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Temporal memory for threatening events encoded in a haunted house

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ABSTRACT

Despite the salient experience of encoding threatening events, these memories are prone to distortions and often non-veridical from encoding to recall. Further, threat has been shown to preferentially disrupt the binding of event details and enhance goal-relevant information. While extensive work has characterised distinctive features of emotional memory, research has not fully explored the influence threat has on temporal memory, a process putatively supported by the binding of event details into a temporal context. Two primary competing hypotheses have been proposed; that threat can impair or enhance temporal memory. We analysed two datasets to assess temporal memory for an in-person haunted house experience. In study 1, we examined the temporal structure of memory by characterising memory contiguity in free recall as a function of individual levels of heart rate as a proxy of threat. In study 2, we replicated marginal findings of threat-related increases in memory contiguity found in study 1. We extended these findings by showing threat-related increases in recency discriminations, an explicit test of temporal memory. Together, these findings demonstrate that threat enhances temporal memory regarding free recall structure and during explicit memory judgments.

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Introduction

Threatening experiences affect our day-to-day lives, impacting our memory for years to come. As salient, or important, these memories feel in our minds, we know that memories of threatening experiences are not veridical; rather they are prone to distortions while leaving memory confidence intact (Bennion et al., 2013; Rimmele et al., 2012). Specifically, threat-related physiological arousal, (increases in heart rate) can bias individuals to forget contextual information, which can link background, information of an event to its surrounding context in memory (Clewett & Murty, 2019). While, the majority of research has studied threat-related disruptions in associative memory, by characterising how specific items bind with spatial features (Bouvarel et al., 2022; Kim et al., 2013; Steinmetz & Kensinger, 2013; Waring et al., 2010) or to each other (e.g. Madan et al., 2012; Okada et al., 2011), emerging literature seeks to characterise binding to a temporal context. Here, we investigate the influence of threat on temporal memory using a quasi-naturalistic paradigm, a visit to a haunted house attraction, attempting to disentangle how threat may enhance or impair temporal memory.

Prior research has found that events are stored sequentially, such that individuals are biased to recall events in the order in which they were encoded. This type of temporal memory is thought to rely on binding individual event items to the slow drift of a temporal context over time, which maintains

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the relative order of encoded items in memory (Howard & Kahana, 2002). This process allows us to preserve the contiguity of memory, such that individuals are more likely to recall items that occurred closer together in time (Howard et al., 2008). While temporal order and memory contiguity have been well-studied within neutral and non-threatening contexts, less is known about how threat impacts these processes. On one hand, threat could enhance the salience, or the importance of individual event items, which may allow for stronger associations within temporal context (Talmi et al., 2019) and/or provide more information about relative memory strength to resolve temporal order (DuBrow & Davachi, 2014). However, given the known disruptions to the binding of specific items to contextual information (e.g. spatial contexts), threat could disassociate specific information from temporal context and, in turn, disrupt memory contiguity and temporal memory (DuBrow & Davachi, 2013). In line with this latter interpretation, representations of spatial context and temporal context have been shown to rely on similar neural structures centered on the hippocampus (Eichenbaum, 2017b; Howard, 2017) and surrounding parahippocampal cortex (Jenkins & Ranganath, 2010; Tubridy & Davachi, 2011; Wang & Diana, 2017).

A major challenge in studying the influence of threat on temporal memory emerges from the constraints of laboratory-based designs. In typical laboratory experiments, specific items of interest are shown one at a time, and then individuals are asked to resolve the temporal order of different items using recency judgments or assessments of memory contiguity in free recall. However, in these paradigms, the intermittent nature of stimulus presentations may down-weight the continuity of drift in temporal context, making it harder to resolve a modulating role of threat. One solution to address this concern is to use quasi-naturalistic events in which events unfold naturally over time (Lee & Chen, 2022). This type of design allows one to test temporal memory for stimuli that are aligned to the natural drift of temporal context. A recent study utilised this approach by having individuals view emotional movie clips and then characterise implicit and explicit metrics of temporal memory. This study found that high-emotion video clips enhance temporal memory when participants were explicitly instructed to make recency judgments but did not influence more implicit measures of memory contiguity in free recall (Dev et al., 2022). Thus, open questions remain about the general role of threat on temporal memory and the mixed results of this study may be that the video stimuli was ineffective in provoking subjective levels of fear and levels of physiological arousal, or heart rate, high enough to see prominent effects of threat on memory. To address this alternative, we tested individuals in a quasi-naturalistic high-arousal setting.

The current study analysed two datasets to assess individuals' temporal memory for an in-person haunted house. Across both studies, participants navigated a haunted house experience in which they were faced with varying levels of threat across different segments, evoked by multisensory cues (e.g. actors in full costume, abrupt noises related to threatening items like guns/chainsaws, special effect lighting, etc.). In study 1, we examined temporal memory by characterising an implicit memory test aimed at capturing the contiguity of memory in a free recall structure as a function of individual levels of physiological arousal which we operationalised as average heart rate. In study 2, we followed up on study 1 by replicating marginal findings of memory contiguity and included an explicit test of temporal memory, recency discrimination, for naturalistic events of high and low levels of experienced threat. These studies were then used as a basis to arbitrate between two competing hypotheses: whether threat impairs or enhances temporal memory.

Study 1: motivation

In study 1, the role of experienced threat on temporal memory was characterised by memory contiguity in free recall. Participants experienced an in-person haunted house while collecting heart rate data and then returned to the lab one week later for a free recall task describing their memories of their experience at the haunted house. At the time of running study 1, the haunted house consisted of six threatening segments. We found that participants showed idiosyncratic threat responses to each segment, which may represent how threatening each segment was perceived (Figure 1). We also leveraged findings from a previous analysis of the study 1 dataset completed by our research team that heart rate can be used as a proxy of threat as it was found that average heart rate predicts subjective reports of fear (Stasiak et al., 2023).

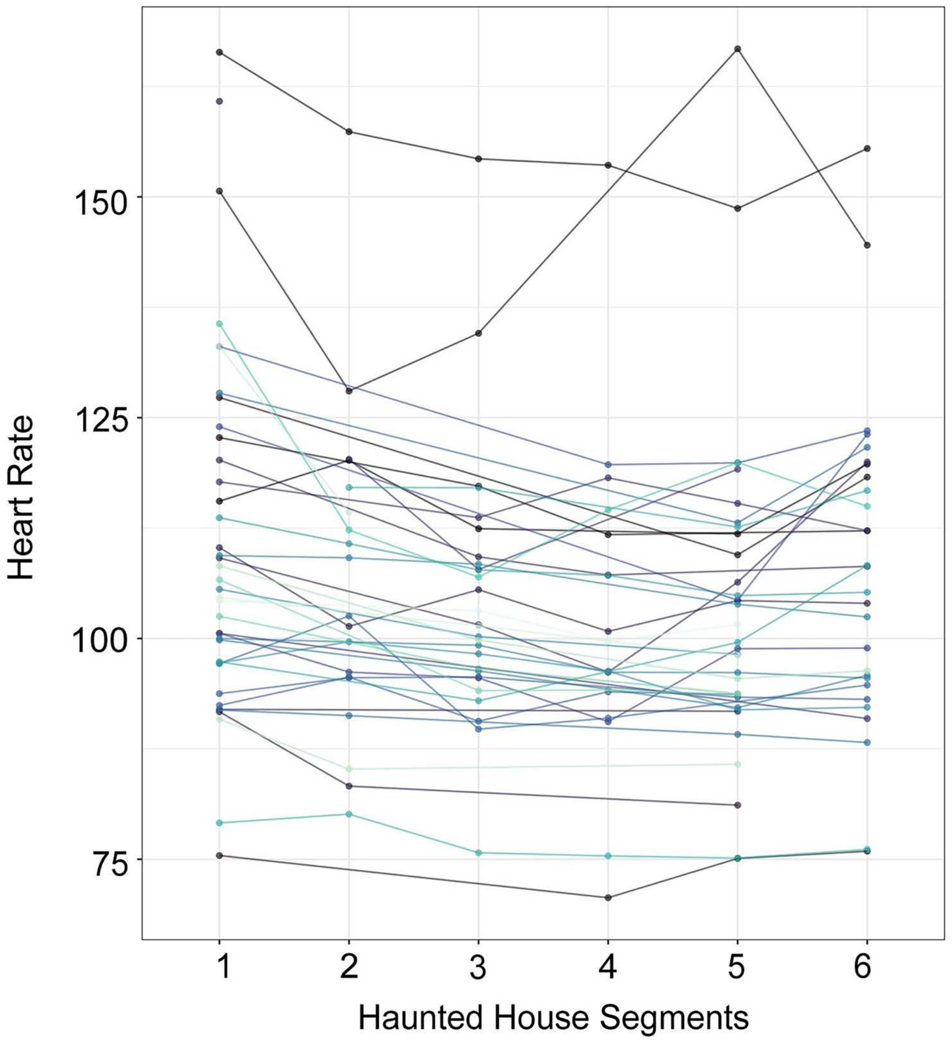

Figure 1. A visualization of heart rate variability among participants within the six haunted house segments of study 1.

Study 1: methods and analysis

Participants

Fifty-four participants ($n = 54$) were recruited via flyers posted around the Philadelphia community. Given the limited availability of the haunted house being open, our recruitment plan was to recruit as many participants as possible while the haunted house attraction was open (late September to early November). Participant exclusion included: lack of fluency in English ($n = 2$), having previously visited the haunted house that year ($n = 1$), dropping out of the study ($n = 1$), lost/missing free recall data due to technological issues ($n = 3$), and missing heart rate data for all segments of the haunted house due to technological issues ($n = 1$). Seven participants had a non-response for the forward transition calculation for all 6 segments of the haunted house, resulting in them being excluded from the analysis. After exclusions and accounting for non-responses in the data, the final sample included 40 participants ($n = 40$, $\bar{x}_{age} = 24.2$ yrs, $sd_{age} = 3.85$, 19 female). Participants were further screened for being between the ages of 18 and 34, not having a history of seizures, ability to walk comfortably for one hour, not having cardiovascular disease, and having no contraindications for MRI studies (imaging data not presented in this article). All participants gave informed consent approved by the

Institutional Review Board at Temple University and were compensated with a free ticket to the haunted house along with $70 in the form of Visa debit cards for their time during the study.

Procedure

Before entering the haunted house attraction at Eastern State Penitentiary in Philadelphia, PA (https://easternstate.org/halloween/), participants completed informed consent, were fitted with Firstbeat heart rate monitors (Firstbeat Technologies Ltd., Jyväskylä, Finland), and filled out questionnaires, while baseline heart rate measures were collected in our lab space. Detailed baseline heart rate procedures are included in the methods of Stasiak et al. (2023). While we did collect heart rate data during the laboratory portion of the visit, this data was not included in the final analyses given the major contextual differences between measurements taken in the laboratory versus the haunted house, as individuals were stationary in the laboratory and mobile in the haunted house. All heart rate data used in analyses for this paper are those collected during the haunted house experience.

Participants and research assistants were provided transportation to the haunted house in small groups of 3-5. Heart rate recordings taken during the haunted house began just before participants entered the haunted house. Each section of the haunted house was marked by the research assistant who pressed the "Lap" button on the Firstbeat recorder tablet at the beginning and end of each section. The complete procedure for heart rate recording and data cleaning during the haunted house is included at length in the methods of Stasiak et al. (2023).

Participants were given instructions regarding the order they would traverse through the haunted house, this consisted of the participants having to walk in a single file line, without touching the participants to the front or back of them. We also instructed participants they would lead the group for at least one segment to allow all participants the opportunity to experience the haunted house as the lead member of the group. Participants were not told that they would be recalling their experience from the haunted house during the one-week delay session. All participants experienced the 6 segments in the same order. Each section consisted of different themes with various staged events each night: (1) Lock Down, (2) Blood Yard, (3) Machine Shop, (4) Infirmary, (5) Quarantine 4D, and (6) Break Out. The structured aspect of the haunted house allowed for a consistent experience for all participants during the experience and segment-unique events also occurring consistently allowed for the assessment of temporal memory. Before the first group of participants, our research team did preliminary walkthroughs to check the consistency of the haunted house on a nightly basis. Notably, the focus of all of our analyses is on these segment-unique events, which are parallel to items in a traditional laboratory-based paradigm. Last, after each segment participants provided verbal judgments to assess the scariness of the six segments of the haunted house ("How scary was that last section for you?") on a scale from 1 ("Not scary at all") to 5 ("Extremely scary").

Participants were explicitly asked to not discuss their experience with other participants during the experience or before their return for the one-week delay session, but otherwise were told to experience the haunted house as if they attended the experience as any other guest normally would. The visit to the haunted house took approximately 55.2 min on average. At the end of the haunted house, participants were debriefed and transported back to the lab.

At a one-week delay, participants returned to the Temple University Brain Imaging Center and were asked to complete a surprise-free recall task during scanning (again, fMRI data not presented here). During the free recall task, participants were instructed to describe everything they could remember about their experience in the haunted house. Participants were instructed to talk for at least 10 min but were told that more time is better, resulting in an average recall time of 11.8 min. Free recall was recorded in the scanner using Audacity.

Analysis

The focus of the analysis for study 1 was to determine how often individuals recalled memories with intact temporal structure for each segment, reflecting memory contiguity. To characterise memory contiguity, following prior work by (Diamond & Levine, 2020), we calculated the forward–backward transition score the tendency to make forward transitions in memory for each segment of the haunted house.

For this analysis, free recall scripts were scored to identify any segment-unique events that occurred during the haunted house. This scoring was performed by two independent raters for 5 random transcripts with an inter-rater reliability estimate of 84.5%. This score is at an acceptable agreement level among raters (McHugh, 2012). After scoring for segment-unique events, each discrete recall of an event was coded for which segment it occurred in and where in the segment it occurred. We also characterised where each event occurred during recall before analysing the participant's unique recall. A master list of segment-unique events was compiled by multiple team member recordings from a preliminary walkthrough of the haunted house. For each event that occurred within a segment, we calculated whether the next recall was forward or backward in time (as dictated by the sequence of events at encoding). Given the example sequence of events; A, B, C, and D, if a participant recalled an event (event A) and then made a forward transition to an event that occurred later in the tour (event C), that segment of free recall would be scored with a +1. If a participant recalled an event (event D) and then made a backward transition to an event that occurred before the tour (event B), that segment of free recall would be scored with a −1. We then calculated the mean score of forward–backward transitions for each of the six segments, such that values closer to 1 indicated a high forward transition score, 0 an equivalent forward and backward transition, and −1 high backward transition score. Any incomplete responses in participant free recall data resulting in a non-response for the forward transition score calculation was noted as a NaN. A non-response for the forward transition calculation occurred when a participant did not move forward or backward when recalling their memory from the haunted house or recalled less than 2 events in total. Summary statistics for forward transition scores are noted in Table 1.

To remove any subjectivity in scoring recall data, free recall transcripts were scored for events in the order they were presented within the recall. We also revisited our data to flag moments of recall in which a participant explicitly acknowledged that events happened in the reverse order (i.e. "we experienced [event B], but before that, we saw [event A]"), this was scored as −1, or a backwards transition. Only two participants ($n = 2$) out of forty ($n = 40$) explicitly stated that events happened in the reverse order, and each of them only did this once.

To determine if forward transition scores were influenced by threat-related arousal, we next performed a mixed-effects model in R using the lmerTest package (Kuznetsova et al., 2017), comparing a null model with participant-level random intercepts (forward transition score ∼ (1 | participant)) against a model which included heart rate as a predictor (forward transition score ∼ heart rate + (1 | participant)). Significance was determined by incrementally adding single factors to baseline models and using chi-squared tests to determine if the inclusion of the additional factor increased the overall model fit as assessed by *BIC* and *AIC*, and if model comparisons reached an alpha level of $p < .05$. Summary statistics for variables were calculated using the emmeans package in R (Lenth et al., 2023).

In brief, the Firstbeat software collected raw interbeat interval (IBI) data and transformed it into heart rate by beats per minute. Using the artifact correction module within this software, IBIs that surpassed the limits for minimal and maximal duration limits were removed (Saalasti et al., 2012).

Study 1: results

We analysed how threat-related arousal was related to the forward transitions in recall, finding that increases in heart rate during segments of the haunted house showed a marginally positive association with forward transitions in recall ($\chi^2(1) = 3.20$, $p = .073$; null model; *AIC*: 408.5, *BIC*: 417.9; heart rate model comparison[1]; *AIC*: 407.3, *BIC*: 419.8, Figure 2) suggesting that individuals made more forward transitions during recall that were associated with

Table 1. Summary statistics of all variables within study 1 and study 2.

	Forward Transition Score		Imputed Forward Transition Score		Temporal Order Accuracy		Heart Rate	
	mean	SD	mean	SD	mean	SD	mean	SD
Study 1								
All Segments	0.23	0.83	–	–	–	–	106.1	18.1
Study 2								
High Threat Segments	0.46	0.63	0.61	0.55	0.59	0.17	–	–
Low Threat Segments	0.23	0.70	0.44	0.66	0.52	0.23	–	–

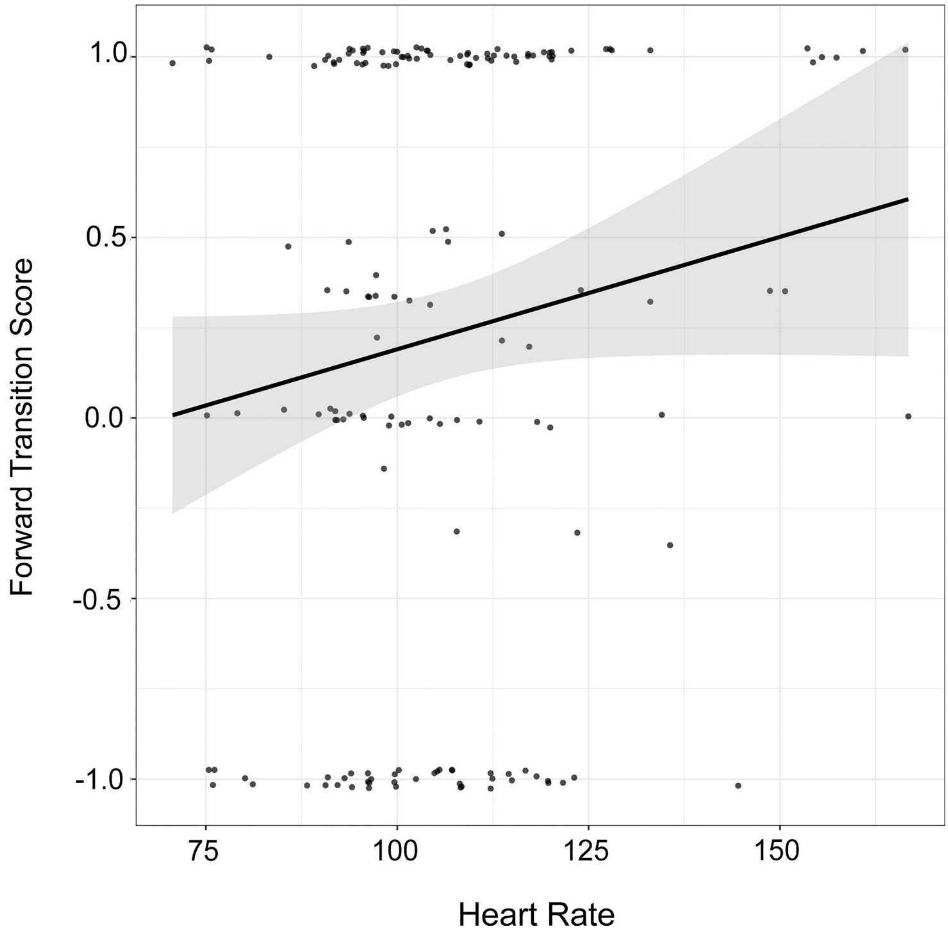

Figure 2. A mixed-effects model indicates a marginal association towards more forward transitions in recall when individuals encoded events during times of increased heart rate ($p = .073$).

sections and events of the haunted house that had increased amount of heart rate ($\beta = 0.00623$, $se = 0.0035$, $t(164) = 1.79$, $p = .076$). Notably, this finding remained unchanged when we removed the two participants who explicitly indicated recalling items out of order ($\chi^2(1) = 3.14$, $p = .076$; null model; *AIC*: 380.9, *BIC*: 390.1; heart rate model comparison; *AIC*: 379.8, *BIC*: 392.0).

Study 1: summary

In study 1 at a trend level of significance, we found that there were greater forward transitions in free recall when participants had higher levels of heart rate. However, study 1 was only able to test memory contiguity compared to heart rate, as we did not include explicit measures of temporal memory. Heart rate for each participant, throughout the segments on the haunted house, displayed substantial variation (seen in Figure 1), further complicating how we interpret this marginal association between the variables. Furthermore, the relationship between threat and memory was assessed across events that were designed to have consistent high levels of experienced threat, perhaps yielding less variability amongst stimuli to leverage a high versus low threat analysis.

Study 2: motivation

In study 2, we leveraged the new design of the haunted house at Eastern State Penitentiary to answer our research questions more directly, and further elaborate on our findings from study 1 in a more structured design. Study 2 featured four distinct segments; two of which were designed to induce high levels of threat and the other two were designed to induce low levels of threat. Again, these segments were not manipulated by the researchers, but by the organisers of the haunted house event. Further, we include an explicit measure of temporal memory by having participants complete a recency discrimination task for events that occurred in each segment. Finally, given prior work showing that the effects of threat on memory may unfold over time via consolidation (Yonelinas & Ritchey, 2015), we included both immediate and delayed memory tests.

Study 2: methods and analysis

Participants

Fifty-five participants ($n = 55$) were recruited from flyers posted around the Philadelphia community. Recruitment of participants was identical to study 1, due to the limited availability of the haunted house being open, our recruitment plan was to recruit as many participants as possible given our staffing resources. We completed a post hoc power analysis based on the effect size from the temporal reconstruction analysis in the study completed by Dev et al. (2022). This study used naturalistic stimuli to examine the effects of fear on temporal memory and found an effect size of $r = -0.28$. We then converted this effect size to Cohen's *d* ($d = 0.58$) we were able to calculate a post hoc power analysis. To determine the number of participants needed to achieve an effect size of $d = 0.58$ at 80% power with a $p < .05$ significance level, we found a minimum of 48 participants would have been needed to reach the desired effect modelled by Dev et al. (2022) for study 1 and study 2.

Eligibility for the study was determined if a potential participant met the following criteria: between the ages of 18 and 34, have no history of any neurological diseases, no known learning disorder, be a fluent or native English speaker, and never have been to Eastern State Penitentiary for the haunted house attraction before. Two participants ($n = 2$) were excluded from all analyses for not completing the delay portion of the task, yielding a sample of fifty-three participants ($n = 53$, $\bar{x}_{age} = 21.1$ yrs, $sd_{\text{age}} = 2.77$ yrs; 30 female, 2 non-Binary). For the forward transition analysis, four participants ($n = 4$) had a non-response for the forward transition calculation for all segments of the haunted house at both the immediate test and delay test, resulting in them being excluded from the analysis, yielding a final sample of forty-nine ($n = 49$, $\bar{x}_{age} = 21.2$ yrs, $sd_{\text{age}} = 2.83$ yrs; 29 female, 2 non-Binary). For the recency discrimination analysis, an unforeseen computer error during the immediate test of recency discrimination judgments resulted in the exclusion of 5 participants ($n = 5$) from this analysis, yielding a final sample of forty-eight ($n = 48$, $\bar{x}_{age} =$ 20.8 yrs, $sd_{\text{age}} = 2.23$ yrs; 27 female, 2 non-Binary). All participants gave informed consent approved by the Institutional Review Board at Temple University and were compensated with a free ticket to the haunted house along with $60 in the form of Visa debit cards for their time during the study.

Procedure

Participants and researchers arrived at a remote site on the haunted house property in small groups of 3-5. Upon arrival at the meeting area, participants answered demographic questions on tablets provided and additionally received Firstbeat heart rate monitors (see study 1 methods above). However, due to unexpected circumstances in the experimental setup (i.e. setting up participants at the haunted house), we were unable to collect enough heart rate data to include in study 2 analyses.

Similar to study 1, participants entered the haunted house with a research assistant leading the group, unaware they would be completing a memory task after their experience within the haunted house. The participants then experienced each segment in the same order: (1) Delirium, (2) Take 13, (3) Machine Shop, and (4) Crypt. Like in study 1, the order and structure of haunted house was fixed and consistent, as organised by the haunted house attraction, each night for study 2. Self-reported fear judgments were recorded by participants during their walkthrough of the haunted house to confirm segments of the haunted house were of high levels of threat (Machine Shop, Crypt) and of low levels of threat (Delirium, Take 13). This was determined as following each segment, participants were asked to rate how fearful they found each segment on a scale from 1 (Not fearful at all) to 5 (Extremely fearful) on a note card after each segment. This note card was collected after participants responded to the last segment. The visit to the haunted house took approximately 37 min on average.

Participants then returned to the offsite location and completed an immediate memory test and filled out various questionnaires after the walkthrough using provided laptops. One-week later, a follow-up memory test was completed online. At the immediate test, participants were only queried on half of the events (one high threat segment and one low threat segment, randomly assigned for each participant), while all 4 events were probed at the one-week delay session. At each session, participants completed two memory tests: cued-free recall and recency discrimination (detailed below).

Cued free recall task

Participants were cued with a segment from the haunted house and asked to recall everything they could remember (i.e. "type everything you can remember about the 'Delirium' section of the tour".). The order of recall cues was randomised across participants. Participant transcripts were excluded from analysis if they recalled the wrong event in response to the cue. In total, 9 transcripts were excluded from the analysis of free recall transcripts due to participant error in following directions.

Recency discrimination task

Like in study 1, segment-unique events were determined by a walkthrough completed by research assistants prior to beginning the study, resulting in a list of 8–10 segment-unique events for each segment. Participants made recency judgements by choosing which description of two segment-unique events of the same segment occurred first. On each trial, pairs of events consisted of two neighbouring events drawn from the same segment. In total, 5 recency discrimination pairs were drawn from Delirium, Machine Shop, and Crypt segments, while 4 recency discrimination pairs were drawn from Take 13. An example of the questions the participants were prompted with was: "Which event occurred earlier within Delirium? Large spiders or Spinning tunnel". Participants then had to select one event that they believed occurred earlier within that given section. The presentation of when the correct answer appeared was randomised across trials. Due to a staged event not occurring on one given night, 4 participants had 3 questions removed from their recency discrimination analysis. Like study 1, summary statistics are listed in Table 1.

Analysis

We first utilised the fear judgment data to confirm differences between high level threat segments and low-level threat segments (as indicated by participants within the haunted house). We utilised a repeated measures ANOVA to compare fear ratings of high threat segments (Machine Shop, Crypt) against low threat segments (Delirium, Take 13) while accounting for delay and an error term for participant-level random effects (1 | participant). To determine group means and standard error for analyses, estimated marginal means were utilised.

Free recall data was analysed to quantify the forward transition score for each segment as detailed in study 1. Likewise, to remove any subjectivity in scoring recall data, free recall transcripts were scored for events in the order they were presented within recall. Two participants ($n = 2$) explicitly stated that events happened in reverse order. To remove scorer subjectivity from scoring we did not omit these participants from the final analysis, but we have included a post hoc analysis to clarify the nominal difference in the inclusion of these participant transcripts.

To retain accuracy in a repeated measures ANOVA, we opted to impute all data points where there was a loss of data due to a non-response for the forward score. This imputation was completed by use of the MICE package in R (Buuren & Groothuis-Oudshoorn, 2011). We utilised predictive mean matching for 100 iterations to impute these missing data points to avoid issues in data analysis. However, we included an analysis that omitted all non-responses to make sure models are fitted to the same size of the dataset. This approach for missing data is only used for this ANOVA analysis to limit the analysis excluding entire participants when one data point is missing. To highlight comparisons between our imputed data and raw data we included both analyses, the first with our imputed data and the second when we opted to omit non-responses in forward transitions. We included the summary statistics, calculated using the emmeans package in R (Lenth et al., 2023), for the imputed scores and the scores omitting non-responses in Table 1 to further emphasise the similarity between the two variables.

A repeated measures ANOVA including participant fear judgment was conducted to confirm that our findings generalise when using subjective, idiosyncratic markers of fear (i.e. self-reports) when accounting for participant-level random effects.

Recency discrimination judgments were scored as a binary variable of correct or incorrect for each question and aggregated over segments resulting in a temporal accuracy score to test for temporal accuracy. We utilised repeated measures ANOVA with the inclusion of high and low threat, delay, and an error term that accounted for participant-level random effects to assess whether individuals had significant recency discrimination across conditions.

Similar to the analytical approach that was used to relate physiological arousal to temporal memory in study 1, we completed a mixed effects modelling approach comparing temporal accuracy in the recency discrimination judgement task with fear judgements. We compared a null model which included participant-level random intercepts (temporal accuracy ~ (1 | participant)) against a model that included self-report of fear as a predictor (temporal accuracy ~ fear ratings + (1 | participant)).

Finally, we wanted to determine if our study 2 measures of temporal memory (forward transition scores and temporal accuracy) were related. We again utilised a multi-level modeling approach comparing a null model including participant-level random intercepts (temporal accuracy ~ (1 | participant)) against a model that included forward transitions as a predictor (temporal accuracy ~ forward transitions + (1 | participant)).

Study 2: results

Fear judgements

We found that there was a significant difference of fear judgment ratings for high threat versus low threat segments ($F(1, 210) = 102.6$, $p < .001$, *Cohen's* $f = 0.70$, Figure 3; $\bar{x}_{high\ threat} = 3.47$, $se = 0.099$, 95% CI:[3.3, 3.7]; $\bar{x}_{low\ threat} = 2.06$, $se = 0.099$, 95% CI:[1.9, 2.3]) confirming our approach to compare memory across these conditions.

Forward transitions in recall

To assess the forward transitions in recall collapsed across segments we wanted to test whether there were differences in forward transition scores between high threat and low threat events, and whether this changed as a function of delay. After an imputation to recover data missing due to participant non-responses, results conceptually replicated study 1, such that individuals made more forward transitions ($F(1, 290) = 7.31$, $p < .01$, *Cohen's* $f = 0.16$) in high-threat events ($\bar{x}_{high\ threat} = 0.61$ $se = 0.052$, 95% CI:[0.51, 0.71]) versus low-threat events ($\bar{x}_{low\ threat} = 0.44$, $se = 0.052$, 95% CI: [0.34, 0.54], Figure 4) indicating relatively intact temporal structure as forward transition scores were higher in high threat segments compared to low threat segments. This effect remained the same when, in lieu of imputing missing data, we opted to exclude non-responses in the forward transition scores from the analysis, ($F(1, 185) = 5.41$, $p < .05$, *Cohen's* $f = 0.17$) in high-threat events ($\bar{x}_{high\ threat} = 0.46$, $se = 0.072$, 95% CI:[0.32, 0.60]) versus low-threat events ($\bar{x}_{low\ threat} = 0.23$ $se = 0.072$, 95% CI: [0.088, 0.37]) indicating relatively intact temporal structure as forward transition scores were higher in high threat segments compared to low threat segments.

Notably, this pattern of findings remained unchanged when we removed the two participants who explicitly indicated they were recalling items out of order when imputing data (main effect of threat: $F(1, 278) = 6.86$, $p < .01$, *Cohen's* $f = 0.16$) and when omitting non-responses (main effect of threat: $F(1, 175) = 4.85$, $p < .05$, *Cohen's* $f = 0.17$).

In this first analysis, we compared pre-determined high and low threat segments. We next wanted to examine if this relationship remained if we used subjective reports of fear rather than pre-determined categories (i.e. high threat, low threat) to predict forward transitions. Since we are utilizing a mixed level modeling approach, we opted to omit non-responses in the forward transition scores from our models. We determined the best model by comparing a null model which included individually specific intercepts against a model including fear ratings as a predictor. While we did not find significant increases in fear judgments predicted the forward transition scores ($\chi^2(1) = 2.19$, $p = 0.14$; baseline model**;** *AIC*: 392.7, *BIC*: 402.4, comparison model; *AIC*: 392.5, *BIC*: 405.5) we believe that this nonsignificant finding may be a result of the subjectivity in fear judgement reports and the implicit nature of the forward transition score analysis Figure 5.

Recency discrimination accuracy

We next wanted to assess overall recency discrimination across segments of high threat and low threat at immediate and delayed memory tests. We found temporal accuracy during recency discrimination judgments greater in the high threat ($\bar{x}_{high\ threat} = 0.59$, $se = 0.020$, 95% CI:[0.55, 0.64]) versus low threat ($\bar{x}_{low\ threat} = 0.52$, $se = 0.020$, 95% CI:[0.48,

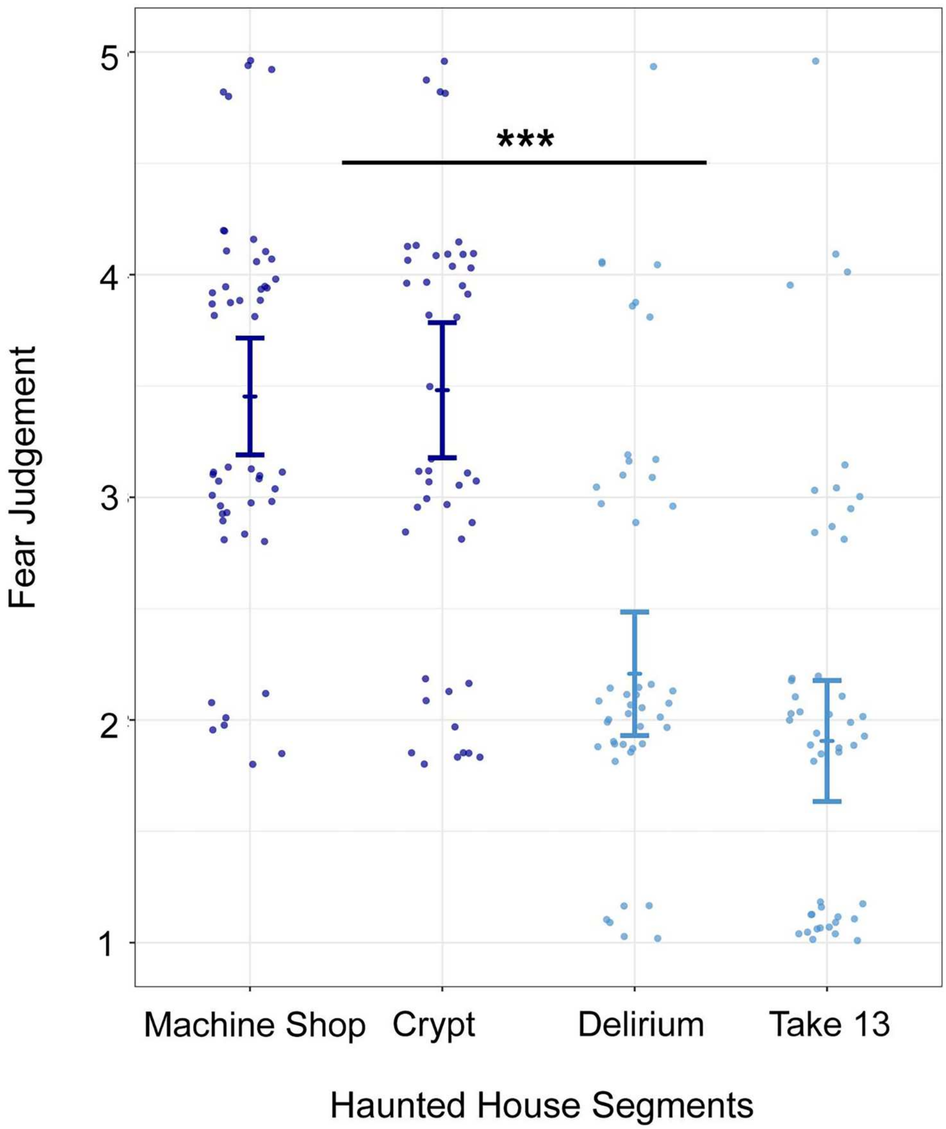

Figure 3. Repeated measures ANOVA found higher fear responses for high versus low threat segments ($p < .001$).

0.56]) segments of the haunted house ($F(1, 188) = 7.24$, $p < .01$, *Cohen's* $f = 0.20$, Figure 6).

We also found that increases in fear judgments predicted temporal accuracy. This was determined by comparing a null model including individually specific intercepts against a model including fear ratings as a predictor ($\chi^2(1) = 6.00$ $p < .05$, baseline model; *AIC*: −7.26, *BIC*: 3.73, comparison model; *AIC*: −11.3, *BIC*: 3.39, Figure 7) suggesting that increases in fear judgements increase temporal accuracy ($\beta = 0.030$, $se = 0.012$, $t(276.5) = 2.49$, $p < .05$).

Relationships across temporal memory measures

To determine if our implicit and explicit measures of temporal memory were related, we examined if they were positively associated with each other on a segment-by-segment basis. This was determined by comparing a null model which contained temporal accuracy against a model including forward transition scores. when excluding non-responses in forward transition scores from our analysis, we found that

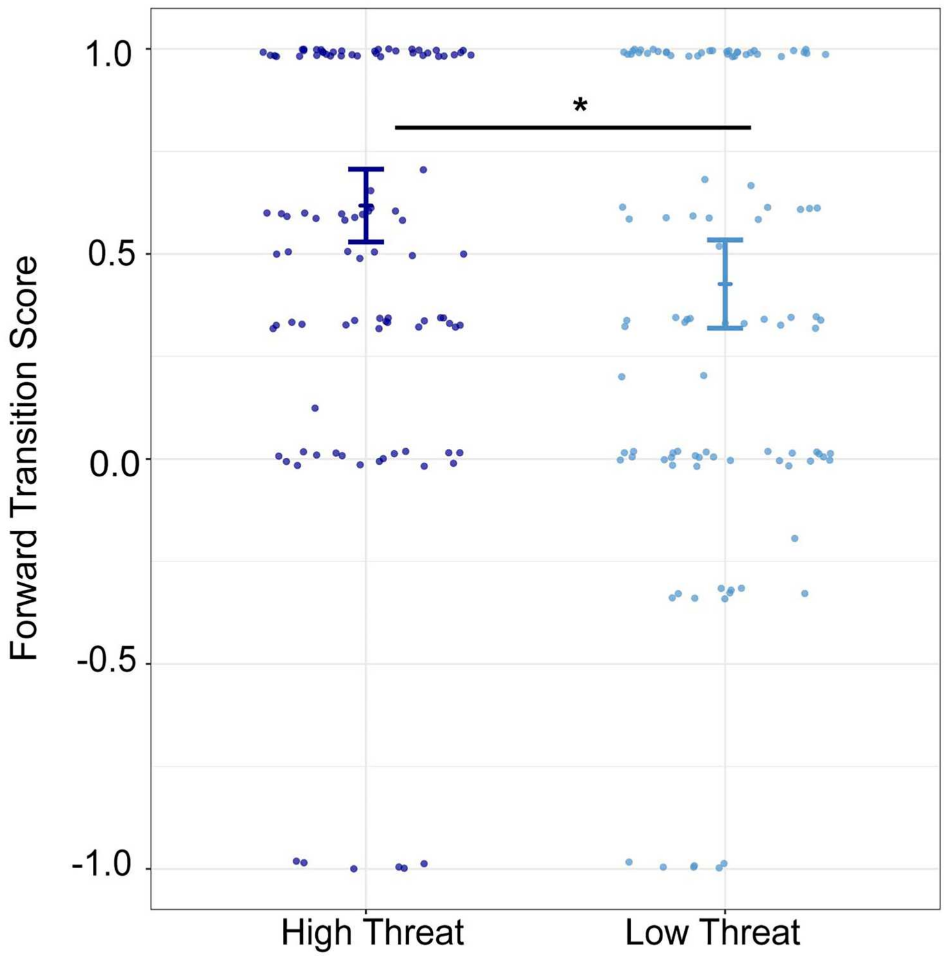

Figure 4. Repeated measures ANOVA conceptually replicating study 1, showing greater forward transitions in recall for high versus low threat events (figure depicts imputed data points, $p < .05$).

increases in temporal accuracy predicted more forward transitions in recall. ($\chi^2(1) = 10.50$, $p < .01$, baseline model; *AIC*: −102.2, *BIC*: −92.9, comparison model; *AIC*: −110.7, *BIC*: −98.3, Figure 8), such that as temporal accuracy increased there were more forward transitions in free recall ($\beta = 0.061$, $se = 0.019$, $t(149.9) = 3.27$, $p < .01$).

Study 2: summary

In study 2, we conceptually replicated the findings from study 1 showing greater forward transitions for high threat versus low threat events. Study 2 further elaborated study 1 by showing higher temporal accuracy using an explicit measure of temporal memory. Notably, in study 2, we were able to show that threat influences both measures of temporal memory (forward transitions in recall and recency discrimination judgments) were enhanced using either objective measures of threat (i.e. pre-determined segments of the haunted house) or individually specific subjective measures of threat(i.e. fear judgments). Finally, given that this study included two measures of temporal memory, we were able to explore the relationship between them, showing that they were positively related. This last finding shows that similar underlying mechanisms may be driving implicit and explicit markers of temporal memory.

Discussion

While a large body of literature has characterised enhancements or distortions in memory for highly emotional events, less research has explored the

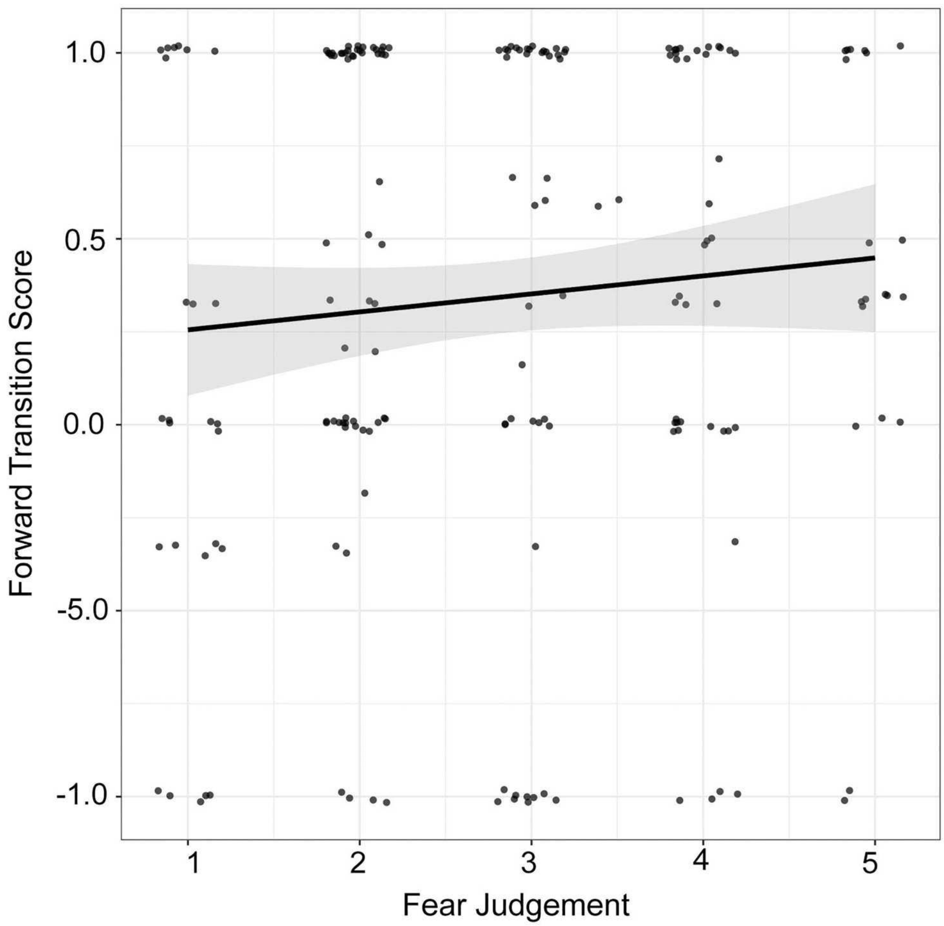

Figure 5. The mixed-effects model did not predict greater forward transitions in recall for higher fear judgments ($p = .14$).

influence of threat on temporal memory, particularly in more ecologically valid, immersive settings. In study 1, we found a marginal effect that heart rate related to threat predicted greater forward transitions in recall, an implicit test of temporal memory. In study 2, we were able to conceptually replicate and extend findings from study 1, such that threat enhanced temporal memory when tested explicitly by recency discrimination judgments and implicitly by forward transitions in free recall. Together these findings show that threat is associated with an enhancement of temporal memory.

Entering this study, we had two competing hypotheses; that memory could either; (1) enhance temporal memory by increasing binding with temporal context and/or increasing relative memory strength, or (2) impair temporal memory by disrupting the binding of items to a temporal context. Our findings support an enhancement of temporal memory via threat, both when threat was measured by heart rate (study 1) or by explicit fear judgments (study 2). There are multiple ways in which threat could putatively enhance temporal memory. In one interpretation, individuals could increase the strength of specific event details to resolve temporal memory, such that threat could still disrupt temporal context binding by leaving temporal memory intact. Indeed, prior research has shown that recency discrimination tests can be resolved either by associative mechanisms or solely by using relative item strength (i.e. the relative novelty of each item) (DuBrow & Davachi, 2013, 2014). In high threat environments, levels of threat may enhance the strength of event items, making relative novelty comparisons between them easier.

However, we believe the interpretation of enhanced item memory driving temporal memory is

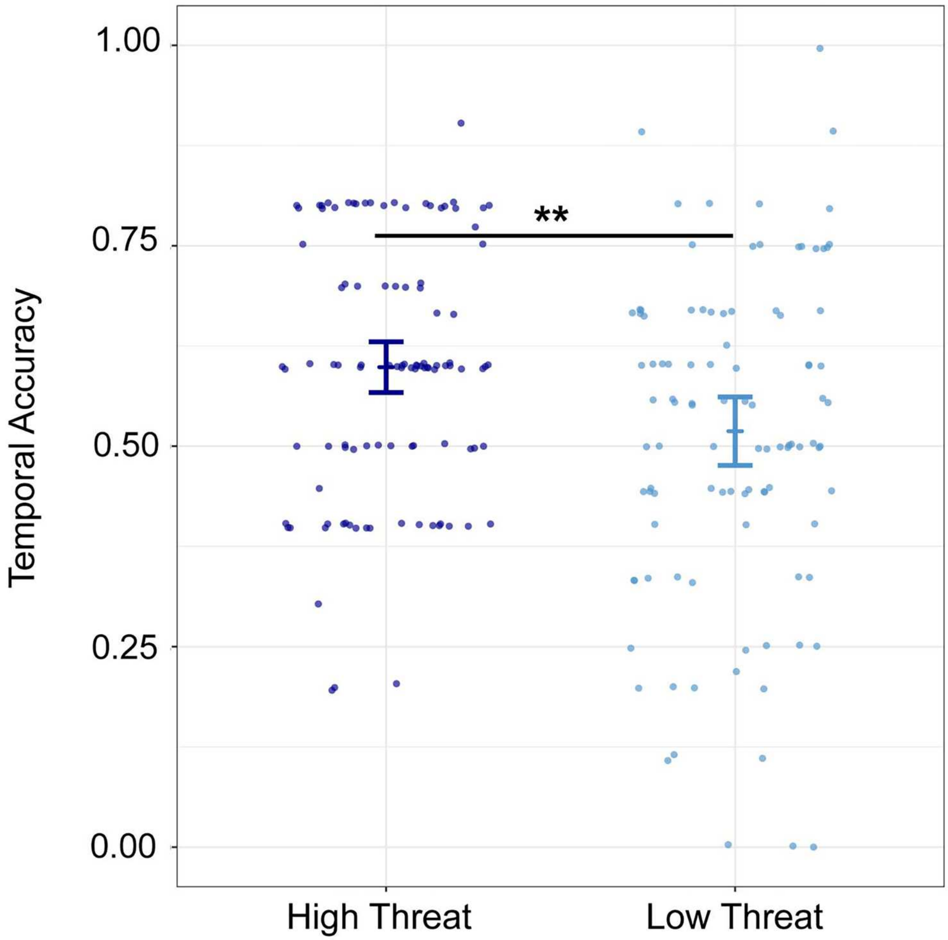

Figure 6. Repeated measures ANOVA demonstrated better temporal accuracy for the recency judgment task for high versus low threat events ($p < .01$).

unlikely, namely because we saw similar patterns of findings both across recency discriminations and forward transitions in free recall. While recency discriminations could easily be supported by specific item memory, free recall is thought to be more supported by the binding of items into a slowly drifting internal context that includes the passage of time. Given this mechanism, an alternative viewpoint is that threat enhances the binding of salient items to this internal, temporal context, thus providing the structure to support forward transitions, which is in line with some recent computational models of emotional memory (Talmi et al., 2019). One interesting feature of this type of mechanism, is that temporal memory would be sensitive to disruptions by prediction errors/temporal judgments. Prior work has shown that prediction errors may disrupt older temporal judgments (Yazin et al., 2021), which may be more prominent using naturalistic memoranda. However, our data may not directly speak to this point as the haunted house did not impact expectations strongly or contain a broader narrative. Future work using more narrative-based, threatening memoranda (i.e. horror movies, trauma narratives) could help resolve the intersection of threat, prediction errors, and temporal memory.

This later interpretation, however, raises some challenges integrating these findings into the broader literature, which shows disruptions in associative memory under threat. Specifically, one must wonder whether there is something particularly different about binding items into temporal versus spatial context. Prior literature has found that these two contextual features may indeed behave in the

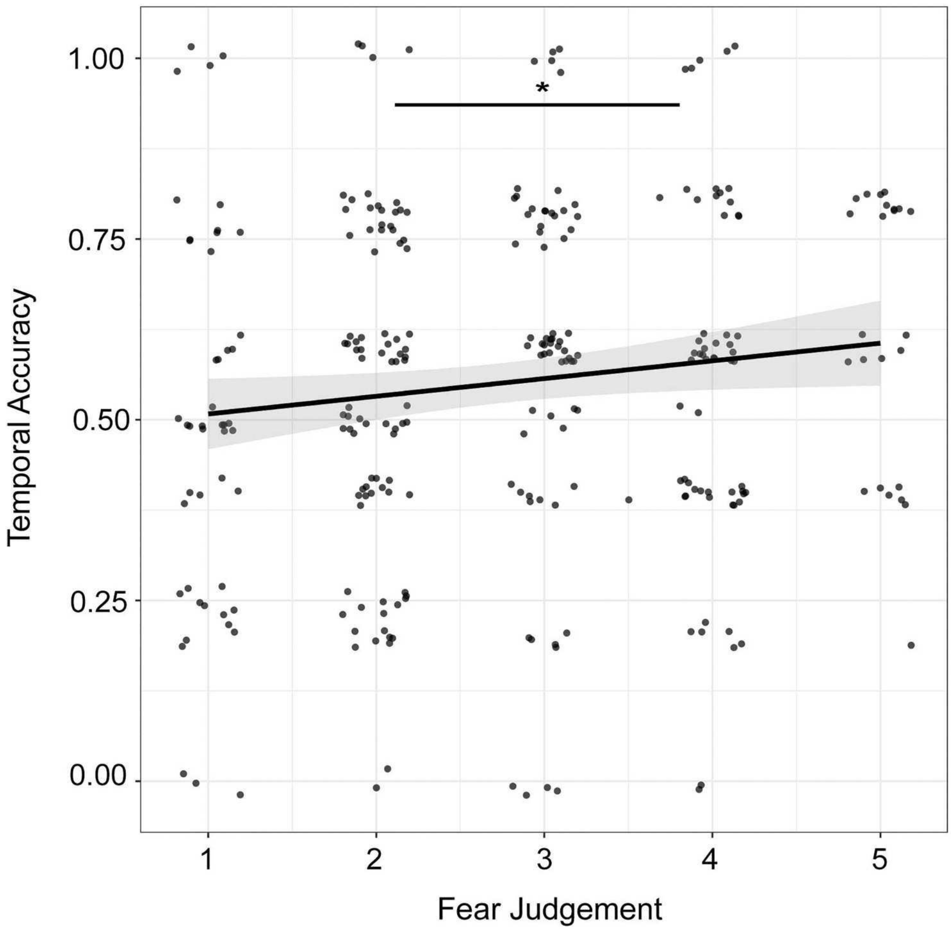

Figure 7. The mixed-effects model demonstrated better temporal accuracy for greater fear judgments ($p < .05$).

same way. Hippocampal and parahippocampal engagement are known to predict both better spatial and temporal memory, such that changing spatial contexts can have downstream consequences on temporal context (Alexander et al., 2020; Banquet et al., 2021; Eichenbaum, 2017a; Turk-Browne, 2019). These similar neurobiological mechanisms in the hippocampus are thought to code both space and time (Alexander et al., 2020; Banquet et al., 2021; Eichenbaum, 2017a; Turk-Browne, 2019). However, our data suggests that they may be treated differently given that we saw an enhancement in temporal memory. Future work is needed to resolve the differential or parallel effects of threat on item-spatial context and item-temporal context binding.

One reason spatial and temporal context may be disassociated under threat is their relative salience when encoding the event, such that spatial context may be more peripheral to the event and temporal context more central. There are models of emotional memory, namely the arousal-biased competition (ABC) model (Mather & Sutherland, 2011) and the emotional binding items model (Yonelinas & Ritchey, 2015), that provide frameworks that balance our current findings with prior work showing disruptions in associative binding. In the ABC framework, threat enhances the bindings of items with any other information that is goal-relevant at the moment, and conversely disrupts the associative binding with low-priority information. The emotional binding items model addresses that items bound to contexts are forgotten more quickly than items bound directly to an emotion. Through the lens of these frameworks, the binding of event details to a temporal context would be greater solely for threatening items, while other more mundane, less

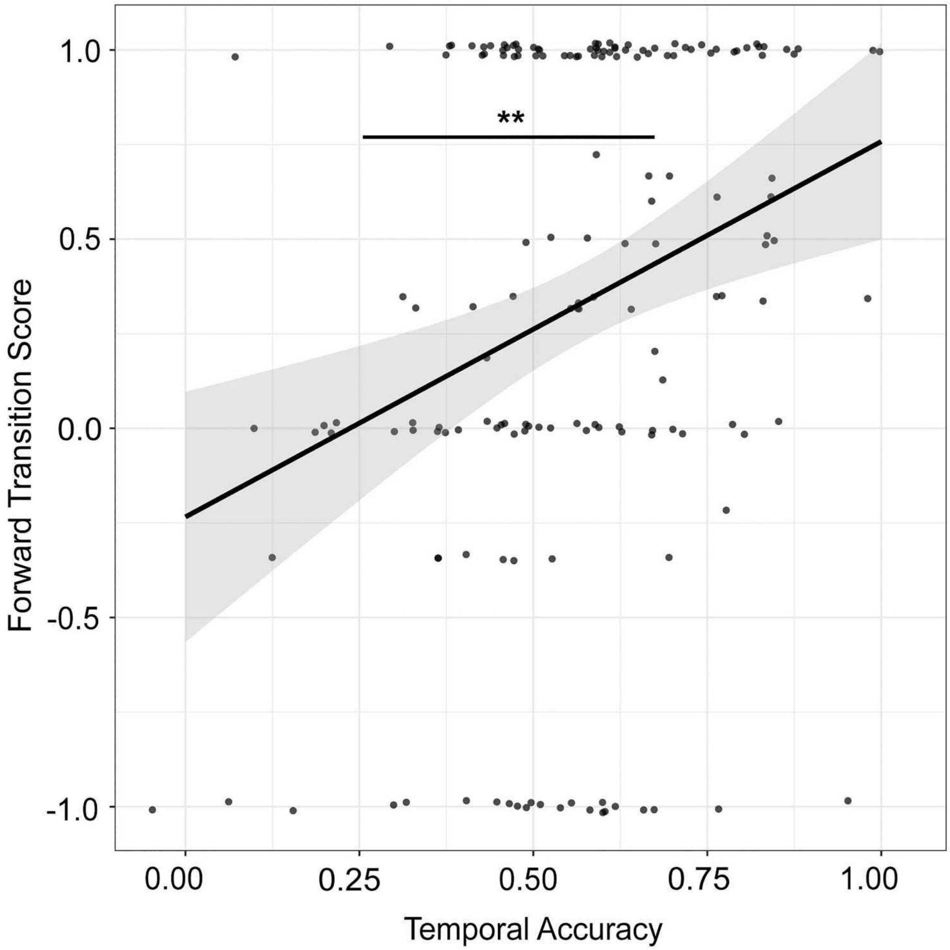

Figure 8. A mixed-effects model predicted that as forward transitions in recall increased, temporal accuracy increased ($p < .01$).

threatening, details that were encountered in a given event would be actively down-weighted. Notably, our recency judgment task and memory contiguity scoring procedures, heavily weighted high-priority items, as these were salient events, either due to their novelty or that they only occurred once per segment. One prediction that falls out of this interpretation is that if there was a prioritisation of threatening information and a neglect of more mundane information, there would be less interference from the mundane information when delineating between temporal events in high threat contexts.

Similarly, the emotional binding model suggests that engagement of the amygdala, which is reliably engaged by threat, promotes the emotional binding of items and also the binding of peripheral information to the emotional event within the amygdala (Yonelinas & Ritchey, 2015), which in our paradigm could reflect temporal context. These effects of memory enhancements are also able to become more resistant to forgetting even over a long period, indicating the benefits of arousal on the longevity of threat-related memories. This aligns well with our findings that threat-related temporal memory enhancements were sustained at a one-week delay. Thus, the integration of these two models of emotional memory help to illuminate the binding of items into a temporal context and the strength of these associations over time.

There were a few components of the study that limit the interpretability of the findings, particularly through the above frameworks. While naturalistic methodology gave us a wider range of stimuli that can better capture real-life events, this approach introduced idiosyncratic features of each individual's encoding event that could not be assessed in real time or explicitly probed during memory tests. Using this approach, a component we could not control for was the presentation order of segments, with the first two segments being low threat while the last two were high threat. Since the order of the segments within the haunted house was fixed our study could not account for any results that may have come out of this confound. In future work, having the ability to change the order of naturalistic stimuli that have varying levels of threat could be randomised to help mitigate any confounds. Another concern is the events that were more "verifiable" as segment unique events within the haunted house were the more threatening, salient events, as opposed to the more mundane, unimportant, events. Thus, our recency discrimination test, and our forward transition score of free recall (specifically in study 2), only allow us to test for highly salient events, not a culmination of varying levels of threat. Critically, both the ABC and emotional binding model makes predictions about different types of associative memory, which we are not able to directly address. Future work characterising similar constructs in the lab using more traditional stimuli (i.e. word lists) or more narrative-like stimuli (i.e. horror movies) by use of other forms of physiological data collection mechanisms (i.e. skin conductance and pupil dilation) are needed to verify our predictions about selective trade-offs of threatening versus non-threatening information in long-term memory. One last limitation of this study is that we did not investigate individual differences in how individuals were oriented toward threats. For example, many individuals that go to haunted houses are "thrill-seekers", which is a different motivational orientation to threat than those that were purely experiencing. We speculate that a contributing factor to why we did not find a significant relationship between subjective reports of fear to predict forward transitions is the subjectivity in both self-reported fear judgements and our implicit free recall test lacked this threat sensitivity measure. Future work needs to analyse this affinity to threat in a more structured study using more controlled stimuli, such as horror movies, as memoranda.

Although prior work has provided a rich context for understanding how threatening situations result in memory distortions, rarely has this been probed in the context of temporal memory (see (Dev et al., 2022)). Our results demonstrate that threat enhances temporal memory both using implicit measures of how individuals organise memory in free recall and explicit measures of recency discrimination judgements. Thus, our data expands prior work on memory distortions under threat, with strong implications for scenarios in which resolving temporal structure of events is crucial both in terms of cognitive processes during credit assignment/decision-making and more societally important areas like eye-witness testimony and psychotherapy. Our future work will extend this line of research using more mechanistic approaches, such as functional neuroimaging and computational modelling to further understand how and when threat enhances temporal memory.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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