret images as locations. Participants were also told to create a story for each image connecting it to the previous picture. These instructions promoted the feeling that pairs of sequential images were meaningfully connected. Participants were allowed 8 s to construct each story – 6 s with image presentation and 2 s without image presentation. Then, participants were asked to rate how successful they were in constructing a story connecting two consecutive images, using a 5-point Likert scale (1 = "Not at all"; 5 = "Very successful"). The instructional materials given to participants have been uploaded to a public repository a public repository (https://github.com/paulcbogdan/EmoTemporal).

The negative and neutral images were similar to those used in previous studies conducted by our group (Dolcos et al., 2020a; Dolcos et al. 2020b; Dolcos et al., 2022), involving composite images with dissociable foreground and background components. These composite images were created using modified versions of pictures obtained from standardised collections, as follows: the International Affective Picture System (IAPS; Lang et al., 1997), Geneva Affective Picture Database (GAPED; Dan-Glauser & Scherer, 2011), Military Affective Picture System (Goodman et al., 2016), Nencki Affective Picture System (NAPS; Marchewka et al., 2014), and Emotional Picture Set (EmoPicS; Wessa et al., 2010). The negative and neutral composite images were matched for complexity, brightness, contrast, human presence, and animal presence. A validation study ($N = 53$), using 9-point Likert scales, confirmed that the emotional images were all negatively-valenced ($M_{Valence} = 2.81$; $SD_{Valence} = 0.75$) and arousing ($M_{Arousal} = 5.68$; $SD_{Arousal} = 0.89$), while neutral

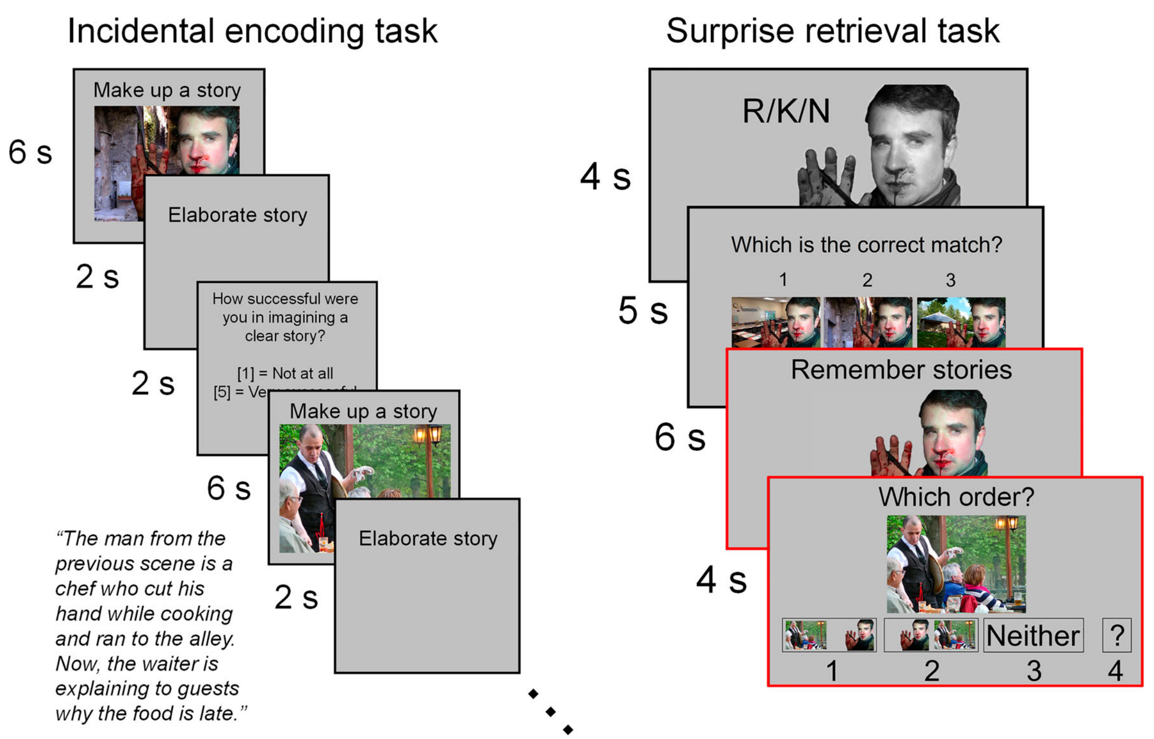

Figure 2. Task diagrams. Incidental encoding task. Participants viewed an image and imagined a story (neither written nor spoken) connecting it to the previous one. Next, participants rated their success in crafting a story. **Surprise retrieval task.** First, participants completed a Remember/Know test for the foreground component of an encoding image or a foil. Second, if the foreground was not a foil, participants were asked to match the foreground with its corresponding background component. Third, temporal associations were tested using the foreground as a *cue* image followed by a *target* image (see the two screens in red), and participants had to indicate whether the latter image was originally shown: (1) immediately before the cue, (2) immediately after the cue, or (3) neither immediately before nor immediately after (e.g. several trials away, in either direction). Participants could also indicate that they (4) had no memory of the order. Here, we only report results from the temporal association question.

images were neutral ($M_{\text{Valence}} = 4.95$; $SD_{\text{Valence}} = 0.63$) and non-arousing ($M_{\text{Arousal}} = 3.54$, $SD_{\text{Arousal}} = 0.49$).

2.1.3. Retrieval task

Participants began the surprise retrieval task (Figure 2 right) immediately upon finishing the encoding task, but the stimuli were organised in the five retrieval blocks such that the effective retention interval for each stimulus was approximately sixty minutes. In each retrieval trial, participants made three responses (see Figure 2), but the present focus is only on the third response, which probed temporal associative memory across 120 trials (60 using a negative cue & 60 using a neutral cue). For this question, participants were shown a *cue image* and asked to retrieve its associated stories. Afterward, participants were shown a *target image* and were asked to indicate its original temporal position relative to the cue image: (1) immediately before, (2) immediately after, or (3) neither immediately before nor immediately after. If participants had no memory of the order, they were instructed to indicate so by choosing (4) "I don't know". Of the 120 temporal association questions, 45 trials used a negative cue and neutral target, 45 trials used a neutral cue and negative target, 15 trials used a negative cue and negative target, and 15 trials used a neutral cue and neutral target. Thus, most associations were tested between one negative and one neutral image, consistent with our focus on directionality during encoding while equating the overall valence among both images. For each condition, "After" was correct in 55 trials (if the cue's position was trial n, target was $n + 1$), "Before" was correct in 55 trials (target was $n - 1$), and "Neither" was correct in 10 trials (target was $n \pm 3$). The trial numbers here represent the final design used for the replication study but varied slightly between participants in the discovery study.

Option 3 ("Neither") was included to prevent decisions based on using a process of elimination during memory testing. For example, suppose a participant encoded the series of images, A-B-C. Later, the retrieval test uses B as the cue and A as the target. Suppose the participant has no memory that *A came before B*. However, they recall that *C came after B*, and thus can infer that *A is not after B*. If the retrieval test lacks "Neither" and the only two options are *A came before B* and *A came after B*, then via a process of elimination the participant can conclude that *A came before B*. In other words, the participant could still accurately report what image came before based on memory for what came after, which runs counter to our focus on directionality. By including "Neither" as a third option, responses based on a process of elimination become less likely. Hence, even though our hypotheses do not target "Neither" memory, including this option was methodologically important.

2.1.4. Temporal memory conditions

Analyses focused on how the order of negative and neutral images during encoding influenced temporal associative accuracy. Hence, the statistical tests were done based only on data from mixed-valence retrieval trials, where the cue and target images had different valences. The results were organised in terms of the four retrieval conditions illustrated in Figure 1: Negative-Before, Neutral-Before, Negative-After, and Neutral-After, where "Negative" and "Neutral" refer to the valence of the cue image. For example, Negative-Before requires retrieving the association between the negative cue image and the (neutral) target that came before. Because analyses only targeted mixed-valence trials, Negative-Before and Neutral-After require the retrieval of associations encoded *Neutral-to-Negative*, which will be enhanced if emotion elicits backward-favouring effects. On the other hand, Neutral-Before and Negative-After require the retrieval of associations encoded *Negative-to-Neutral*, which will be enhanced if emotion elicits a forward-favouring effect.

For each of the four retrieval conditions, hit rate, false alarm rate, and corrected accuracy were measured. *Hit rate* constitutes the rate of accurate responses for a given condition – e.g. the hit rate for Negative-Before is the proportion of trials where participants indicate that the neutral target is "Before". *False alarm rate* constitutes the rate of inaccurate responses of a given type and represents participants' general tendencies to respond a given way towards a given cue regardless of the correct answer – e.g. the Negative-Before false alarm rate is the proportion of negative cue trials where the neutral target was After or Neither but participants indicated "Before". *Corrected Accuracy* is the difference between the hit rate and false alarm rate for a given condition. Measuring corrected accuracy was vital for ensuring an unbiased comparison, as participants showed a bias towards responding "After" more often than "Before", and cue valence could interact with this bias.

2.1.5. Analysis

The corrected accuracy and false alarm rate data for each condition were submitted to two-way ANOVAs, using Cue Valence (Negative vs. Neutral) and Target Position (Before vs. After) as factors. The focus was on the Valence × Position interaction, as it represents a Negative-to-Neutral vs. Neutral-to-Negative comparison. To make this clear, the Results figure below illustrates memory accuracy for both the four retrieval conditions and the two implied encoding order conditions. Confirmatory analyses were also conducted to rule out the possibility that participants were simply retrieving the valence of target images rather than retrieving the target images themselves (Supplemental Materials 1). Additionally, further confirmatory analyses were carried out to test our hypotheses via signal detection modelling, measuring sensitivity (d′) and criterion scores (c) in place of corrected accuracy and false alarm rates. These tests reiterated the conclusion below on the impact of encoding order on temporal associations (Supplemental Materials 2).

2.2. Results

Analyses of the discovery study data yielded initial evidence of a forward-favouring effect of emotion on temporal associations. That is, participants showed the highest memory when retrieving what neutral stimulus came *after* a *negative cue* or when retrieving what negative stimulus came *before* a *neutral cue* (Figure 3). This pattern was significant, as evidenced by the two-way ANOVA showing a Cue Valence × Target Position interaction effect on corrected accuracy, $F[1, 55] = 6.25$, $p = .02$, $\eta^2 = .10$. To examine whether this forward-favouring effect generalises regardless of which stimulus is used as the cue, post hoc t-tests were conducted. These revealed that, when cued with a negative image, participants better retrieved neutral images that followed than neutral images that preceded, *t*

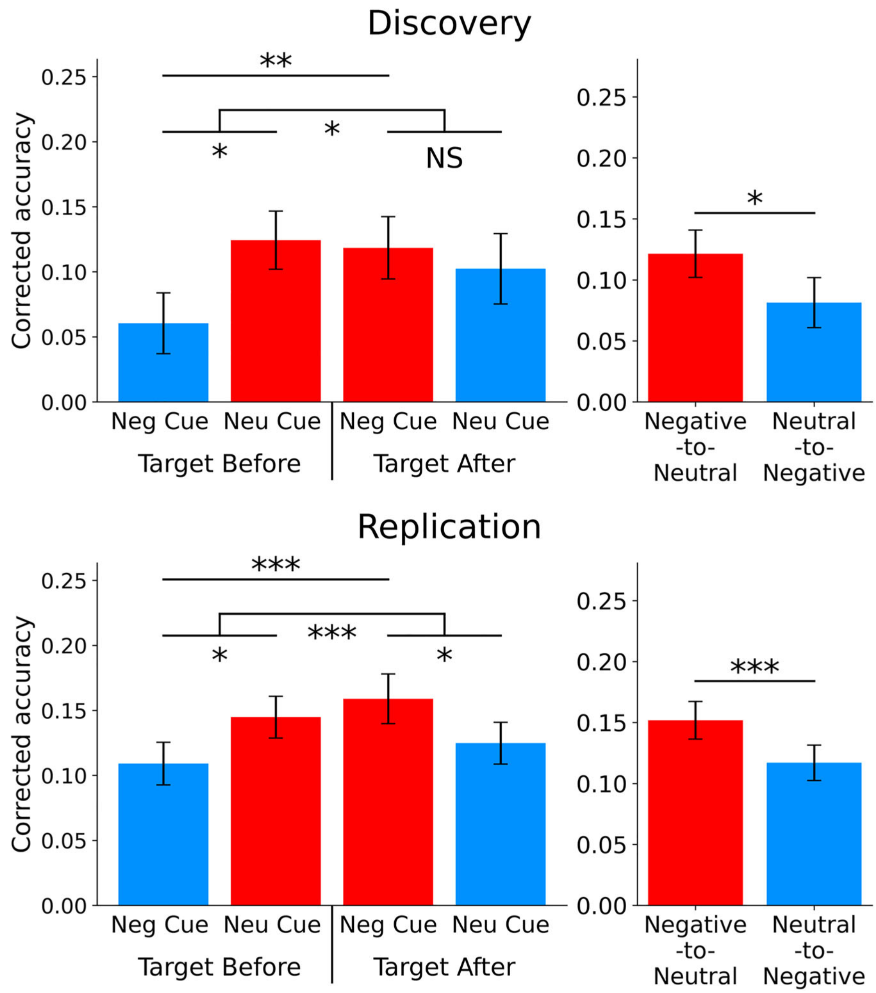

Figure 3. Forward-favouring effect of negative arousal on corrected temporal accuracy. Left. The four bars represent the four retrieval conditions: (1) trials with *Negative [Neg] cues* where the correct answer is that the Neutral target came *Before*, (2) trials with *Neutral [Neu] cues* where the correct answer is that the Negative target came *Before*, (3) trials with *Negative cues* where the correct answer is that the Neutral target came *After*, and (4) trials with *Neutral cues* where the correct answer is that the Negative target came *After*. The second and third conditions, in red, measure Negative-to-Neutral encoding, whereas the first and fourth conditions, in blue, measure Neutral-to-Negative encoding. Increased Negative-to-Neutral encoding, as seen here, indicates a forward-favouring effect of emotion. **Right.** The Cue Valence × Target Position interaction effect is represented here as a pair of bars, comparing Negative-to-Neutral vs. Neutral-to-Negative explicitly. The Negative-to-Neutral measurements are the averages of the two red bars on the left side, while Neutral-to-Negative values are the average of the two blue bars on the left side. NS, $p > .10$; *, $p < .05$; **, $p < .01$; ***, $p < .001$.

[55] = 2.53, $p = .01$, $d_z = 0.34$. When cued with a neutral image, participants showed nominally greater retrieval of negative images that preceded than those that followed, $t[55] = 0.99$, $p = .32$, $d_z = 0.07$. Although this difference was well short of significance, it would be further investigated in the better-powered replication study. Taken together, the emerging patterns suggest that participants encoded stronger temporal association when the encoding order was Negative-to-Neutral (red bars) rather than Neutral-to-Negative (blue bars; Figure 3) (Table 1).

To investigate whether these differences in memory accuracy may have been facilitated by differences in the success of story formation, we additionally compared the conditions' story success ratings. We found that Negative-to-Neutral encoding was actually linked to lower success ratings ($M = 2.90$ [2.70–3.11]) than Neutral-to-Negative encoding ($M = 3.10$ [2.92–3.28]), $t[54] = 2.10$, $p = .04$, $d_z = 0.28$. Hence, the enhanced memory seen for the Negative-to-Neutral condition arose *despite* slightly impaired story formation linked to that condition.

Table 1. Discovery study response rates.

Encoding order	Cue valence	Target position	Response			Corrected accuracy
			Before	After	Neither	
Neu-to-Neg	Negative	Before	**31.5%**	36.9%	19.6%	6.0%
Neg-to-Neu	Neutral	Before	**38.9%**	35.4%	14.4%	12.2%
Neg-to-Neu	Negative	After	24.0%	**47.1%**	17.3%	11.8%
Neu-to-Neg	Neutral	After	25.4%	**45.0%**	17.9%	10.2%

There were four (2 × 2) retrieval conditions, representing Cue Valence × Target Position, which map onto Neutral-to-Negative (Neu-to-Neg) and Negative-to-Neutral (Neg-to-Neu) encoding orders. The response percentages in bold indicate the rates of correct responses for a given condition.

Although not the primary focus of the study, the two-way ANOVA structure above was also used to investigate the false alarm rates. This revealed a main effect of Target Position, $F[1, 55] = 11.9$, $p = .001$, $\eta^2 = .17$ (Figure S3). That is, participants incorrectly responded that the target image came after the cue more often than incorrectly responded that it was before. False alarms were not impacted by the Target Position × Valence interaction, $F[1, 55] = 0.39$, $p = .53$, $\eta^2 = .01$, but this aspect would be further investigated in the replication study.

2.3. Discussion

The discovery study demonstrated a forward-favouring effect of arousal, whereby Negative-to-Neutral pairs yielded stronger associations than Neutral-to-Negative pairs. This pattern arose even though stories were less successfully formed in the Negative-to-Neutral condition, which rules out an alternative explanation that stories could be better formed going from negative to neutral stimuli (Murray & Kensinger, 2012). By showing this forward-favouring effect, the discovery study puts forth initial results, which we aimed to replicate in a pre-registered study (https://osf.io/xn7jt/). Along with these effects on memory accuracy, the discovery study also showed a false alarm bias towards responding "After". The replication study further examined this pattern and tested the possibility that arousal moderates this false alarm bias in an additional pre-registered hypothesis (motivated also by preliminary data beyond the discovery study).

3. Study 2: pre-registered replication

3.1. Methods

One-hundred fifty participants were recruited from the local university (53% female, 45% male, 2% other; $M_{age} = 18.8$; $SD_{age} = 1.08$) and completed the encoding and retrieval tasks for this study (133 participants completed the study in person, and 17 participants completed it online). Following the pre-registered exclusion criteria also used for the discovery study, 17 participants were excluded for low response rates on the temporal association question. This sample size was motivated by pre-registered power analyses, which used an expected effect size of $d_z = 0.29$ that corresponds to the Valence × Position interaction effect on correct accuracy, above. This effect size was established based on pooling data from the discovery study and a separate pilot study (additional $N = 25$). The effect size suggests data from 133 participants provides 93% power for detecting the interaction effect. All participants provided informed consent under a protocol approved by the Institutional Review Board and received course credit for participation.

Task design and analyses were the same as for the discovery study. This includes conducting the same confirmatory analyses that ruled out the possibility that participants retrieved the target image's valence, rather than the image itself (Supplemental Materials 1) and showed how the findings below on corrected accuracy and false alarm rates also appear when examining sensitivity (d′) or criterion (c) scores (Supplemental Materials 2). The data and Python code needed to reproduce the results below have been released in a public repository (https://github.com/paulcbogdan/EmoTemporal).

3.2. Results

Analyses yielded further evidence supporting a forward-enhancing effect of emotion on temporal associative memory. Paralleling the discovery sample results, the two-way ANOVA yielded a significant Cue Valence × Target Position interaction, $F[1, 55] = 19.4$, $p < .001$, $\eta^2 = .13$ (Figure 3). Importantly, post hoc t-tests further showed that when cued with a negative image, participants better retrieved neutral images that were encoded after than neutral images that were encoded before, $t[132] = 2.33$, $p = .02$, $d_z = 0.20$. Analogously, when cued with a neutral image, participants better retrieved negative images that preceded than those that followed, $t[132] = 2.01$, $p = .046$, $d_z = 0.17$. The t-test results provide converging evidence that temporal associations are stronger when encoded Negative-to-Neutral rather than Neutral-to-Negative.[1] Investigation of the story success ratings showed that Negative-to-Neutral encoding yielded similar success ratings ($M = 3.13$ [3.02–3.26]) as Neutral-to-Negative encoding ($M = 3.17$ [3.06–3.29]), $t[130] = 1.33$, $p = .19$, $d_z = 0.12$.[2] Hence, as in the discovery study, the identified forward-favouring effect of emotion on memory cannot be explained by differences in story formation success (Table 2).

Finally, analysis of the false alarm rate data using a two-way ANOVA again showed significant effects. This includes a significant main effect of Target Position on false alarm rates, $F[1, 132] = 141.5$, $p < .001$, $\eta^2 = .52$ (Figure S3). That is, participants incorrectly responded "After" more often than incorrectly responded "Before". In addition, the false alarm rate data showed a significant Valence × Position interaction, $F[1, 132] = 5.28$, $p = .02$, $\eta^2 = .04$. Hence, this "After" bias was pronounced for the Negative condition.

3.3. Discussion

The results showed a clear replication of the forward-favouring effect initially seen in the discovery study. Based on the post hoc t-tests, we can now also conclude that the forward-favouring effect arises regardless of whether a negative image is used as a cue (better ability to retrieve the neutral image that came after) or a neutral image is used as a cue (better ability to retrieve the negative image that came before). Interestingly, the overall average levels of corrected accuracy were higher in the replication study than in the discovery study. This may be because the discovery study was primarily conducted online whereas the replication study was primarily in person, which prompts higher engagement. Nonetheless, identifying significant results across both settings speaks to the findings' robustness. Along with effects on memory encoding, the replication study also showed a significant Valence × Position interaction effect on false alarm rates and criterion scores (c), meaning that negative images also enhanced the bias towards responding "After" even when it was not the correct answer. Such effects are notably independent of emotion's impact on memory encoding, whose analyses accounted for false alarm biases by focusing on corrected accuracy or sensitivity (d′). Overall, the false alarm results point to a potentially interesting link between emotion and directionality in information processing, which may extend beyond memory encoding.

4. General discussion

Returning to our originally presented scenario, if insulted in a conversation, one would likely better retrieve what was said immediately afterward than what was said immediately beforehand. The discovery and replication studies provide converging evidence supporting this point. Specifically, the studies showed that emotion elicited a forward-favouring bias in temporal associations – participants encoded stronger associations between negative stimuli and subsequent neutral stimuli than between negative stimuli and preceding neutral stimuli. This finding arose irrespective of emotion's effects on the successful formation of stories, speaking to the relevance of this emotional memory mechanism beyond the present design. These results and related patterns linked to false alarm rates are discussed below.

4.1. Emotional temporal memory

Several studies have investigated the impact of emotion on memory with a focus on temporal

Table 2. Replication study response rates.

Encoding order	Cue valence	Target position	Response: Before	After	Neither	Corrected accuracy
Neu-to-Neg	Negative	Before	**30.0%**	38.4%	21.2%	10.9%
Neg-to-Neu	Neutral	Before	**34.5%**	34.4%	19.9%	14.4%
Neg-to-Neu	Negative	After	17.6%	**54.6%**	18.2%	15.8%
Neu-to-Neg	Neutral	After	17.9%	**44.9%**	19.7%	10.4%

There were four (2 × 2) retrieval conditions, representing Cue Valence × Target Position, which map onto Neutral-to-Negative (Neu-to-Neg) and Negative-to-Neutral (Neg-to-Neu) encoding orders. The response percentages in bold indicate the rates of correct responses for a given condition.

associations (reviewed in Petrucci & Palombo, 2021), but the findings are mixed. Most similar to the present research are the studies on temporal re-ordering, which likewise focused on temporal associations among neighbouring stimuli. Some studies report that participants can better re-order lists of arousing stimuli than lists of neutral stimuli (Dev et al., 2021; Schmidt et al., 2011), whereas other studies report emotional impairment of re-ordering (Huntjens et al., 2015; Maddock & Frein, 2009). The present research tackles this question by specifically measuring the retrieval of individual associations. In doing so, our findings emphasise that emotion has specific and asymmetric effects in encoding temporal associations.

Although the earlier re-ordering studies did not investigate directional effects of arousal, other branches of emotional memory research have examined forward/backward effects but did not identify directional dissociations like we did. For instance, mood research shows both backward and forward enhancement. Inducing a negative mood, such as by presenting a series of negative images, leads to enhanced retrieval of neutral stimuli shown 9–33 min beforehand or afterward (Tambini et al., 2017). Similarly, presenting a list of neutral stimuli and then inducing a negative mood leads to enhanced retrieval of the preceding list (Nielson et al., 2005; Nielson & Powless, 2007). Hence, these studies did not find the forward-favouring effect we identified, suggesting that longer-lasting affective states may influence memory differently.

Studies on the emotional oddball show both backward- and forward-impairing effects, particularly when negative oddballs are used (see meta-analysis by Schlüter et al., 2019). That is, participants typically show impaired free recall for neutral stimuli immediately preceding or following the negative oddball. This bidirectional impairment differs from the present findings and could be due to the surprise elicited by oddballs, which may cause impairing effects that mask otherwise enhancing properties. Retrieval design may also be a differentiating factor, as most oddball studies have used free recall tests targeting item memory and hence differ fundamentally from the present associative recognition design – see the model by Talmi et al. (2019) on emotion's retrieval-related mechanisms associated with free recall.

It is also worth noting that some more general studies on associative memory have included backward/forward distinctions in their designs without the specific goal of investigating temporal dissociations. In these studies, pairs of stimuli were briefly presented sequentially in each trial, and later participants were asked to retrieve one stimulus using the other as a cue (Madan et al., 2012; Madan et al., 2017). These studies show no directional difference in retrieval. This suggests that the deep encoding used for the present design – forming stories and viewing images over a longer time – may be necessary to elicit a forward-favouring effect.

4.2. A new emotional trade-off?

Trade-offs are a common theme in the literature on emotional memory. Adolphs et al. (2001) argue that negative emotional memory involves a gist/detail trade-off, such that arousal enhances the likelihood of remembering the gist of an experience while sacrificing memory for details. Likewise, Kensinger et al. (2007) argue that negative arousal narrows attention and memory, which enhances the encoding of central features of a scene while impairing memory for peripheral features. Mather and Sutherland (2011) put forth the Arousal-Biased Competition model, which states that arousal enhances perception and memory of high-priority information while impairing processing of low-priority information. Building on these ideas, Bisby and Burgess (2017) argue that negative arousal upregulates item memory encoding while impairing memory for an emotional item's associations with other pieces of information (but see Bogdan et al., 2023). A notable thread across these trade-offs is the relevance of attention-related mechanisms. Negative stimuli capture and narrow attention (Carretié, 2014; Easterbrook, 1959), which leads to a decreased focus on peripheral/contextual details and goal-irrelevant information (Mather & Sutherland, 2011). However, when attention-related effects are accounted for, enhancing effects of emotion on memory for spatial contextual details are also found (Bogdan et al. 2023).

The forward-favouring patterns found here may likewise reflect a trade-off that, too, could involve attention-related mechanisms. Specifically, the present biases could arise from arousal disrupting processing of preceding information (Dolcos & McCarthy, 2006) and/or heightening alertness for upcoming information (Kim et al., 2021; Sussman et al., 2013). Note, however, that heightened alertness leading to enhanced processing is not universally identified, and some studies found that emotion can also impair processing of upcoming stimuli (Most et al., 2005; Most et al., 2007). Nonetheless, beneficial effects of emotion on attention are often seen when upcoming neutral information is goal-relevant or when cognitive changes are needed in response to the information (Kim et al., 2021; Mather & Sutherland, 2011). For the present task, the goal was to quickly craft a story, which required focus and flexibility – much like many negative events outside the laboratory. In this setting, the alertness elicited by emotion may have empowered encoding for subsequent neutral information. Thus, although not every prior report has identified enhancing effects of emotion on attentional focus, this may be a suitable explanation for the present findings.

The novel temporal bias shown here also carries theoretical importance beyond just shedding light on the role of attention. By investigating the relatively unstudied temporal domain, the present findings inform efforts for unified theories of emotional memory that synthesise spatial, temporal, and other effects. Further broadening this direction, the present research sets the stage for work bridging these memory processes to clarify the emotion's impact on other processes, such as reasoning and reinforcement learning. Logical inference, decision-making, and mental simulation are, in many ways, rooted in memory retrieval (Schacter et al., 2007; St. Jacques et al., 2008; Zeithamova et al., 2012) and, in particular, retrieval of temporal associations – i.e. knowledge of how one state of the world begets another.

The results on false alarm rates additionally showed significant effects, which speak to retrieval-based mechanisms. Specifically, we found that participants were biased towards responding "After", even when it was not the correct response, and this bias was most prominent following negative cues. Taken together with our findings on accurate memory, negative stimuli both enhance encoding of temporal associations with upcoming information and promote the retrieval of analogous false associations. These results are broadly consistent with earlier emotional memory research. For instance, studies have largely shown both increased rates of recognition/recollection for emotional stimuli and increased rates of false alarms for negative lures (Brainerd et al., 2008; Corson & Verrier, 2007; Dolcos et al., 2005; Sharot et al., 2004; Weymar et al., 2013; Zhang et al., 2021). Studies investigating valence-related differences specifically argue that heightened false alarms are linked to negative but not positive lures (Brainerd et al., 2008; Zhang et al., 2021). Yet, even for just negative arousal, the impact on false retrieval is not totally clear, as some studies suggest that negative arousal may instead decrease false alarms in various situations (Mirandola & Toffalini, 2016; Van Damme, 2013). In either case, this topic has seen much less research in the context of standard relational memory studies, in part because such studies typically use alternative-forced-choice designs that do not measure false alarms. However, the present results show that this may actually be a fruitful topic for investigation. In particular, investigating temporal associations may be valuable as it bears importance for understanding emotion's impact on general information processing and causal reasoning. The next section further illustrates these broader possible connections by considering how a directional trade-off may manifest outside the laboratory.

4.3. Broader implications

The patterns identified here may reflect mechanisms behind key symptoms of affective disorders. Specifically, involuntary retrieval of negative memories is a symptom of post-traumatic stress disorder and is also seen in depression and anxiety (Desmedt et al., 2015; Stramaccia et al., 2021; Sutherland & Bryant, 2007). To explain this phenomenon, earlier studies on emotional memory trade-offs have argued that arousal's impairing effects lead to gist-like representations of the details and context surrounding a traumatic event (Bisby et al., 2020; Brewin et al., 2010; Dolcos, 2013). Such gist-like representations, in turn, cause people to inappropriately retrieve the memories of a past traumatic event, even when their retrieval context does not match the actual trauma's context – e.g. a veteran hearing a loud noise and retrieving a war memory, even when they are outside a combat environment.

Along the same lines, we found reduced memory for associations between arousing stimuli and what happened before, which may reflect gist-like representations of preceding details. Such representations could prompt inappropriate and involuntary temporal retrieval, which may lead people to perceive neutral stimuli as likely indicators of upcoming negative events – e.g. a veteran hearing a loud noise and inferring that their building will soon collapse due to an explosion. Inappropriate retrieval like this resembles the generalisation of conditioned stimuli seen in fear conditioning research (Dunsmoor &

Murphy, 2015). Interestingly, emotion regulation strategies can be employed to mitigate decontextualisation in the spatial domain, for instance by engaging attentional control to focus on contextual information during encoding (Bogdan et al., 2023; Dolcos et al., 2020a) or retrieval (Denkova et al., 2013; Denkova et al., 2015; Iordan et al., 2019). Applied to temporal memory, such strategies may also deter weakened memory for what occurred before an emotional event.

The false alarm rate findings are also relevant for understanding how individuals process negative information. Our findings show how participants more readily make assumptions about what followed a negative stimulus. These results may shed light on the nature of catastrophising by clarifying how negative events can trigger irrational but intense inferences about the future (Brewin et al., 2010; Sansone et al., 2013). This topic has not been previously studied under the lens of temporal relational memory, but this may be a productive new avenue for investigation.

Finally, aside from the relevance of the findings to affective disorders, the present work speaks to other memory topics too. For example, memory is a key issue for the use of eyewitness testimonies in criminal proceedings (Loftus, 1996, 2019). Temporal information – the events leading up to or following a scene – has critical value. However, we show how preceding information may be the most susceptible to emotional memory failures. This is a new factor to consider when evaluating the reliability of memory, and adds to the evidence on why testimonies may be inaccurate even if they are vivid.

5. Conclusion

The present research provides robust pre-registered evidence for a novel bias in the impact of negative emotion on temporal associations. Compared to neutral stimuli, unpleasant stimuli lead to stronger associations with upcoming information than with preceding information (a forward-favouring effect). These results speak to the value of investigating temporal associations at a fine-grain level by isolating and probing memory between specific sequential pairs. In addition, these findings have conceptual and practical implications. Conceptually, they inform multifaceted theories of memory that link different cognitive domains and lay the foundation for research on how these temporal emotional biases may be integrated with emotion's effects on spatial contextual associations. Practically, they point to the roots of affective memory pathways that define many clinical conditions, which may inform treatment strategies. We anticipate that these findings will stimulate future research to further explore and integrate the impact of emotion on various dimensions of associative memory.

Notes

1. The pre-registration form also details one additional hypothesis related to the item memory and spatial relational memory tests, whereby emotion was expected to yield more trials where participants had accurate responses to both tests. This hypothesis was confirmed (t[132] = 3.27, p = .001, d_z = .28), but this result was planned for a separate report. This finding replicates and extends results by Bogdan et al. (2023), which challenge evidence of impaired relational memory by emotion (Bisby and Burgess, 2017).
2. Two participants did not respond to the success ratings prompts.

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Data availability statement

The instructional materials given to participants, analytic code, and replication study data have been uploaded to a public repository (https://github.com/paulcbogdan/EmoTemporal).

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