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Negative Emotional Events Retroactively Disrupt Semantic Scaffolding of Temporal-Order Memory

Mason McClay[1], Nina Rouhani[2], and David Clewett[1]
[1] Department of Psychology, University of California, Los Angeles
[2] Department of Psychology, University of Southern California

Emotional responses pervade everyday life and exert temporally extended effects on cognition. Prior work shows that these modulatory effects of emotion on memory are highly selective, with semantic overlap helping to determine which nearby neutral details are prioritized in long-term memory. Although this has been demonstrated in item recognition, less is known about how emotion interacts with semantic information to influence temporal-order memory. Here, we developed an emotional oddball task in which participants encoded lists of neutral words that were either semantically related to or unrelated to a perceptually deviant emotional or neutral oddball word. We hypothesized that an adaptive memory system should selectively enhance temporal-order and recall memory for information that precedes or follows a conceptually related emotional stimulus. We found that order memory was enhanced for word pairs that preceded a semantically related neutral oddball, suggesting that semantics helps to scaffold temporal encoding processes. By contrast, emotional oddballs retroactively disrupted this mnemonic benefit of semantic overlap on temporal-order memory. Emotional oddballs also led to proactive impairments in order memory irrespective of semantic relatedness. After a 24-hr delay, emotion enhanced recall of preceding, semantically unrelated words. Encountering an emotional oddball also enhanced recall for subsequent words irrespective of semantic relatedness. Our findings suggest that emotion bidirectionally and selectively disrupts the temporal organization of memory, while also enhancing memory for individualized, unrelated elements of an emotional episode.

Keywords: temporal memory, emotion, episodic memory, semantic scaffolding

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Emotional events lead to the formation of vivid and lasting memories (Kensinger et al., 2007; LaBar & Cabeza, 2006; Mather & Sutherland, 2011; Yonelinas & Ritchey, 2015). However, we cannot always predict when something important will happen. It is therefore worth holding onto seemingly trivial information temporarily in case it acquires relevance in the future. For example, imagine walking over some grooved and seemingly innocuous lines on a trail during a hike. Soon thereafter, you suddenly encounter a snake farther down the trail. When remembering this experience the next day, the mundane markings that once seemed unimportant may spring to mind, because they have acquired predictive meaning of the emotional event that follows. An adaptive memory system should be able to link such details together as early as possible so that you can reconstruct the relevant details (the trail lines) to help avoid similar threats in the future (the rattle snake). Similarly, it is likely important to remember events following the encounter with the rattle snake, like trail markers, to remember how to escape threats in the future. Given that mental resources are limited, it would be inefficient to store the deluge of sensory inputs that are not relevant to or predictive of a source of threat (e.g., your hunger level or a discarded water bottle on the trails). A memory system that selectively retains the order of emotionally relevant details may be better equipped to reconstruct meaningful memory representations that guide adaptive behavior than a memory system that enhances consolidation processes indiscriminately. Such behaviors could include enhancing the ability to predict an important sequela of events. It could also include simply supporting the ability to accurately represent and reconstruct an emotional episode in memory, which is important for understanding and deriving meaning from important experiences.

Consistent with this scenario, models of emotional memory suggest that semantic relevance may be a guiding force for emotion's selective influence on memory (Dunsmoor et al., 2022). For instance, both priority binding (Hadley & Mackay, 2006; Mackay et al., 2004) and arousal-biased competition (ABC; Knight & Mather, 2009; Mather & Sutherland, 2011) models of emotional memory emphasize the role of emotion in prioritizing memories for goal-relevant, attention-grabbing, and semantically relevant information. Furthermore, memory-retrieval models implicate both emotion and semantic relatedness in the preferential retrieval of specific information (Polyn et al., 2009; Talmi & Moscovitch, 2004). Recent evidence further suggests that emotion or reward learning can

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Mason McClay https://orcid.org/0000-0002-6679-3096
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Correspondence concerning this article should be addressed to David Clewett, Department of Psychology, University of California, Los Angeles, 5558 Pritzker Hall, Los Angeles, CA 90095, United States. Email: david.clewett@psych.ucla.edu

selectively benefit temporal or item memory for otherwise neutral information that is conceptually associated with those salient events (Dunsmoor et al., 2015; Hennings et al., 2020; Patil et al., 2017; Rouhani et al., 2023). This converging evidence suggests that semantic relevance of neutral information to an emotional event may determine whether otherwise mundane information becomes stabilized in long-term memory.

While much empirical work shows that emotion has highly selective effects on long-term memory (Kensinger et al., 2007; Mather & Sutherland, 2011; Williams et al., 2022), there is conflicting evidence as to how emotional events influence memory for neutral temporally adjacent items as well as surrounding contextual (e.g., spatial or temporal) information. For instance, evidence from emotional oddball studies has shown that recall is impaired for items preceding or following emotional oddballs compared to neutral oddballs (Talmi et al., 2019), at least insofar as those neighboring items do not receive special attention (Clewett et al., 2017; Hurlemann et al., 2005; Sakaki et al., 2014; Schlüter et al., 2019; Strange & Dolan, 2004; Strange et al., 2003). Furthermore, while word list studies have found retroactive enhancement of memory for neutral stimuli preceding an emotional stimulus (A. K. Anderson et al., 2006; Smith & Beversdorf, 2008), other studies have shown an impairment or no effect on recognition memory for stimuli preceding an emotional event (Hadley & Mackay, 2006; Hurlemann et al., 2005; Knight & Mather, 2009; Strange et al., 2003), for neutral images encoded in the same block as emotional images (B. Wang & Ren, 2017), and for memory of word pair associates (Madan et al., 2012). However, other studies that have investigated memory for contextual information surrounding the presentation of taboo words have found that the presence of an emotional event leads to enhanced memory for spatial information, in particular where words were presented on a screen grid (MacKay & Ahmetzanov, 2005) and surrounding neutral words (Brierley et al., 2007; Guillet & Arndt, 2009). Beyond item memory, negative emotional stimuli have also been shown to enhance memory for spatial information (D'Argembeau & Van der Linden, 2004). Other research on temporal-order memory and emotion has demonstrated that the presence of a negative event is associated with enhanced order memory across a range of media, including emotional scenes within a film (Dev et al., 2022), the source of the experimental block in which an image was presented (Petrucci & Palombo, 2021), and the sequence order of images connected by an imagined narrative (Bogdan et al., 2025).

One way to reconcile these disparate findings is to account for interactions between stimulus priority and an emotionally arousing stimulus (Mather & Sutherland, 2011). For example, according to ABC theory, emotional arousal will amplify the effects of priority in perception and memory, such that arousal enhances processing salient information even further, while also suppressing the processing of less salient information. The ABC model is supported by empirical evidence from oddball studies demonstrating that emotionally arousing oddballs enhance memory for preceding images that are either goal-relevant or prioritized in top-down attention (Rimmele et al., 2016; Sakaki et al., 2014). One important feature of the study by Sakaki et al. (2014) is that participants were not aware of which stimulus was goal-relevant until they encountered the oddball itself. Specifically, sequential items needed to be held in working memory until participants encountered a prioritized black-framed oddball that appeared immediately after. Thus, the modulatory effects of emotion can enhance priority retroactively or at least modulate the strength of representations that are still being held in mind. In its current form, the ABC model broadly construes priority as a goal-relevant or perceptually salient stimulus (Mather & Sutherland, 2011). Yet, it also stands to reason that conceptual, or semantic, overlap can enhance the priority of an otherwise neutral stimulus. Such prioritization may be driven by the need to form causal links between conceptually similar information, especially when these associations are relevant to survival (Hadley & Mackay, 2006; Mackay et al., 2004).

Although existing findings suggest that emotion may influence memory for items and their contextual associations differently, less work has examined how emotion influences memory for the temporal associations between sequences of information, such as remembering the order of events (see Palombo & Cocquyt, 2020; Petrucci & Palombo, 2021, for reviews of the relevant literature). What is more, the relatively sparse empirical research on emotion and temporal organization of memory has yielded mixed findings across a range of different temporal-order memory measures (Petrucci & Palombo, 2021). For instance, some studies have found enhanced temporal source memory (i.e., memory for "when" something occurred) for intrinsically emotional images over neutral images (D'Argembeau & Van der Linden, 2005; Rimmele et al., 2012). However, other work has shown that emotional learning leads to temporal source misattributions for conceptually related neutral items encountered prior to or following a fear-conditioning procedure (Hennings et al., 2021). Further complicating this picture, other work implementing item-level rather than source-level temporal-order memory measure has shown that negative emotion can sometimes enhance (Clewett & McClay, 2024; Dev et al., 2022; Knight & Mather, 2009; Schmidt et al., 2011) memory for the precise order of individual items. Negative emotion also appears to influence other aspects of temporal-order memory. Namely, it has been shown that temporal duration discrimination is more accurate for threatening compared to non-threatening sounds (Cocenas-Silva et al., 2012).

One additional limitation of prior work on emotion and temporal-order memory is that it has rarely investigated the influence of semantic relevance to the emotional event (e.g., Dev et al., 2022). Semantic relevance has been shown to play a strong role in guiding the clustering of memories during free recall and the allocation of attentional resources during encoding (Mackay et al., 2004). Thus, understanding how emotion interacts with semantic relevance in organizing and reconstructing memory is essential, since real-world emotional events are often semantically or causally related to their surrounding contexts (e.g., Ehlers et al., 2004; Ehlers & Wild, 2022).

Here, we sought to address these limitations by testing if emotion selectively binds semantically related information preceding or following an emotional event in temporal-order memory. To this end, we created an emotional oddball word sequence paradigm in which we manipulated the emotionality of oddball words as well as the semantic relevance of neutral information preceding or following those oddballs. Participants encoded word lists composed of two distinct semantic categories of words. Critically, the middle word of each list was either an emotional or a neutral perceptual oddball word that belonged to one of the two semantic categories. Following the encoding of each list, participants were tested for their memory of the temporal order (i.e., which word came first) between neutral word pairs. The word pairs were either semantically relevant or irrelevant to the oddball category. Participants then returned for a free recall test 24 hr later to examine if emotion stimuli had long-term consequences for encoding otherwise neutral items, particularly given their semantic relatedness to the emotional stimulus (e.g., Dunsmoor et al., 2015). We predicted that semantic relevance to the oddball category would lead to better temporal order and free recall performance. We also predicted that these selective memory enhancements for semantically related information would be greater for lists with emotional oddballs compared to lists with neutral oddballs, demonstrating an emotion-related benefit for item and associative memory. Finally, based on previous research that found effects of emotional oddball exerting memory-enhancing effects on relevant information preceding versus following the oddball (Smith & Beversdorf, 2008), we predicted that selective memory enhancements would be strongest for information encountered prior to the oddball (retroactive enhancement) compared to items following the oddballs (proactive enhancement), given that these preceding details have the most predictive utility for the emotional event.

Method

Data Collection

Participants

Sixty-one healthy adults (29 female; $M = 25.30$ years, $SD = 3.23$) were recruited from https://Prolific.co, a website that connects researchers with eligible participants based on a wide range of inclusion criteria. Eligibility criteria included (a) age of 18–35 years old; (b) American or Canadian nationality; (c) English first language; (d) normal or corrected-to-normal vision; (e) no history of serious head injuries (e.g., concussion); (f) previous participation in 50 studies on Prolific to ensure familiarity with online study protocols and minimize data variability due to noncompliance or lack of engagement; and (g) a minimum 90% approval rating on Prolific (percentage of studies for which the participant has been approved by the experimenter). Prior to starting this experiment, a power analysis was performed to estimate the appropriate sample size for a generalized linear model (GLM) with three predictors (oddball valence, semantic similarity, and item event source). Informed by prior literature that manipulated emotion, semantic relevance, and event (Smith & Beversdorf, 2008; $n = 28$), as well as the effect size from a similar sequence learning experiment that used a GLM with two predictors (emotion and condition; GLM model comparison: $w = .59$; Clewett & McClay, 2024), we assumed a moderate-to-large effect size for a GLM with our three predictors of interest (emotion, semantic relevance, and event; $f^2 = .2$). This power analysis estimated a sample size of 51 participants. However, we assumed that online data collection would yield more noise than traditional lab-based memory experiments, so we opted to increase our target sample size to 55. Recruitment criteria included no self-reported history of psychiatric, neurological, or major medical illnesses or current use of psychoactive medication. All study protocols were approved by the institutional review board at the University of California, Los Angeles, and participants received monetary compensation for their participation.

A total of six participants were excluded from analyses based on poor performance or noisy behavioral data. Three participants were excluded for low performance on the temporal-order memory test (average temporal-order memory performance was below 50%); one participant was excluded for not passing encoding response variability metrics (making more than four of the same encoding judgments in a row, as assessed via the "careless" package in R; Yentes & Wilhelm, 2018); and two participants were excluded for taking too long on the Day 1 temporal-order memory task (1 hr over the expected experiment duration). These exclusions left us with our target sample size of 55 for all temporal-order memory analyses.

Experimental Paradigm

Word-Stimuli Sets

A total of 560 words (20 words for each of 28 semantic categories) were selected from Pereira et al. (2018) and the Affective Norms for English Words word database (Bradley & Lang, 1999). Word category identification was determined by spectral clustering of word2vec semantic embeddings in a previous study (Pereira et al., 2018). These word stimuli were chosen by the first author to match semantic categories of words in the Affective Norms for English Words database as well as to create 14 unique encoding lists that consisted of 23 words from two different categories. One word from each category was selected to be the neutral oddball (all valence and arousal ratings made on a scale from 1 to 9; M valence = 5.61; range valence = [4–7.39]; SD valence = .81; M arousal = 3.73; range arousal = [2.43–6.11]; SD arousal = .67), and one emotional word was chosen to be the emotional oddball (M valence = 2.54; range valence = [1.48–4.48]; SD valence = 0.79; M arousal = 5.44; range arousal = [3.38–7.24]; SD arousal = 0.78); comparisons between negative and neutral oddballs yielded ps < .001, from each category (see Supplemental Tables 1 and 2 for oddball exemplars and normative valence and arousal ratings).

Emotional oddballs were selected to be negative, since predictions were primarily concerned with the memory-enhancing effects of negative events. Importantly, stimulus relevance and emotion identity were fully randomized across all participants, such that any given list could include an emotional or neutral oddball or be selected as an oddball relevant or irrelevant list. Oddball word length was controlled across emotion condition (average word length emotional oddballs = 6.5; average word count for neutral oddballs = 6.3; $p > .05$). Because of the levels of randomization in the task (described below), word concreteness, frequency, and length were not equalized across categories. However, we controlled for these features by modeling them as random-effect covariates in our linear mixed modeling analyses.

Online Data Collection

All phases of the experiment took place on Qualtrics and Pavlovia. The word sequence-encoding task and memory tests were conducted in PsychoPy (Peirce, 2007). Consent, surveys, and the free recall task took place on Qualtrics, whereas the sequence-encoding task, distractor tasks, temporal-order memory test, and delayed free recall test took place on Pavlovia. On Day 1, participants were routed from Prolific.co to Qualtrics to initiate the surveys and then routed to Pavlovia to perform the encoding and temporal-order memory tasks. On Day 2, participants were routed from https://Prolific.co to Qualtrics to initiate the free recall task.

Word-Sequence Encoding

In this within-subjects design, participants studied different lists of 23 words that included 22 neutral words and one perceptually deviant oddball word that occurred in the middle of the list (14 word lists total). During sequence encoding, each word appeared for 3 s. Participants were instructed to press a button to indicate whether each word was concrete (i.e., represented a tangible object) or abstract (i.e., represented an idea) as quickly as possible via a "space bar" press. A centrally presented white fixation cross was displayed in between each word for 2 s.

Within each list, the first 11 words (Positions 1–11) and last 11 words (Positions 13–23) were neutral nouns from two conceptually distinct categories (e.g., dwellings vs. gatherings). Critically, the 12th (middle) word was an "oddball" noun that was *bolded* and presented in red font to make it stand out from the other words in the list. In half of the lists, the oddball word was negative and arousing (e.g., "massacre"), while in the other half, the oddball word was neutral and not arousing (e.g., "meeting"). This item order was designed to ensure that the retroactive and proactive word pairs had equal bin sizes within each list. Further, the item order enabled the testing of as memory unique word pairs with an equal number of intervening words as possible, as is common in memory experiments testing temporal-order memory for different item pairs (e.g., Clewett et al., 2020; Clewett & McClay, 2024; DuBrow & Davachi, 2016; Heusser et al., 2018; McClay et al., 2023; Wen & Egner, 2022). There were seven emotional lists and seven neutral lists in total.

In each word list, 11 words were conceptually related to the oddball word (e.g., neutral words related to gatherings), whereas the other 11 words were not conceptually related to the oddball word (e.g., neutral words related to dwellings). The structure of word encoding was the same across lists, with adjacent relevant and irrelevant words alternating in a pairwise manner (see Figure 1D). Specifically, each list began with two oddball-irrelevant items, then two oddball-relevant items, then two oddball-irrelevant items, and so forth. The purpose of this pairwise structure was to maximize the number of valid word pairs for the ensuing temporal-order and distance memory tests. This manipulation ensured that to-be-tested word pairs came from the same condition (i.e., both oddball-irrelevant), spanned three intervening words, and did not contain the oddball word.

The order of categories within and across lists, order of words within categories, assignment of oddball relevant or irrelevant categories, and the assignment of oddball types (emotional or neutral) were fully randomized for each participant. This approach ensured that no two participants encountered the same word sequence, thereby minimizing order effects. To avoid inducing sustained negative moods, the order of emotional and neutral list presentation was pseudorandomized so that no more than two emotional or neutral lists were presented in a row.

Delay Distractor Task

To reduce potential recency effects in memory, participants performed a 45-s arrow distractor task after studying each word list. Participants viewed a rapid stream of either left-facing (<) or right-facing (>) arrow symbols. These arrows were displayed in the middle of the screen for 0.5 s and were separated by a 0.5-s fixation cross. Participants simply had to indicate the direction of each arrow as quickly as possible via button press.

Temporal-Order Memory Tests

Following the distractor task, participants were shown pairs of words from the prior sequence and had to make two memory decisions. First, participants were tested for temporal-order memory by indicating which of the two words had appeared first in the prior sequence. Second, participants rated the temporal distance between those same two words, which included the following options: "very close," "close," "far," or "very far" apart (e.g., Clewett et al., 2020; Ezzyat & Davachi, 2014). Crucially, each word pair was always presented with three intervening items during encoding and was therefore always the same objective distance apart. The side of the screen each word was presented (left or right) on was randomized. Given that the main goal of this study was to assess whether emotion influences processes that may relate to predictive utility—that is, understanding how emotion influences memory for the potential sequelae of events leading up to or following something emotional—we do not report the temporal distance in the current article.

To examine time-dependent influence of oddballs on temporal-order memory, we tested memory for two types of neutral word pairs: (a) words preceding the oddball word, or retroactive word pairs; and (b) words that followed the oddball word, or proactive word pairs. The structure of the event sequences as well as the specific positions tested is displayed in Figure 1D. There were 14 word lists, and four retroactive word pairs and four proactive word pairs, resulting in 64 memory trials for each word pair type across the entire experiment.

Delayed Free Recall Test

Participants returned 24 hr later to complete a surprise delayed free recall and recognition tests for all words that were studied on Day 1. Delayed free recall was uncued, and participants were instructed to remember as many words as possible. Participants were allotted 10 min for the free recall task in Qualtrics. Since overall recognition memory performance was poor (M recognition = .51; standard error of the mean = .09, not statistically different from chance, $p = .66$) and was not central to the primary hypotheses, we do not present recognition results in the current article.

Emotional Valence and Arousal Ratings

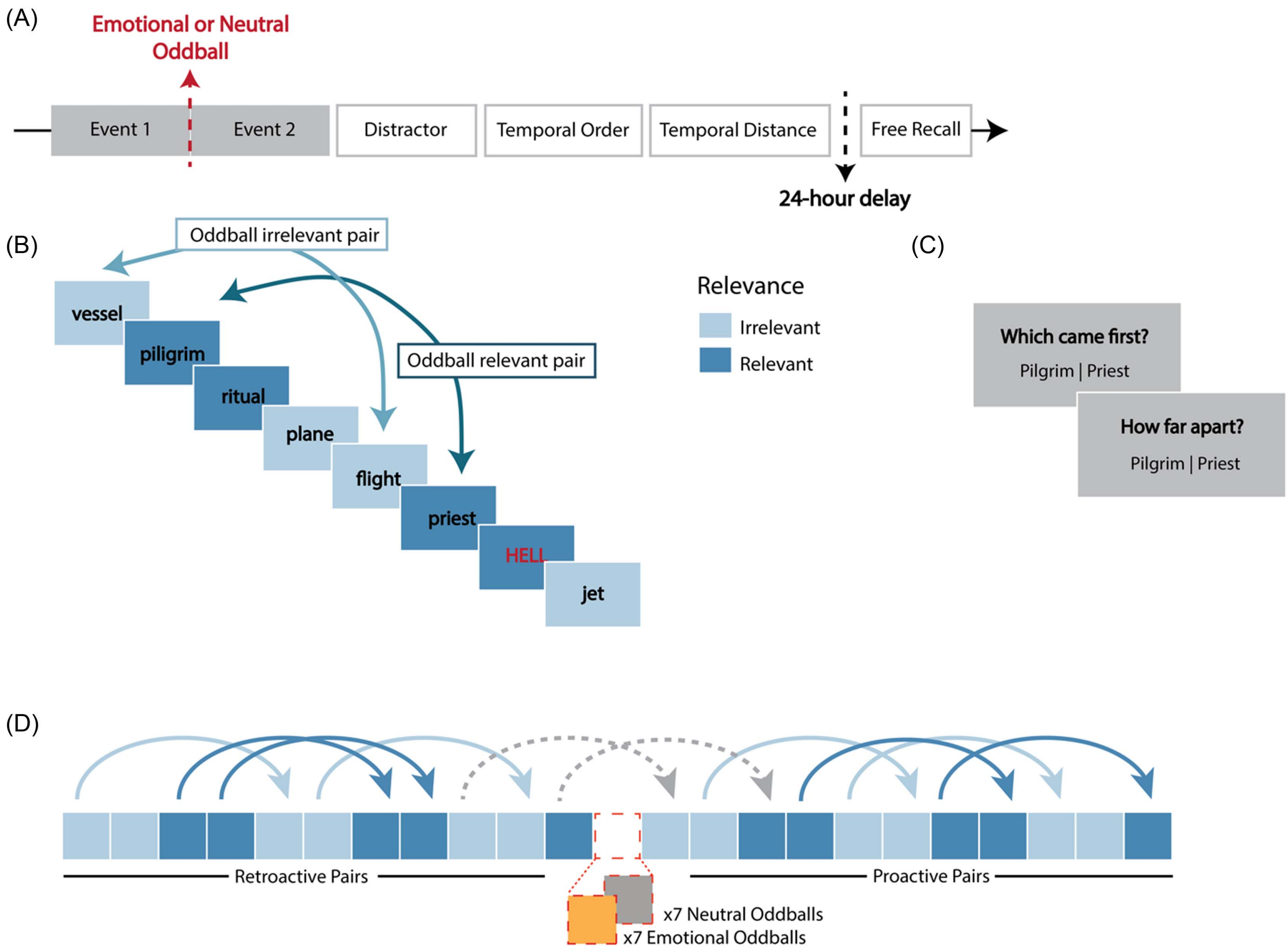
To determine if valence or arousal was more predictive of temporal-order memory, normative valence and arousal ratings were sourced for the oddball words from a database developed by Warriner et al. (2013).

Continuous Measure of Semantic Relevance to the Oddball-Relevant Category

A continuous trial-wise metric of semantic similarity was computed using the word2vec algorithm (Mikolov et al., 2013). We extracted word embeddings (600 dimensions) for each word and computed a representational similarity matrix of cosine similarity for each participant-unique list (see Figure 2). From these matrices, we computed oddball category relevance by extracting the average semantic similarity of each word to the other words from its respective list's oddball category (e.g., priest, church, shrine, and so on if the oddball category was "religion"). We excluded oddball words from this analysis because emotional words tend to be represented more abstractly in semantic embedding space (e.g., Snefjella et al., 2019). Therefore, we extracted average similarity to the oddball category words excluding the oddball word itself.

Figure 1

Sequence-Encoding Oddball Task and Temporal-Order Memory Test



Note. (A) Timeline of the experiment. Participants completed word list encoding followed by a distractor task and pairwise temporal order and distance tests. Participants then returned 24 hr later to perform a surprise free recall test for the words studied on Day 1. (B) During the sequence-encoding oddball task, participants studied lists of 23 words from two distinct semantic categories and had to indicate whether each word represented something concrete or abstract. After studying 11 successive neutral words, participants were presented with a bolded-red word that was either emotional or neutral and semantically related to one of the categories. These bolded words served as oddballs, which parsed each continuous 23-item sequence into two discrete events. Following the oddball words, participants then viewed 11 more neutral words from the two semantic categories. (C) After a short distractor task, participants performed a temporal order judgment followed by a distance judgment. During the temporal order test, participants indicated which of two presented words appeared first. During the temporal distance test, participants rated how far apart they thought the two words were from each other using one of four possible ratings, ranging from "very close" to "very far" apart. (D) Arrows indicate all word pair combinations that were tested during the temporal-order memory and distance tests. Four pairs came before the oddball (retroactive pairs), and four pairs came after the oddball (proactive pairs). Participants encoded 14 lists, seven of which included an emotional oddball and seven of which included a neutral oddball. See the online article for the color version of this figure.

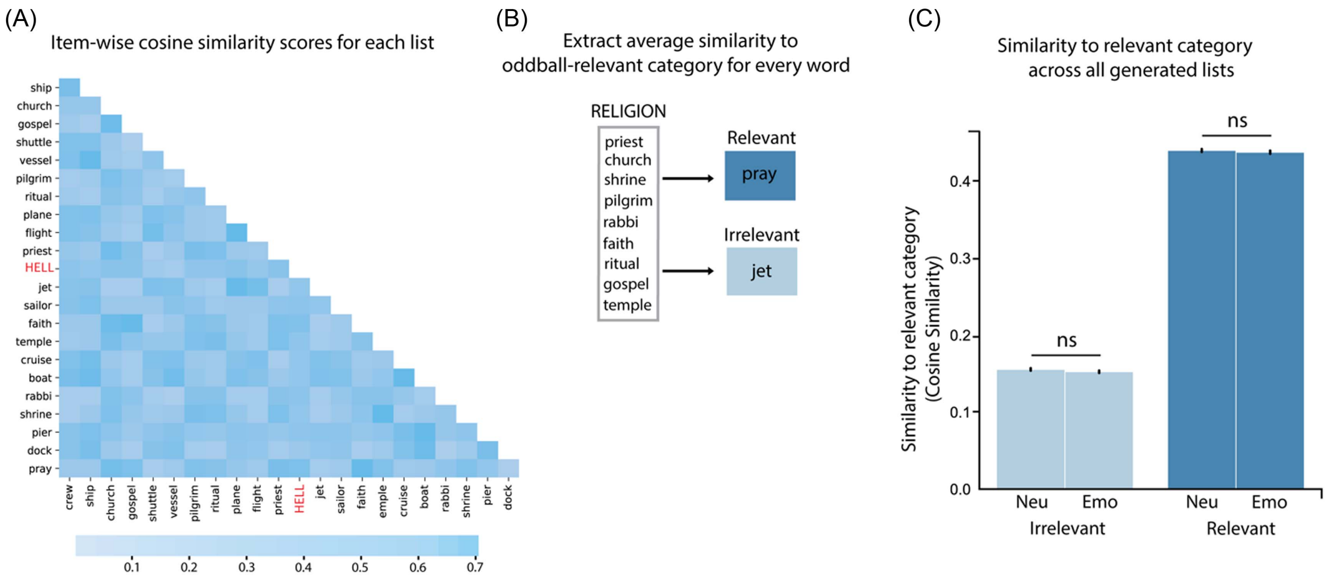
Higher relevant category scores indicate greater average semantic similarity between a word and its list's oddball-relevant category.

Mixed-Effects Models of Memory Metrics

To test our key hypotheses that semantic relevance and emotion interact to influence temporal-order memory, we performed generalized linear mixed-effects analyses using the glme4 packages in R (https://cran.r-project.org/web/packages/lme4/; Bates et al., 2014). Trial-level normative ratings for the valence and arousal for each oddball word were mean-centered and entered into the model as fixed-effect predictors. Intercepts for each participant were specified as random effects, enabling us to account for individual differences in emotion-memory relationships.

We tested whether a word's event position relative to the oddball (1 = preoddball; 2 = postoddball) influenced temporal-order memory and free recall. Furthermore, to test whether emotion interacted with semantic relevance to influence temporal-order memory and recall, we also included a two-way interaction term for relevance-by-emotion and three-way interaction term for relevance-by-emotion-by-event. We created two series of linear mixed-effects models, one series for each dependent variable (temporal order and free recall hits). Temporal-order memory accuracy for the item pairs was coded as a binary variable (1 = correct, 0 = wrong) and modeled

Figure 2
Example of List-Wise Word-Embedding Similarity to the Relevant (Oddball) Category



Note. (A) To derive a trial-level continuous metric of semantic relevance to the oddball category, a representational similarity matrix was created using word2vec for each unique participant-level word list. (B) The average semantic similarity between each item in a word pair and all items in the oddball category (excluding the oddball word) was calculated for each word pair. (C) Relevant word pairs were more similar to items in the relevant categories than irrelevant categories across emotional and neutral lists and did not differ between emotional and neutral lists. Error bars = 95% confidence interval; ns = not statistically significant. See the online article for the color version of this figure.

as the dependent measure in logistic mixed-effects regression models. Free recall accuracy was calculated as the percentage of correctly recalled words and modeled as the dependent measure in the linear mixed-effects models.

In all reported models, relevance refers to the continuous similarity to the relevant (i.e., *oddball*) category (see the Continuous Measure of Semantic Relevance to the Oddball-Relevant Category section). For visualization purposes, however, semantic relevance is dichotomized based on semantic category identity. To test whether normative valence or arousal of the oddball was a stronger predictor of memory outcomes, we performed model comparisons for all within-event (preoddball or postoddball) analyses between models with normative-valence or normative-arousal terms.

Trial-level random intercepts for category type (e.g., house; school; ocean) were entered as a covariate in each model to account for potential differences in memoranda across distinct semantic categories (word length, concreteness, and frequency). For all analyses, the statistical significance of the regression models was determined using model comparisons, which resulted in χ^2 values and corresponding p values. To disentangle the effects of semantic relevance and valence/arousal on memory, we also performed simple slopes analyses by examining how emotional valence/arousal ratings influenced all memory outcomes at low (unrelated) and high (related) levels of semantic relevance (Aiken et al., 1991).

Memory Data Exclusions

All analyses excluded the first trial due to potential primacy effects in memory. Due to experimenter error, three of the 322 encoded stimuli were repeated on average two lists per participant. All analyses reported here exclude entire lists with repeated stimuli.

Transparency and Openness

All data, code, and materials are shared publicly on the Open Science Framework at https://osf.io/58d2c/ (McClay et al., 2024). All participants in this study provided written informed consent.

Results

Emotional Oddballs Led to Slower Response Times During Encoding

First, as an attentional manipulation check, we examined if emotional oddballs influenced the response times of the word concreteness judgments during encoding. As expected, participants were slower to judge oddball words compared to other words in the list, $t(55) = 10.01$, $p < .001$; Figure 3. Trial-level mixed-effects analyses of the oddball trials revealed a significant main effect of the oddball valence, $t(55) = -2.65$, $p = .008$, and arousal, $t(55) = 2.55$, $p = .014$, on response times, such that increasingly negative and arousing oddballs induced significant slowing effects. These findings suggest that negative stimuli led to an increase in attention during encoding.

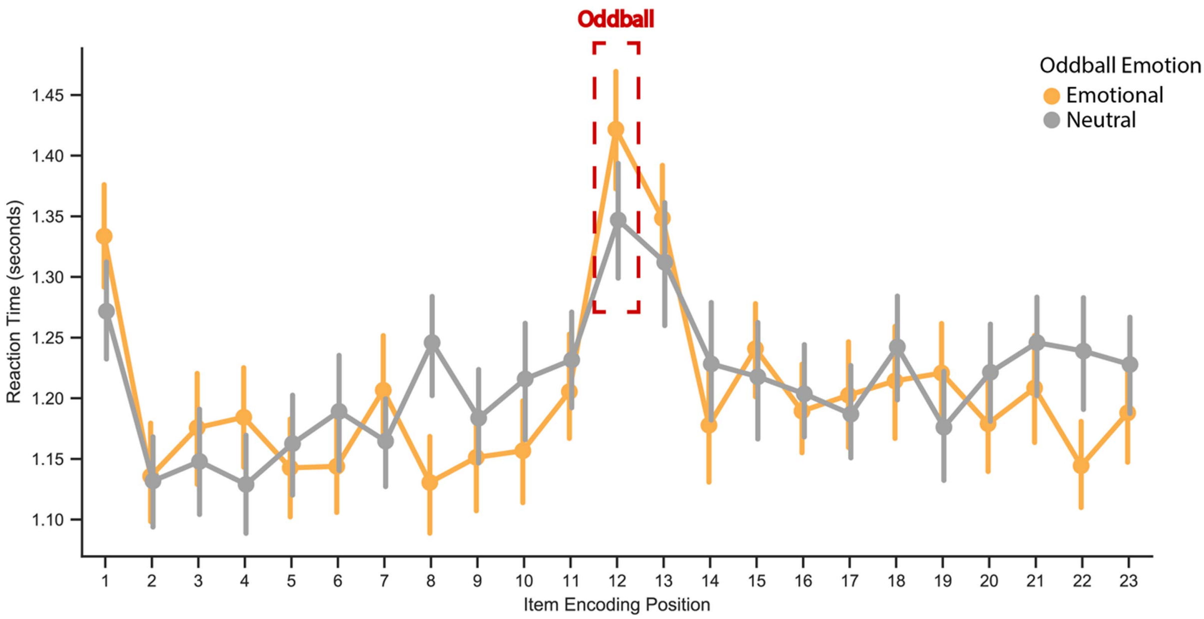
Temporal-Order Memory Results

Emotional Oddballs Disrupted Semantic Scaffolding of Temporal-Order Memory

To test our main research question that emotion's effects on temporal-order memory persist through time and interact with semantic relevance, we performed a linear mixed-effects model with a relevance-by-emotion-by-event interaction term. The results revealed a significant relevance-by-emotion-by-event interaction

Figure 3

Oddball Words Elicited an Increase in Response Times Over the Course of the Word Lists Across



Note. Compared to neutral words, response times for concreteness judgments were slower for both emotional (yellow) and neutral oddballs (gray), especially for emotional oddballs. The dashed red box represents the location of the oddball word in each list (i.e., 12th position). Dots = mean reaction times; error bars = standard errors of the mean. See the online article for the color version of this figure.

effect on temporal-order memory, $\chi^2(2) = 2.57$, $p = .013$. To determine which factors drove this three-way interaction effect on memory, we performed separate logistic mixed-effects analyses with a relevance term, an emotion term, and relevance-by-emotion interaction term for the preoddball and postoddball events, separately. To breakdown these distinct temporal effects explicitly, we report the results for these two events in separate sections below.

Retroactive Effects of Neutral Oddballs

For trial pairs preceding the oddball (retroactive pairs), we found a significant relevance-by-emotion interaction, $\chi^2(1) = -2.92$, $p = .004$; see Figure 4A. Model comparisons showed that a model with a relevance-by-normative valence term was a better predictor of temporal-order memory than a model with a relevance-by-normative arousal term, $\chi^2(1) = 4.63$, $p < .001$, indicating that negative valence was a stronger predictor than arousal for temporal-order memory performance as a function of relevance.

To determine if this retroactive interaction effect was driven primarily by the item pair's relevance to neutral or emotional oddballs, we performed simple slopes analyses on the preoddball pairs. We found that semantic relevance to the neutral oddball categories was positively related to temporal-order memory ($\beta_1 = .22$, $z = 3.34$, $SE = .07$, $p < .001$), whereas the slope for the association between semantic relevance to emotional oddball categories and temporal-order memory was not ($\beta_1 = .05$, $z = -.78$, $SE = .07$, $p = .443$). This finding runs counter to our original hypothesis that emotion would retroactively enhance temporal-order memory for pairs conceptually related to the oddball category. Instead, it reveals that relatedness to the neutral oddball categories—rather than emotional ones—tended to benefit memory. Together, the interaction effect suggests that encountering a negative emotional oddball retroactively impairs the mnemonic benefit of semantics on scaffolding temporal encoding processes.

Proactive Effects of Emotional Oddballs

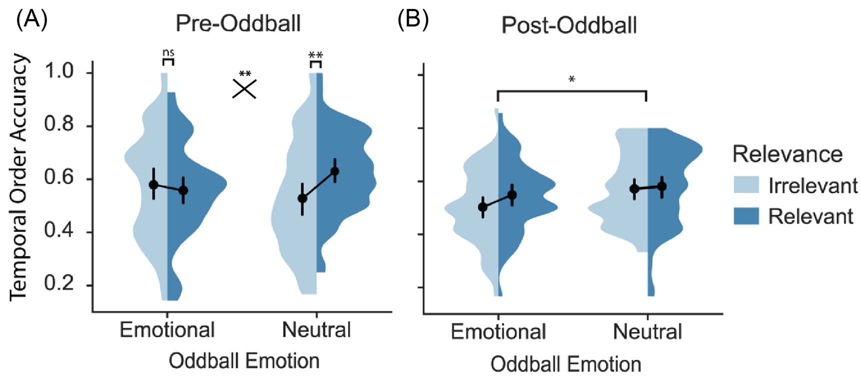
Next, we examined how emotional oddballs influenced memory for ensuing trial pairs as a function of their conceptual relevance. Contrary to our hypothesis that emotion would proactively enhance temporal-order memory for pairs conceptually related to the oddball category, we observed a negative main effect of emotion for trial pairs following the oddball word (proactive pairs). Specifically, emotional oddballs proactively impaired temporal-order memory irrespective of semantic relevance, $\chi^2(1) = -2.64$, $p = .007$. Importantly, there was no significant relevance-by-emotion interaction effect on temporal-order memory for postoddball word pairs (see Figure 4B), suggesting that the impairing effects of emotion on memory occur in a wholesale manner. Like the retroactive results, model comparison shows that a model with a normative valence term was a better predictor of temporal-order memory for items following the oddball compared to a model with a normative arousal term, $\chi^2(1) = 4.63$, $p < .001$.

Delayed Free Recall Results

Thus far, we have shown that, contrary to our original predictions, emotional oddballs did not benefit temporal-order memory for related item pairs. Rather, encountering something negative disrupted an otherwise beneficial retroactive effect of salient neutral oddballs on memory, with preceding, related pairs receiving a boost in memory

Figure 4

Retroactive and Proactive Effects of Emotion on Temporal-Order Memory as a Function of Semantic Overlap



Note. (A) Semantic relevance to the neutral, but not emotional, oddball categories was positively related to temporal-order memory for preoddball word pairs. However, this retroactive enhancement of temporal-order memory was impaired when oddballs were negative relative to when they were neutral. (B) Temporal-order memory was impaired for postoddball emotional word pairs, irrespective of their semantic relevance to the oddball category. Error bars = 95% confidence interval; ns = not statistically significant. See the online article for the color version of this figure.
* $p < .05$. ** $p < .01$.

under neutral circumstances. Emotion also has strong effects on free recall, which can also be shaped by semantic relevance (Smith & Beversdorf, 2008). Motivated by prior work examining temporally dynamic effects of emotion on both item recognition and free recall (see Schlüter et al., 2019, for a useful review), we next tested how all these factors interacted to potentially also influence long-term memory. Because we intentionally avoided presenting the emotional item as part of the tested item pairs in the temporal order test, this recall analysis also provided insight into how emotional memories influenced the recall of temporally proximal information.

Emotional Oddballs Selectively Boost Long-Term Memory for Preceding Irrelevant Information, but Nonselectively for Ensuing Information

To test our main hypothesis that emotional oddballs would selectively benefit long-term recall of related items (e.g., Dunsmoor et al., 2015), we performed a linear mixed-effects model with a relevance-by-emotion-by-event interaction term. The results of this analysis revealed a significant relevance-by-emotion-by-event interaction effect on free recall, $\chi^2(2) = 2.64$, $p = .008$. To determine which factors drove this three-way interaction effect on free recall memory, we performed separate linear mixed-effects analyses with a relevance term, an emotion term, and relevance-by-emotion interaction term for the preoddball and postoddball words. As with the temporal-order memory results, we report these follow-up tests for the items studied preoddball and postoddball in their own sections below.

Retroactive Effects of Emotional Oddballs on Delayed Recall

For preoddball words, we found a significant relevance-by-emotion interaction, $\chi^2(1) = 2.09$, $p = .036$; Figure 5A. Model comparison shows that a model with a relevance-by-normative valence term was a better predictor of recall accuracy for preoddball items compared to a model with a relevance-by-normative arousal term, $\chi^2(1) = 1.51$, $p = .012$.

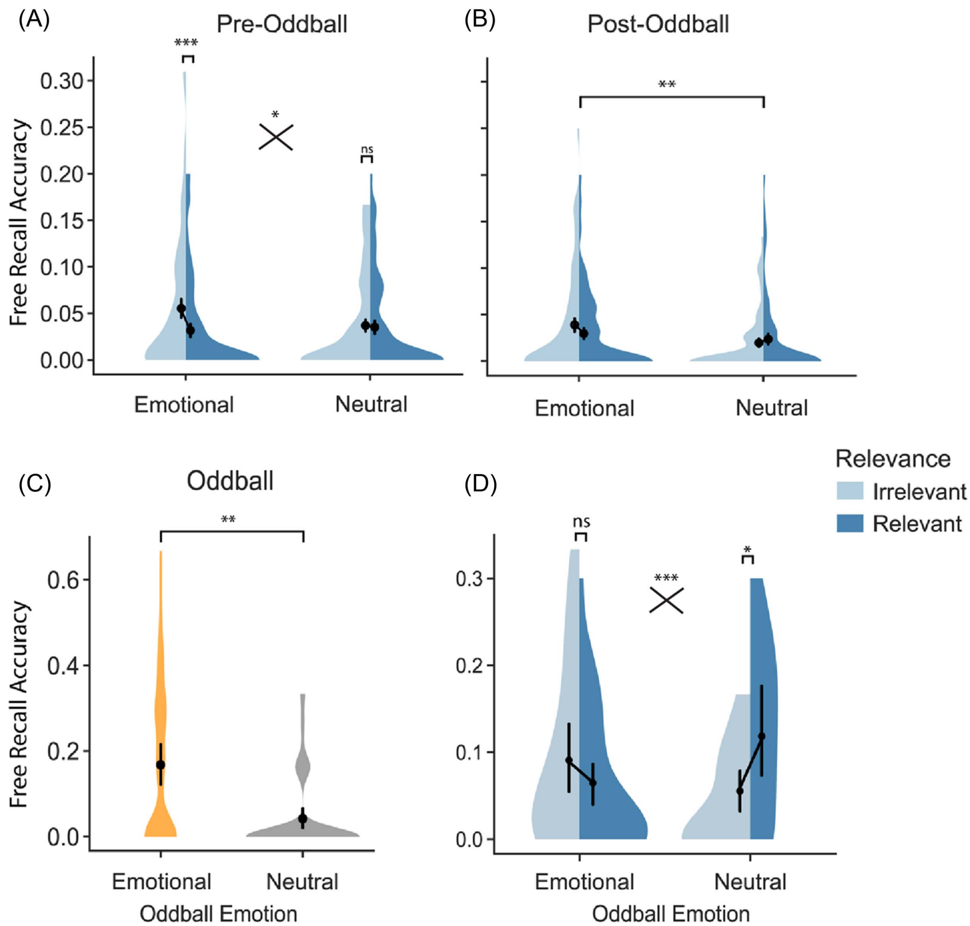
To determine if this retroactive interaction effect was driven primarily by relevance to neutral or emotional oddballs, we next performed simple slopes analyses on the preoddball words. We found that semantic relevance to the emotional oddball categories was related to worse recall accuracy ($\beta_1 = -.61$, $z = -3.71$, $SE = .16$, $p < .001$), whereas semantic relevance to neutral oddball categories was not significantly related to recall accuracy ($\beta_1 = -.11$, $z = -.64$, $SE = .17$, $p = .521$). In other words, word stimuli were more likely to be remembered if they were less semantically relevant to the emotional oddball category. This finding ran counter to our original hypothesis that emotion would retroactively enhance free recall memory for words conceptually related to the oddball category.

Proactive Effects of Emotional Oddballs on Delayed Recall

The next free recall analysis had the same setup as before but was specifically focused on items that were studied after the oddballs, potentially revealing different effects of time, relatedness, and emotions on long-term memory. There was no relevance-by-emotion interaction effect on free recall for postoddball words ($p > .05$). However, in line with our predictions that emotional oddballs would enhance memory for ensuing items, we observed a significant main effect of emotion on recall of postoddball words, $\chi^2(1) = 3.01$, $p = .005$; Figure 5B, with emotional words proactively enhancing free recall irrespective of their semantic relevance to the oddball category. Model comparison shows that a model with a normative valence term was a better predictor of recall accuracy for preoddball items compared to a model with a normative arousal term, $\chi^2(1) = 2.86$, $p = .008$.

Figure 5

Emotional Oddballs Selectively Enhanced Delayed Free Recall of Irrelevant, or Conceptually Unrelated, Words Encountered Beforehand, While Nonselectively Enhancing Free Recall of Words Encountered After



Note. (A) Semantic relevance to the emotional, but not neutral, oddball category was related to worse recall accuracy for preoddball words. (B) Recall accuracy was enhanced for words following emotional oddballs, irrespective of their semantic relevance to the oddball category. (C) Word-recall accuracy was higher for emotional compared to neutral oddballs. (D) Recall accuracy for relevant words was selectively enhanced when neutral oddballs were recalled. Error bands = 95% confidence interval; ns = not statistically significant. See the online article for the color version of this figure.
$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

Successfully Recalling Neutral Oddballs Was More Closely Associated With Retrieving Conceptually Related Words Compared to Successfully Retrieving Emotional Oddballs

A robust finding in the literature is that emotional items are better remembered than more mundane items, especially after a long delay (Yonelinas & Ritchey, 2015). To see if we could first replicate this emotional enhancement effect for oddball item recall, we next tested whether subjects recalled emotional oddballs more often than neutral oddballs. Consistent with prior work, we observed a significant main effect of emotion on the free recall of oddball words, such that emotional oddballs were remembered more accurately than neutral oddballs, $\chi^2(1) = 3.64$, $p < .001$; Figure 5C.

Free recall provides a window into how retrieved memories, particularly emotional items, might influence how other details of an event are also retrieved. It is well known that semantic relatedness can guide spreading activation effects even in episodic retrieval, whereby relatedness should prime and facilitate retrieval of conceptually related items (Collins & Loftus, 1975). However, the way emotion interacts with these potential priming effects is likely very complex. For example, other research shows that emotional items will dominate and tend to cue each other during retrieval, but this disrupts the retrieval of other neutral items by outcompeting other contextual features that typically benefit retrieval, such as temporal context (Talmi et al., 2019).

Inspired by this work, we next performed an exploratory contingency analysis testing whether the effects of emotion and relevance on free recall performance were contingent on whether the actual oddball from a given list was recalled. More specifically, we were interested in whether the semantic scaffolding effect of neutral versus negative oddball categories observed for the temporal-order memory performance is dependent on whether the oddball itself is remembered. To test this idea, we coded lists by whether their oddball was recalled. We then performed a linear mixed-effects model with free recall accuracy as the outcome and a relevance-by-emotion interaction.

The results revealed a significant relevance-by-emotion interaction effect on free recall, $\chi^2(2) = 3.75$, $p < .001$. To determine which factors drove this two-way interaction effect on free recall memory, we performed separate linear mixed-effects modeling analyses with a relevance term for the neutral and emotional oddball lists, separately (see Figure 5D). A simple slopes analysis revealed that semantic relevance to the emotional oddball categories was not significantly correlated with recall accuracy ($\beta_1 = -.11$, $z = 1.45$, $SE = .08$, $p = .202$). By contrast, when examining recall for the neutral oddball lists, semantic relevance to neutral oddball categories was related to higher recall accuracy ($\beta_1 = .24$, $z = 2.36$, $SE = .14$, $p = .013$). Additionally, we also reran the free recall analyses excluding words that were not also presented during temporal-order memory tests (Items 2 and 22). This is because these items did not benefit from repetition effects (during study and the temporal-order memory test) and therefore were less likely to be remembered after a delay. Excluding these two items did not meaningfully change results, and the same effects remained statistically significant.

In summary, the results of the interaction and follow-up simple slopes analyses suggest that when a neutral oddball was recalled, participants were significantly more likely to remember related words compared to lists when the emotional oddball was recalled.

Discussion

Emotional events have been shown to exert retroactive and selective effects on previously encountered information, resulting in stronger long-term memory for individual items that are semantically related to a subsequent threat (Dunsmoor et al., 2015). These findings have been interpreted as evidence that memories of weak and otherwise mundane experience can become strengthened and stabilized if they overlap with an emotional event (Moncada & Viola, 2007). Behaviorally, this retroactive memory enhancement has been demonstrated for memory of item representations in recognition tasks and free recall tasks (Smith & Beversdorf, 2008), but not for temporal-order memory between items. However, forming meaningful connections between events is arguably one of the most important features of episodic memory, since memory for the order of events supports adaptive and flexible behaviors, including the ability to predict *when* a similar aversive event might occur. We therefore hypothesized that emotional events would selectively and retroactively enhance temporal-order memory between neutral information conceptually related to those salient events.

Our main finding was that perceptually salient neutral stimuli, or oddballs, retroactively enhanced temporal encoding of related information. This finding suggests that semantics can scaffold temporal integration processes in memory when that information acquires new meaning, or significance. Contrary to our main prediction, however, emotional stimuli selectively and retroactively impaired—rather than enhanced—temporal-order memory for preceding, semantically related information. These findings suggest that negative emotion may have retroactively impaired semantic scaffolding in memory. Specifically, semantic relevance to a neutral oddball may have guided selective reinstatement of that category's temporal context, thereby boosting temporal-order memory. On the other hand, semantic relevance to an emotional oddball may have reinstated the emotion above and beyond the overarching temporal context, disrupting memory for the temporal order of words within a sequence. Indeed, this interpretation is supported by the emotional Context Maintenance and Retrieval model (Talmi et al., 2019), which suggests that emotion is an especially strong context that outcompetes semantic-based retrieval processes (Palombo & Cocquyt, 2020; J. Wang et al., 2022).

In addition to shaping the initial temporal structure of memory, we also hypothesized that words relevant to emotional oddballs would be selectively and retroactively prioritized in long-term free recall memory. However, our free recall results showed that items *unrelated* to the emotional oddball category were more likely to be remembered after a 24-hr delay. What might explain this retroactive memory benefit for items that were unrelated to the emotional oddball category? One possibility is, in a similar vein to our Day 1 temporal-order memory results, an emotional competition mechanism (e.g., emotional Context Maintenance and Retrieval model) might disrupt retrieval of emotionally relevant words and disrupt memory for emotionally related information (Talmi et al., 2019). Critically, when participants remembered an emotional oddball from a list, they were just as likely to retrieve a relevant or irrelevant word. But if participants remembered a neutral oddball, they were more likely to also retrieve relevant words compared to irrelevant words. These oddball-contingency effects mirror our temporal-order memory results: Under neutral conditions, salient semantic information can scaffold item and associative memory. By contrast, the mnemonic benefits of conceptual relatedness are disrupted when salience is dictated by negative emotion.

This finding raises two further intriguing possibilities. First, negative oddballs may have acted as a strong avoidance cue during retrieval, such that remembering a negative oddball led to avoidance of semantically related information. For example, recalling "slaughter" may act as a strong avoidance cue for recalling related items, such as "cow," due to the increasingly aversive nature of their association. This could eliminate the semantic-cuing advantage we observed for neutral oddball lists, whereby relevant words were more likely to be retrieved if their salient neutral oddball words were also retrieved. A further possibility in our study is that retrieving negative memories led to retrieval-induced forgetting effects, a phenomenon in which practicing the retrieval of a word results in worse memory for unpracticed items from the same semantic category (M. C. Anderson et al., 1994, 2000). In the present study, retrieving a strong negative oddball memory may have resulted in inhibition of and/or competition between semantically related items, thus resulting in worse memory for items from the relevant category. This effect may have also been enhanced during the study-test delay, where spurious or involuntary retrieval of the negative during the 24-hr delay may have led to greater forgetting of related information. A retrieval-induced forgetting mechanism may explain why the current results contrast from prior findings that emotional oddballs enhanced immediate recall for preceding, semantically related words Smith and Beversdorf (2008). This account, however, is largely speculative, as we did not measure reactivation during the delay, nor did we design this study to use category cues to guide free recall. It is also worth noting that the length of the lists in the Smith and Beversdorf (2008) study differed substantially from our design, given they only used lists of eight items and we used lists of 23 items. Thus, there was likely more competition and interference effects during retrieval in our study, which may have led to different results.

Regarding the carry-forward effects of emotion on temporal encoding, we found a more global amnesic effect: Negative emotional stimuli impaired temporal-order memory irrespective of the semantic relatedness between the memoranda and the oddballs. This finding may suggest that emotional oddballs resulted in an elicitation of negative emotions that tend to make individuals more item-focused rather than context-focused during encoding (Harmon-Jones et al., 2012, 2013). Indeed, the object-based framework of emotional memory suggests that states of arousal can bias attention toward low-level perceptual features at the expense of surrounding contextual information (Kensinger et al., 2007; Knight & Mather, 2009; Mather, 2007). Consistent with our valence-driven results, more recent models of emotional memory highlight the role of negative valence in boosting encoding and consolidation of low-level perceptual information (Bowen et al., 2018) as well as in narrowing attention when presented with negative, goal-threatening information (Kaplan, 1995; Levine & Edelstein, 2009). Together, our findings reveal different bidirectional effects of emotion on temporal binding processes in memory. Emotional stimuli led to a selective, retroactive impairment of semantic scaffolding processes on temporal-order memory as well as a global impairment for the temporal order of ensuing items.

There are several limitations of the present study that warrant consideration. First, it is difficult to fully tease apart semantic relevance and emotionality, because emotional stimuli are often more semantically abstract or atypical than neutral stimuli (Talmi et al., 2019; Talmi & Moscovitch, 2004). To attempt to control for this issue, we extracted the average semantic relatedness scores via word2vec on all words from the oddball-relevant category, excluding the oddball word itself for each word list. However, a potentially stronger matched condition would be able to account for the relevance between neutral items and the emotional stimulus. Future research should explore methods to disentangle these effects. Second, there may be possible item position effects in the current design. Specifically, oddball-related and oddball-unrelated words were always in the same positions in each list. The oddball itself was also located in the same position. This manipulation was initially done to ensure equal bin sizes between retroactive and proactive word pairs as well as to enable an equal number of intervening words between tested word pairs. While including a random effect of list order had no effect on the results, it is possible that practice and repetition may impact memory for the timing of events potentially through the reduction of prediction error. Future studies could use less predictable oddball designs to help control for the influence of potential learning effects.

Moreover, previous work has shown that retroactive effects of emotional events fall within a short window for item recognition (e.g., 4–9 s prior to the emotional event; A. K. Anderson et al., 2006), while other studies primarily test for memory recall of items immediately preceding and following the emotional event or oddball (e.g., Cocquyt et al., 2024; Hurlemann et al., 2005; Smith & Beversdorf, 2008; Strange et al., 2003). With that in mind, we aimed to test temporal-order memory associations between items encoded over longer timespans (20 s between each item in a pair). Due to this design choice, the items within a pair and tested pairs in a list varied in their temporal proximity to the oddball. Future research could control for proximity to the oddball to help elucidate potential local effects of emotion on temporal-order memory.

To completely account for possible item position effects during encoding, future list-based designs could counterbalance the order of relevant and irrelevant items. It is noteworthy that potential position-related effects on memory were still matched across the emotion and neutral word lists, so it is unlikely that this could explain any emotion-related differences in memory. Finally, it may have helped interpreting our current results by including a "true" control list condition with no oddball. This would have allowed us to better determine whether participants were using a general semantic context to help encode and retrieve the order of items, or if the semantic relatedness of a perceptually deviant stimulus, such as an oddball, was necessary to see any semantic scaffolding effects for temporal-order memory.

A potential limitation to our study design was testing temporal-order memory immediately and free recall after a delay. In this way, the temporal-order memory tests could affect participants' ability to recall individual words the next day. While we did not directly analyze any relationships between temporal-order and free recall memory, one interesting pattern in our results was that while temporal-order memory was impaired for proactive (i.e., anterograde) word pairs, memory for those words was enhanced in free recall. This suggests a potential item-context trade-off effect (Kensinger et al., 2007), whereby item recognition was enhanced for items following emotional oddballs at the expense of temporal associative memory. This effect aligns with prior work showing that item-focused encoding can lead to impairments in temporal order encoding (DuBrow & Davachi, 2013).

Our findings add to an increasingly rich but complex literature on how emotion influences different aspects of temporal-order memory (Petrucci & Palombo, 2021). While some studies show that emotion boosts temporal-order memory, others show that memory for a temporal context, or when something happened, can be disrupted by abrupt emotional events. While we initially expected that semantic relevance would interact with emotion to enhance temporal-order memory, it is possible that the predictive value to a negative oddball guided reconstruction of the memory in a way that outcompeted with its true temporal context. Indeed, it may be the case that the effects of emotion on temporal context memory depend strongly on certain factors, such as whether the emotional stimulus provides an overarching thematic context (e.g., thematic arousal; Laney et al., 2004). It could also depend on which types of measurements are used to probe memory structure (e.g., temporal source vs. pairwise memory) and whether the memoranda possess semantic or causal relationships with each other or with the emotionally significant stimulus (e.g., D'Argembeau & Van der Linden, 2005; Hennings et al., 2021). Considering these different various factors may help disambiguate under what circumstances emotion enhances or disrupts temporal-order memory.

Critically, the impact of emotion on temporal context processing has significant implications for clinical theories of memory fragmentation. Memory-related disorders of emotion, such as posttraumatic stress disorder, are characterized by the involuntary retrieval of very specific, individual sensory elements of traumatic episodes (Warning Signal Hypothesis; Dunsmoor et al., 2022;

Ehlers et al., 2002). This suggests that traumatic events may increase the likelihood of experiencing intrusive memories by impairing contextual binding of information encountered during an emotional event (Bisby & Burgess, 2017; Bisby et al., 2020). Indeed, recent functional magnetic resonance imaging research shows that posttraumatic stress disorder patients have an impaired neural representation of the temporal context during extinction learning (Hennings et al., 2021). Our findings that the presence of emotional oddballs disrupted the benefit of semantic relevance on temporal-order memory may align with the idea that negative events disrupt encoding or retrieval of other features that guide the temporal integration of information. Future studies could examine whether disruptions in different aspects of temporal-order memory are related to reduced memory coherence (e.g., worse semantic scaffolding and reduced narrative structure in memory) and whether those memory features relate to specific symptoms in trauma-related disorders.

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