Influence of Naturalistic, Emotional Context and Intolerance of Uncertainty on Arousal-Mediated Biases in Episodic Memory

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Abstract

Threat-related arousal is known to distort memory, biasing individuals towards perceptual details and away from contextual details. This work has mainly been conducted in laboratory settings, limiting the application of findings to real-world experiences. To test how threat-related arousal influences multi-featural memory for complex events, participants navigated an immersive haunted house while physiological arousal data was collected and later recalled memories for the event after a 1-week delay. We found that threat-related arousal resulted in relatively fewer remembered events, but enhanced recall of perceptual details for events that were remembered. Further, the relationship between physiological arousal and perceptual bias was impaired in individuals with high intolerance of uncertainty, suggesting that uncertainty aversion may result in a generalization of threat-related perceptual biases to mundane events. These findings support a model by which heart rate and individual differences in uncertainty aversion interact to shape how threatening events are recorded in long-term memory.

Keywords: episodic memory, free recall, arousal, naturalistic paradigm, autobiographical memory, Intolerance of Uncertainty

Introduction

In threatening situations, such as being held at gunpoint, our hearts start beating faster, our palms grow sweaty, and our information processing is diverted towards the source of threat. With this combination of physiological response and cognitive bias, we can make rapid decisions that allow us to flee to safety or fend off an attacker. While these neurobehavioral responses are refined to ensure homeostatic safety, they also have downstream influences on our memory that can lead to biased representations of the past. For example, when evaluating our memories for threat, we may have almost no recollection for the face of the gun-wielder but can describe the gun in vivid detail. However, questions remain as to what specific aspects of our memory for threatening experiences remain salient after threat exposure and how these memories are moderated by arousal during encoding.

Prior research has shown that arousing contexts divert information processing towards stimuli central to arousal and away from surrounding information (Clewett & Murty, 2019; Heuer & Reisberg, 1992, Reisberg & Heuer, 2004; Yonelinas & Ritchey, 2015). Concordantly, during threatening events, memory is enhanced for information focal to the event at the expense of peripheral stimuli (Clewett & Murty, 2019). Existing findings show enhancements in memory for negative stimuli at the expense of peripheral visual details (Rimmele, Davachi, Petrov, Dougal, & Phelps, 2011), neutral stimuli superimposed on a negative scene (Rimmele, Davachi, & Phelps, 2012), and scene-associated tasks (Kensinger, 2007). However, in these prior studies, memoranda were simple (i.e., a static visual scene), precluding the ability to capture the multi-featural nature of real-life aversive events. Moreover, these studies assess recognition memory by asking participants to make yes/no judgements about what they have seen, which provides a limited scope of individual memory representations. In contrast, naturally occurring memories are temporally nuanced and embedded in broader narratives. Thus, it remains unclear what specific aspects of complex negative events are prioritized during memory encoding under threat.

This gap, in part, has been addressed by autobiographical memory research, which asks participants to freely recall everything they can remember about an event from their personal history. Due to the open-ended nature of free recall, autobiographical memory paradigms allow for naturalistic characterization of memory content and accompanying biases. However, prior studies examining effects of emotion and valance on autobiographical memory composition have typically explored these biases through a dichotomous lens; using Heuer and Reisberg's (2004) proposed definition of centrality, which defines central details as critical to the emotionality or plot of a narrative, prior research has found increased memory for central details after free recall of an emotional, negative event (Berntsen & Rubin, 2002; Talarico, Berntsen, & Rubin, 2009; Wessel & Merckelbach, 1994). However, in using a binary approach to compare detail composition across personal narratives, these autobiographical memory paradigms are unable to probe specific features occurring during encoding, such as physiological arousal, that may contribute to these memory biases. The current study bridges the gap between controlled, laboratory studies and autobiographical memory paradigms and adds to a growing body of literature using staged events (Agnew & Powell, 2004; Diamond, Armson, & Levine, 2020; Diamond & Levine, 2020; St. Jacques & Schacter, 2013) through the use of free recall to assess specific detail memory for a controlled but immersive, naturalistic experience.

An important factor, which may have implications on memory for real-life, arousing environments and may not emerge using static images in a laboratory setting, is individuals' affective responses to uncertainty. In complex environments, there is often a great deal of uncertainty as to what features of the environment will remain constant and which factors will unexpectedly change. Consequently, uncertainty may influence memory in multiple ways. For certain individuals, uncertainty sparks curiosity, which drives exploratory behavior and leads to a broadening of attentional resources (Gruber & Ranganath, 2019). In contrast, for individuals at-risk for anxiety, uncertainty itself is perceived as threatening, compounding the cognitive narrowing processes that occur as a result of environmental threat (Grupe & Nitschke, 2013). However, it is unclear how intolerance of uncertainty (IU), a trait characterized by an individual's inability to manage future uncertainty, affects memory biases in threatening circumstances (Freeston, Rhéaume, Letarte, Dugas, & Ladouceur, 1994). The Uncertainty and Anticipation Model of Anxiety (Grupe & Nitschke, 2013) describes how for anxious individuals, threatening stimuli becomes prioritized during encoding, which leads to a bias in memory for information central to threat. While this model proposes that IU leads to amplified memory for threat, it remains unknown whether anxiety-based memory biases are solely exacerbated after exposure to arousing events or if they additionally influence memory for everyday experiences. Here, we investigate whether uncertainty has domain-general or domain-specific effects on changes in memory.

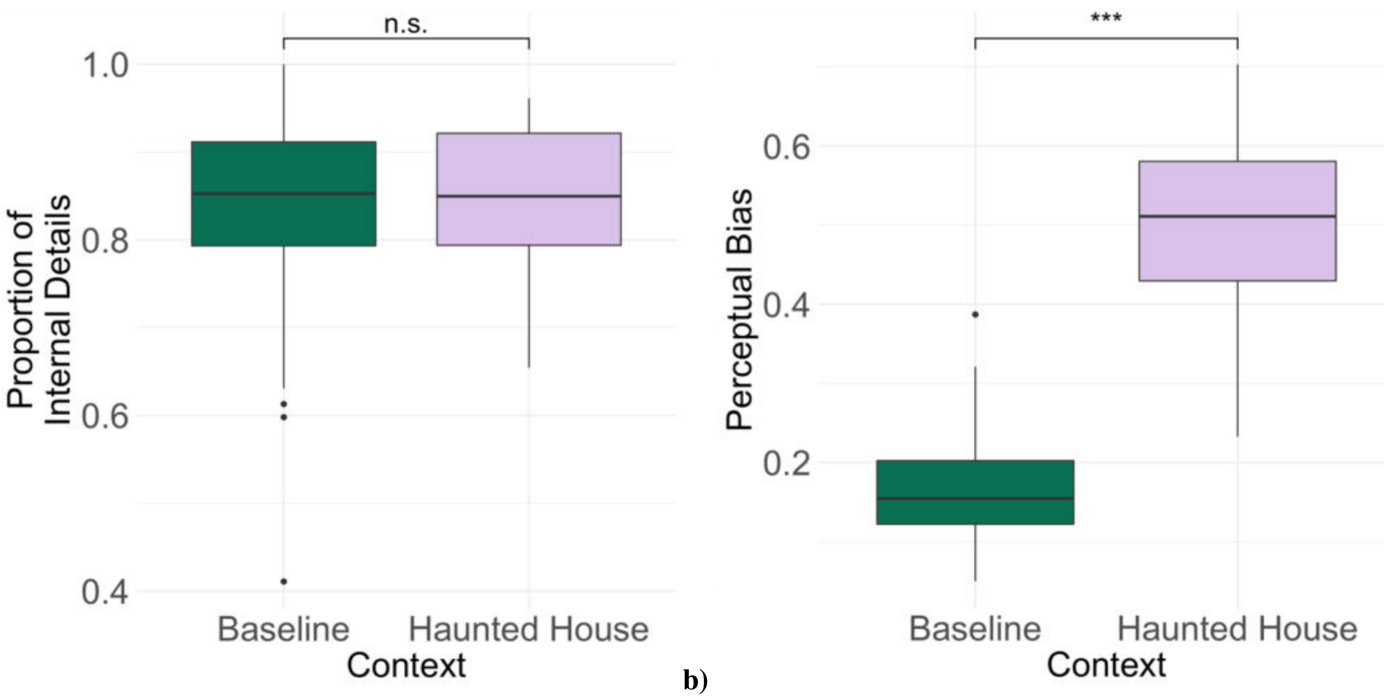
In the current study, we use a novel, naturalistic staged event to explore the impacts of threat and individual differences in uncertainty perception on memory. Participants walked through an immersive haunted house while their heart rate (HR) was recorded. Importantly, the haunted house approximates the complexity of real-life events, with myriad sensory and informational stimuli. Later, participants conducted a free recall task about the event. Recall was scored using the Autobiographical Interview method (Levine, Svoboda, Hay, Winocur, & Moscovitch, 2002) to capture the specific details that are prioritized in memory after exposure to threat. We propose to extend established framework on threat-driven memory biases by elucidating what specific details remain salient in memory after threat. Specifically, we expect to see enhanced memory for perceptual details at the expense of contextual memory, such as details regarding associated actions, locations, and time. Additionally, we use scores on the Intolerance of Uncertainty Scale (IUS) (Freeston et al., 1994; Sexton & Dugas, 2009) to explore whether the pronounced memory biases seen in uncertainty aversion are only enhanced under threat or if they extend to non-threatening environments.

Results

Effect of context on detail memory

First, we examined whether the proportion of episodic memories changed across threat and baseline contexts. We ran a paired *t*-test to look at the proportion of internal details to all details across contexts. There were no differences in the proportion of internal details across threat ($M = .84$, $SD = .08$) and baseline contexts ($M = .84$, $SD = .12$; $t(46) = .37$, $p = .71$, Figure 1a), suggesting that both contexts were matched on the proportion of episode-specific versus episode-nonspecific memories retained. Despite there being no differences in recall of internal details, the proportion of internal detail type recalled differed across contexts. Specifically, memory was biased more towards perceptual and less towards event, place, and time details (perceptual memory bias) in the haunted house ($M = .49$, $SD = .11$) than in the baseline context ($M = .17$, $SD = .07$; $t(46) = 19.26$, $p < .001$, Figure 1b).

To better understand the nature of these perceptual biases, we explored how specific categories of perceptual details were differentially recalled across contexts. Individuals in the haunted house reported significantly more Sensory ($n = 2209$, *percentage* = 78.38%) and significantly fewer Duration & Ordering perceptual details ($n = 194$, *percentage* = 6.88%) than would be expected based on recall of the baseline event ($\chi 2(4, N = 2818) = 1781.9$, $p < .001$, Figure 2).



a) **b)**

Fig. 1. a) A paired t-test shows no difference in the proportion of internal details recalled across threat and baseline contexts. **b)** A paired t-test reveals a significant perceptual memory bias in threat contexts compared to baseline contexts.

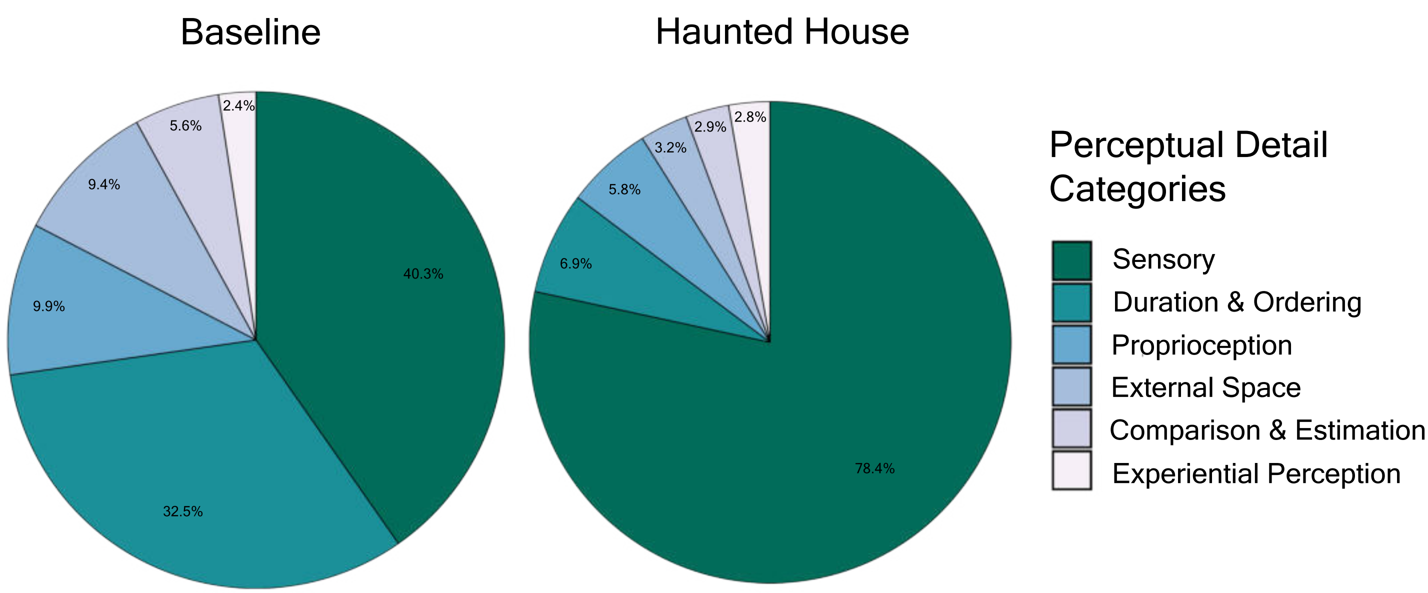


Fig. 2. Perceptual Category distribution in haunted house and baseline.

Examining the modulating effects of arousal on memory

We next looked at the relationship between memory and physiological arousal (average HR). When examining memory for total details, we found that increases in average HR predicted worse overall memory on a segment-by-segment basis (β (306) = -.62, 95% CI: [-1.01, -.39], *SE* = .10, *t* = -5.97, Figure 2) such that including average HR into a baseline model significantly increased the model fit (model comparison: $\chi 2(1) = 32.25$, $p < .001$; heart rate model: AIC = 3079.4, BIC = 3094.3; null model: AIC = 3109.6, BIC = 3120.8).

Interestingly, when examining this relationship in the haunted house only, we found increases in average HR predicted increases in overall detail memory on a segment-by-segment basis (β (261) = .11, 95% CI: [.001, .22], *SE* = .05, *t* = 2.001; model comparison: $\chi 2(1) = 3.96$; $p = .04$; heart rate model: AIC = 2051.3, BIC = 2065.6; null model: AIC = 2053.2, BIC = 2065.6).

Next, we investigated the relationship between perceptual bias memory and arousal. We found that increases in average HR predicted increases in perceptual bias scores on a segment-by-segment basis (β (278) = .003, 95% CI: [.0007, .005], *SE* = .001, *t* = 2.76, Figure 3) such that including HR into a baseline model significantly increased model fit (model comparison: $\chi 2(1) = 6.93$, $p = .008$; heart rate model: AIC = 160.55, BIC = 175.06, $p = .008$; null model: AIC = 165.5, BIC = 176.4). These findings show that while arousal decreases the overall amount of episodic memories, the content of remembered events is biased towards perceptual details. However, when looking at the haunted house alone, there was no relationship between perceptual bias memory and arousal (β (189) = .001, 95% CI: [-.001, .004], *SE* = .001, *t* = .78; model comparison: $\chi2(1)$ = .61, *p* = .43; heart rate model: AIC = 142.26, BIC = 155.31; null model: AIC = 140.87, BIC = 150.66).

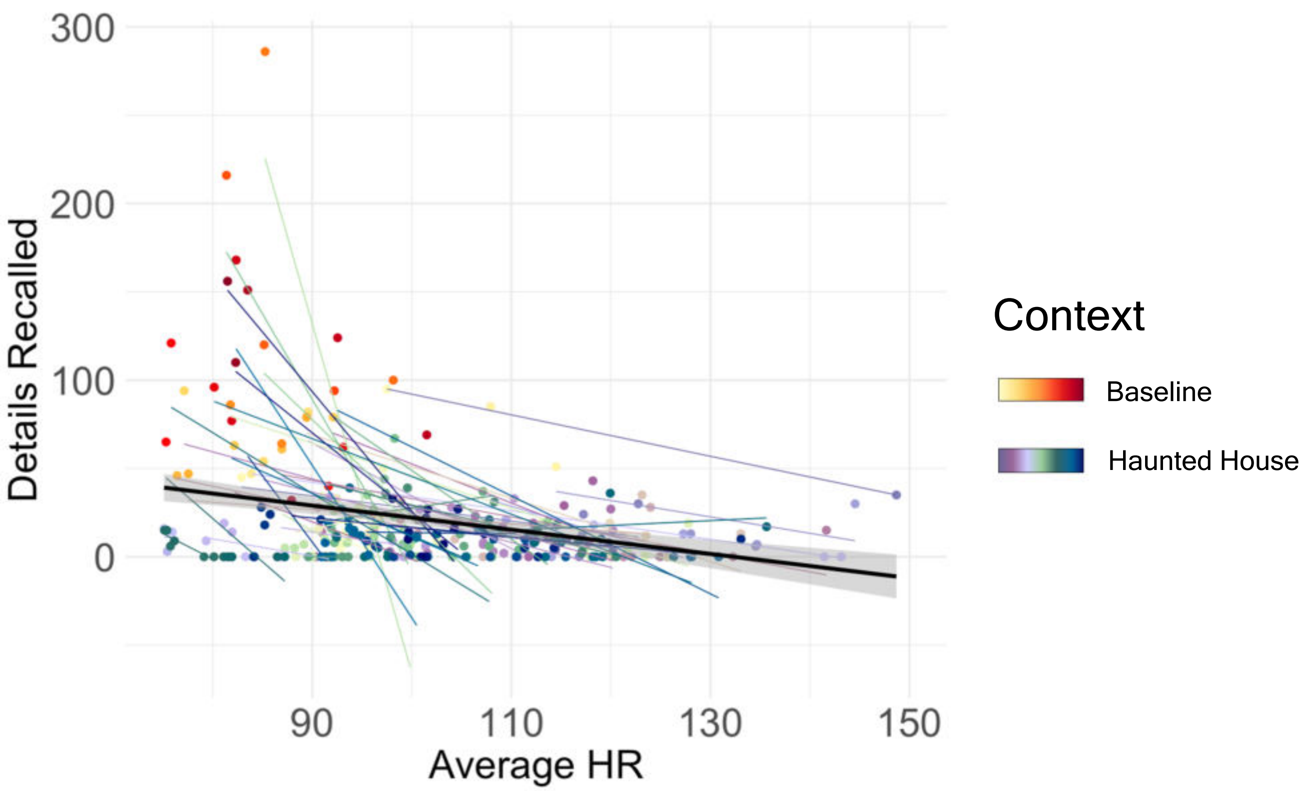


Fig. 2. A mixed-effects model shows that increases in average HR predict decreases in overall memory per segment.

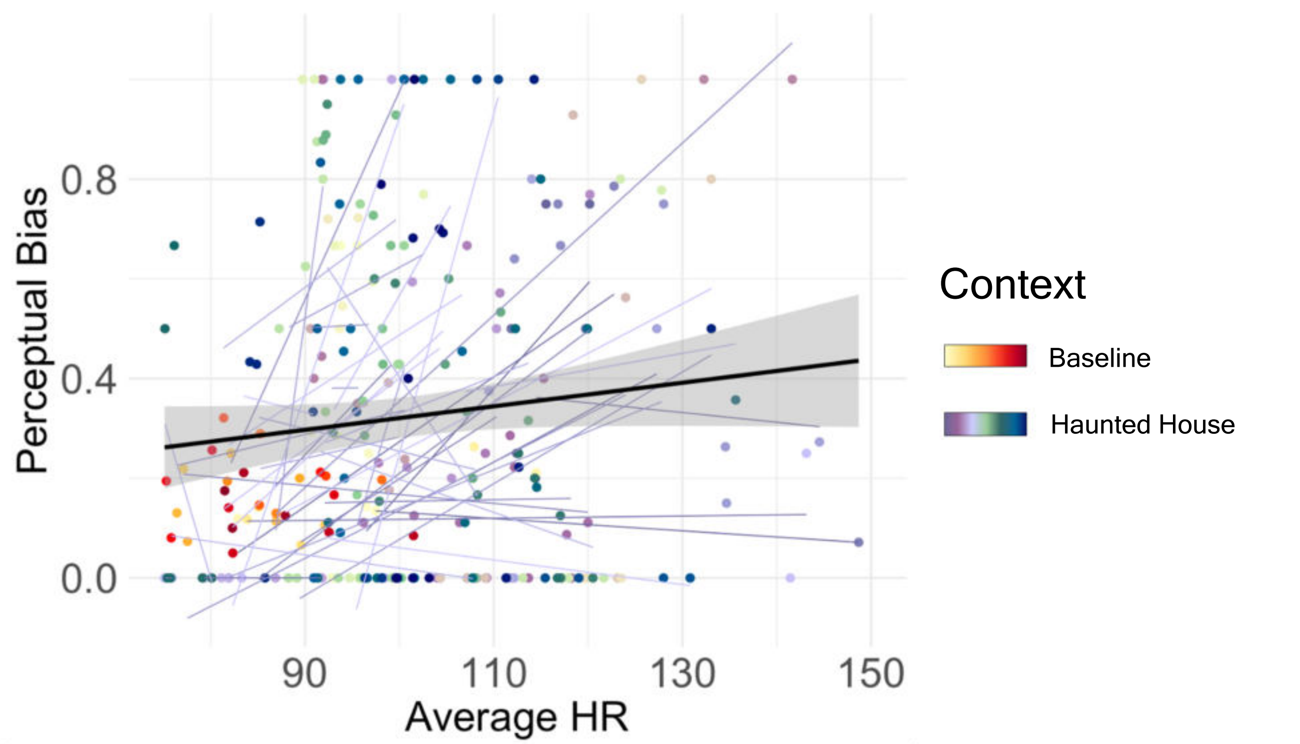
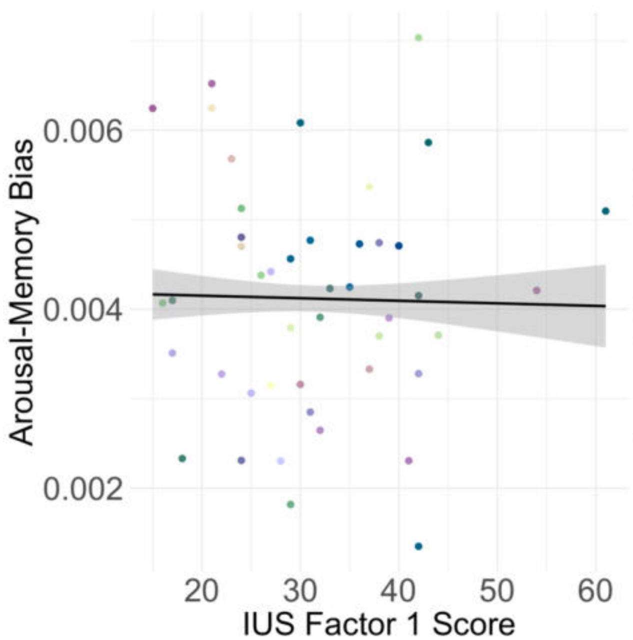


Fig. 3. A mixed-effects model reveals that increases in average HR predict increases in perceptual memory bias per segment.

Individual differences in Intolerance of Uncertainty and arousal-memory bias

Finally, we examined individual differences in the relationship between the arousal-related perceptual biases in memory and IUS scores. The IUS has two separate factors: a behavioral factor and a cognitive factor, which reflect one's ability to cope with past uncertainty and discomfort with future uncertainty, respectively. While the IUS behavioral factor (β (276) = 213.13, 95% CI: [-635.731, 1062.002], *SE* = 431.20, t = .49) did not predict arousal-memory bias across participants (R^2 = .0008, F(1, 276) = .24, p = .62, Figure 5a), increases in the IUS cognitive factor (β (276) = -1428.15, 95% CI: [-2226.25, -630.05], *SE* = 405.41, t = -3.52) significantly predicted decreases in the arousal-memory bias across participants (R^2 = .04, F(1, 276) = 12.41, p < .001, Figure 5b). Specifically, the more troublesome a participant perceives future uncertainty to be, the smaller the arousal-memory bias.

To specify whether this relationship was due to alterations in physiological response or memory in individuals with high uncertainty intolerance, we separately looked at associations between the IUS cognitive factor and differences in arousal and perceptual memory bias. We found that increases in the inability to cope with future unpredictability (β (273) = -.002, 95% CI: [-.004, -1.19], *SE* = .001, *t* = -1.97) predicted decreases in differences in perceptual memory bias across contexts (R^2 = .03, *F*(1, 266) = 10.43, *p* = .048, Figure 5c). No relationship was found between the inability to cope with future unpredictability (β (276) = .03, 95% CI: [-.16, .23], *SE* = .10, *t* = .33) and differences in HR across contexts (R^2 = .0004, *F*(1, 276) = .11, *p* = .73, Figure 5d). Together these findings suggest that individuals with higher cognitive IU show atypical arousal and perceptual memory biases, which may result from overall increases in memory for perceptual details for both baseline and threatening events, independent of changes in HR.



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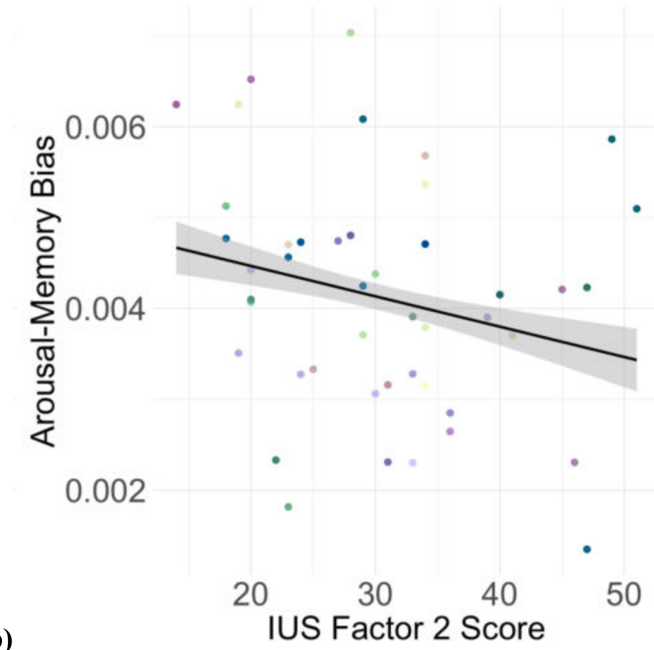

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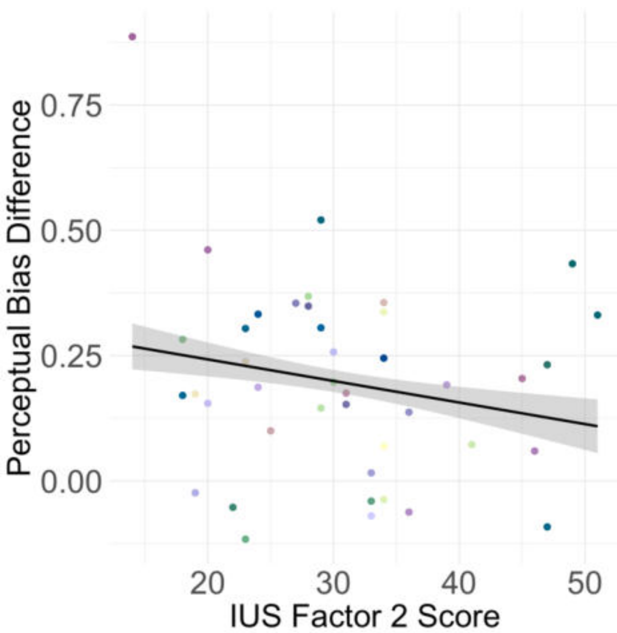

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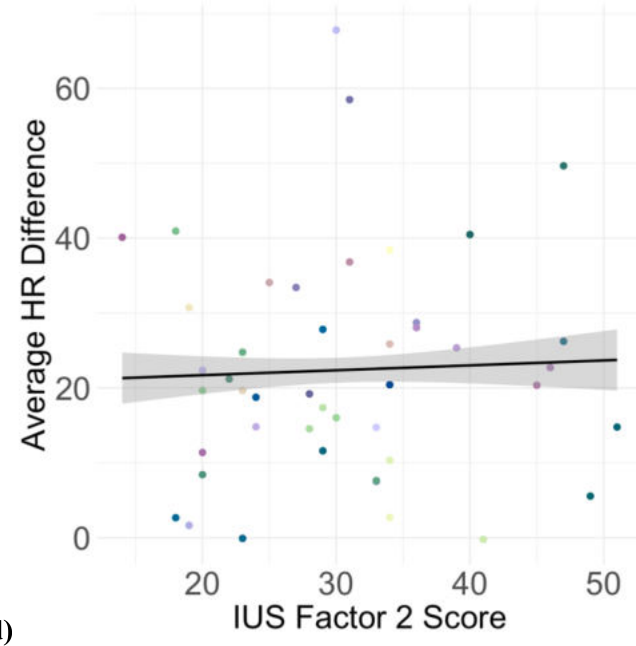

d)

Fig. 5. a) A linear model reveals no relationship between arousal-memory biases and the IUS behavioral factor (Factor 1). **b)** A linear model reveals a negative relationship where decreases in individual arousal-memory biases predict increases in the IUS cognitive factor (Factor 2). **c)** A linear model shows that decreases in differences in the perceptual memory bias across contexts predict increases in the cognitive IUS factor. **d)** A linear model reveals no significant relationship between differences in average HR across contexts and scores on the cognitive IUS factor.

Discussion

In the current study, we investigate factors influencing memory distortions for naturalistic, threatening contexts. Using a standardized method to score unstructured, free recall of autobiographical memories, we found a bias in memory for perceptual details under threat, where a higher proportion of perceptual details are remembered at the expense of memory for contextual details (i.e., event, place, and time details). Moreover, we found an inverse relationship between arousal and memory, where increases in average heart rate (HR) predict decreases in total details recalled. However, when examining the relationship between arousal and perceptual memory bias, we find that increases in average HR predict increases in the proportion of perceptual details recalled. When specifically examining the makeup of perceptual details across contexts, we find that more Sensory and fewer Duration and Ordering details are recalled after exposure to threat.

These results build on current research examining the effects of threat and arousal on attention. Prior research shows that in threatening contexts, attention is diverted towards information central to arousal. A recent neuromodulatory model of memory explains how arousal influences attentional biases in memory (Clewett & Murty, 2019). High arousal environments drive attentional "narrowing", which leads to specific enhancements in memory for threat-central sensory features. Importantly, these enhancements are concurrent with impairments in both peripheral features and context-item binding. Studies examining the effect of arousing stimuli on associative memory have shown impairments in memory for more mundane contextual details that are outside the central scope of attention (Kensinger, Piguet, Krendl, & Corkin, 2005; Kensinger, Garoff-Eaton, & Schacter, 2006, 2007; Mather & Sutherland, 2011; Rimmele et al., 2011).

The present study broadens extant findings on the effect of threat on memory through the use of a naturalistic paradigm that assesses memory using free recall. Moreover, in characterizing arousal during encoding while controlling for exposure to threat, we are able to examine the impact of arousal on threat-based memory biases. We find evidence in support of prior research by showing a dissociation in memory across contexts, where memory is biased towards perceptual details and away from event, place, and time details. Using the Autobiographical Interview scoring method (Levine et al., 2002), we found that enhanced memory for perceptual details, specifically those categorized as Sensory details, is predicted by increases in arousal. This result lends empirical support to the cognitive narrowing effects driven by sympathetic activation detailed in a recent theoretical review (Clewett & Murty, 2019). Further, while we found that increases in arousal predict overall decreases in memory, we see these memories become increasingly dominated by perceptual details. Thus, while memory is generally impaired after exposure to threat, we argue that arousal drives specific retention of item memory with decreased memory for associative information. This is further exemplified in results examining perceptual detail categories. Under threat, memory for item-based perceptual details, Sensory details, is enhanced, while that for Duration & Ordering details, which represent information bound to time and context, is impaired.

Our results also provide insight into how perceptions of uncertainty impact arousal's downstream influence on threat-related distortions in memory, which holds great importance for understanding risk for anxiety disorders. Specifically, we examined whether anxiety-based biases in memory are domain-specific or domain-general and how cognition and arousal influence these factors. The Uncertainty and Anticipation Model of Anxiety (Grupe & Nitschke, 2013) describes how threat differentially affects memory in anxious individuals. Due to heightened threat perception underlying anxiety, individuals are oriented towards threat, which leads to a prioritization of threatening stimuli during encoding and later biases memory towards threatening information. Research has yet to examine whether these biases towards threat are solely enhanced during threat exposure (domain-specific) or if they persist across contexts (domain-general). Here, we found that decreases in arousal-memory biases across contexts predict increases in the Intolerance of Uncertainty Scale (IUS) Cognitive factor, showing that those who are highly averse to future unpredictability show similar levels of threat-based arousal-memory biases across contexts. Moreover, we found that increases in the IUS cognitive factor are predicted by decreases in differences in perceptual bias memory across contexts but have no relationship to differences in average HR across contexts. These results indicate that memory biases stemming from high anxiety risk are domain-general and may dampen the putatively adaptive function of physiological arousal in shaping memory-related processes.

Using the above results, we propose a new model of maladaptive cognitive processing in individuals with high intolerance of uncertainty (IU), where learning systems are tuned to respond as if individuals are under sustained threat, leading to memory biases reflective of perpetual environmental threat. We argue that when individuals perceive uncertainty as an environmental threat, their goals are shifted towards moderating uncertainty in all contexts. Consequently, cognitive resources are continuously allocated towards threat management, leading to biases in memory where all experiences are remembered as if under a state of threat. This bias results in the reinforcement of threat search and management, due to the fact that memory for details, regardless of contextual experience, reflect high threat. Further research should examine whether these attention and memory biases are a result of deficits in the inhibition of threat-activated cognitive resources or overactivation of attentional narrowing towards threat. Moreover, it is important that future studies further examine how this model of threat perception affects individuals with anxiety disorders and PTSD, which have been shown to be associated with greater IU (Raines, Oglesby, Walton, True, & Franklin, 2019).

Future studies should also follow-up on our results showing diverging effects of arousal on memory in the threat context. Within the haunted house alone, we found that increases in HR predict increases in total detail memory, and changes in HR have no predictive effect on perceptual bias memory. These results imply that potential differences in arousal-based memory effects may occur at varying levels of arousal. The Arousal Biased Competition (ABC) model (Mather & Sutherland, 2011) states that high arousal information competes for prioritization in working memory, thus enhancing memory for information eliciting the highest level of arousal. Further, the model describes that increases in the amount of high-priority information competing for attention lead to general suppression effects in memory for high-arousal information. Future research would benefit from closely examining how arousal-biased suppression and enhancement drive differential effects of HR on memory on both macro and micro scales. It is also possible that our threat context only captures a limited range of variability in arousal, thus limiting the amount of possible variability in perceptual memory biases. In order to clarify what mechanisms drive a divergence in between- versus within-context results, future research should explore how multiple levels of arousing threat impact the extent to which perceptual memory is biased. If arousal-based suppression effects and minimal HR variability are present in these results, we would expect future studies to show decreases in perceptual bias memory with exposure to lower arousal threat contexts in comparison to high arousal threat contexts. Exploring how arousal and memory change under different gradients of threat and *when* they change will help to clarify what levels of arousal cause memory to become differentially impacted.

While the present study elucidates specific memory effects that can only be captured in a naturalistic threat setting, future studies would also benefit from examining how controlling for various types and levels of threat impact the results seen here. For example, it is possible that exposing participants to a baseline environment prior to the threat environment lends to incidental capturing of anticipatory threat. Studies extending our results might consider counterbalancing baseline and threat conditions in order to examine whether threat anticipation changes baseline memory composition or IUS effects. Moreover, our results showing differential effects of arousal on total detail memory and perceptual bias memory tell a nuanced story about micro vs. macro level arousal-biased competition effects. To further understand how variations and increases in arousal affect memory distortions, future studies may consider taking more discrete heart rate measures. The current study compares baseline resting HR to arousal under threat while participants are moving. Adding baseline movement and resting threat measurements would allow future researchers to capture the gradient of arousal that may occur under different threatening environments and resulting biases in memory. Additionally, it is equally important for future research to examine whether salient perceptual information exists on a gradient that influences the memory distortions seen in the present study. Though both our baseline and threat contexts contained a variety of both surprising and contextual perceptual information, the difference in physical environments and the contextual relevance of surprise itself may have influenced our perceptual memory bias results. Through the use of more highly controlled settings, future research should examine whether threat-based memory distortions are affected by novel, salient perceptual details.

In conclusion, we extend current research on threat-related memory biases by showing the predictive nature of physiological arousal on memory after exposure to threatening contexts. Moreover, through the use of an immersive paradigm that reflects real-world threat, we elucidate the specific details prioritized in memory after threat exposure. Finally, we explore how arousal-memory biases are differentially affected by IU. We propose a new model of cognition in anxiety where heightened perception of uncertainty in the environment leads to memory biases reflective of perception of threat, even in baseline contexts. Further research is required to understand why these memory biases occur in anxiety. Importantly, this research paves the way for potential new and effective intervention exploration for individuals suffering from clinical anxiety or PTSD.

Methods

Participants

Fifty-four participants (M_{age} = 24.22 years, SD_{age} = 3.97, 26F) were recruited via fliers from the Temple University and Philadelphia communities. Target sample size (n = 41) was based off a recent study examining free recall for a naturalistic, staged event (Diamond et al., 2020). Informed consent was acquired from each participant using methods approved by the Institutional Review Board at Temple University. Participants were excluded from analysis due to lack of fluency in English (n = 2), having previously visited the haunted house this year (n =1), dropping out of the study (n = 1), and missing free recall data (n = 3). Two participants were excluded from heart rate (HR) analyses due to equipment error, and one participant was excluded from Intolerance of Uncertainty Scale (IUS) analyses due to missing data. The final sample included 47 participants (M_{age} = 23.85 years, SD_{age} = 3.78, 21F). Individuals were excluded from participation in the study if they met any of the following criteria: history of seizures, an inability to walk comfortably for one hour, cardiovascular disease, non-native English speaker, falling outside of age requirements (18-34 years old), and contraindications for MRI studies.

General Procedure

The experiment was divided into two parts: an encoding phase, where small groups of 3-5 participants ($M_{\text{group size}}$ = 4.50, $\text{SD}_{\text{group size}}$ = 0.79) consecutively experienced a baseline and threat context; and a retrieval phase, where individual participants completed a surprise free recall task at a 5-7 day delay (M_{days} = 5.98, SD_{days} = 0.79). Participants were paid $70 for participation in both sessions.

Encoding – Baseline Context

All participants were first exposed to a context that served as a baseline, which included our main lab space and adjacent rooms, as well as various spaces in the building (e.g., building lobby, hallway, bathroom, and elevators). Importantly, the baseline context included a variety of discrete locations. This neutral, laboratory context served as a baseline with which to compare any memory and arousal effects that occurred in the threatening, immersive environment. However, we note that this laboratory setting is limited as a perceptual control, as it doesn't fully model the quantity and qualia of information that is experienced within the haunted house.

Participants arrived at the lab at 5:00 p.m. EST and experienced the baseline context for one hour. The haunted house runs seasonally from October to November, so the first experimental session always began at dusk. Upon arrival to the main lab room, participants underwent consent, then were instructed to individually go into an adjacent office to ask questions and receive HR monitors. After putting on their HR monitors in the bathroom, participants completed computerized questionnaires while baseline HR recordings were taken. Baseline HR recordings ended when all participants were finished with their questionnaires and lasted an average of 15.8 minutes. Questionnaires included a demographics form, as well as a series of personality questionnaires including the IUS. After all participants completed their questionnaires, they were provided with digital audio recorders to carry in the haunted house and trained on their use. Last, a research assistant (RA) delivered final instructions to participants in preparation for the haunted house. Participants and accompanying RAs waited in the building lobby while transportation was called via rideshare app.

Encoding – Threat Context

Encoding of a naturalistic, threatening context took place at the seasonal haunted house, Terror Behind the Walls, at Eastern State Penitentiary in Philadelphia, PA. The haunted house lasted about fifty minutes and consisted of six discrete, themed sections: 1) “Lock Down”, 2) “Machine Shop”, 3) “Blood Yard”, 4) “Infirmary”, 5) “Quarantine 4D”, and 6) “Break Out”. Importantly, each unique section draws on common fearful stimuli (e.g., clowns, spiders, cannibalism, hospitals, blood, small spaces), thus capturing a range of idiosyncratic fears and leading to high fear variability within participants across sections. The haunted house had a consistent temporal structure such that participants completed each section in the same order every night. Notably, Terror Behind the Walls offers a highly immersive environment where participants are consistently exposed to visual, tactile, olfactory, and auditory stimuli. For example, in “Blood Yard”, participants would walk through enclosed grassy walls while hearing the distant sound of a chainsaw revving. As they progressed through this section, they began to smell gasoline from the chainsaw as the revving grew louder, and finally, were jump-scared by a screaming, chainsaw-wielding zombie who chased them to the next section.

Before entering the first section of the haunted house, participants were given specific instructions to experience the haunted house as naturally as possible (i.e., as if they were not part of the study) and to refrain from discussing aspects of the haunted house during the experience. Every participant then turned on their audio recorder and was told to remember a random, pre-assigned number (from 1-6) that was written on the back of their recorder. This number designated which section of the haunted house they were to lead the group in, ensuring that each participant led the group in at least one section. Immediately following each section of the haunted house, participants were given instructions to rate how scary they found that section on a scale of 1 (*Not scary at all*) to 5 (*Extremely scary*). After instructions were given, an RA began taking HR recordings. Recordings ended once all participants exited the haunted house and lasted an average of 55.2 minutes. At the end of the haunted house, participants were debriefed and transported back to the lab. This first experimental session typically concluded around 7:30 p.m. EST.

Retrieval

Individual participants arrived at the Temple University Brain Imaging Center approximately one week later where they were surprised with a free recall task. Participants were instructed to verbally describe everything they could remember about their experience in the haunted house, starting with the moment they were asked to turn their audio recorders on and ending with the moment they finished the haunted house. Then, participants were instructed to describe everything they could remember from their experience starting from their arrival to the lab and ending with the moment they left the lab to catch their rideshare car. The order of recall was counterbalanced such that half of the participants recalled the haunted house first, while the other half of participants recalled the lab first. For both threat and baseline context recall, participants were instructed to talk for at least ten minutes but were reminded that more information is better. Haunted house recall lasted an average of 11.8 minutes; lab recall lasted an average of 6.93

minutes. Free recall was recorded in the scanner using Audacity. Following scanning, participants completed additional questionnaires, were paid for their time, and debriefed about the study goals. Notably, the free recall task was collected during functional magnetic resonance imaging (fMRI) data acquisition. While fMRI data is not presented in the current manuscript, it will be characterized in future research.

Analysis

To score free recall transcripts, we modified the Autobiographical Interview (AI) scoring method (Levine et al., 2002). AI scoring modifications were established to standardize the scoring of haunted house and baseline transcripts. This method allows us to capture the extent to which a participant was re-experiencing an event, without concern for objective accuracy. The AI breaks detail memory into two main bins: internal and external details. Internal details are episode-specific and reflect a participant's ability to reimagine and relive an experience. There are five categories of internal details: event (often action or ordering details; e.g., "we put on 3D glasses"), place (e.g., "Eastern State Penitentiary"), time (e.g., "it was 5:00 pm"), perceptual (details in the perceptual field; e.g., "there were glow-in-the-dark spiders"), and emotion/thought (e.g., "I was scared"). Based on prior research showing that perceptual information is enhanced and contextual features are impaired under arousing contexts, we calculated a perceptual bias score by dividing total recalled perceptual details by the total number of perceptual, event, time, and place details recalled. Higher perceptual bias scores indicate a higher proportion of recalled perceptual details when compared to event, place, and time details. External details are details non-specific to an episode and include memory for other events, semantic information (e.g., "I was always afraid of clowns"), repetitions of details, and editorialization of past experiences in the present tense (e.g., "in retrospect, that was scary"). All transcripts were scored by two RAs trained in the AI. To test for inter-rater reliability, each RA independently scored ten transcripts. Inter-rater scoring was highly correlated; correlation coefficients for total internal, total external, and total detail scores were all greater than .99.

In order to elucidate what information comprises perceptual detail memory, we further categorized perceptual details into six discrete categories: Sensory, Experiential Perception (adjectives describing physiological experience or perception of the event), Proprioception, External Space (non-sensory information about the environment), Duration and Ordering (relative temporal information), and Comparisons and Estimations (generalized statements about relative stimuli features and occurrences during the experience). Perceptual details were scored by an RA trained in perceptual detail categorization. To test for inter-rater reliability, two RAs independently scored 10 transcripts. Inter-rater scoring was highly reliable, with scorers at 98% agreement across transcripts.

HR data during encoding was recorded using Firstbeat sports software (Firstbeat Technologies Ltd., Jyväskylä, Finland). This software collects raw HR data in the form of interbeat intervals, which are converted into beats per minute and corrected for artefacts (Saalasti et al., 2004). All HR data was collected through a receiver connected to a tablet. In the haunted house, an RA used a "lap" button included in the Firstbeat software to timestamp the group's entry into and exit of each section. HR data in each section was verified by comparing timestamps for each section to participant audio recordings for the haunted house, allowing for accurate calculation of changes in HR for each section of the haunted house.

The IUS (Freeston et al., 1994) was scored using the two-factor structure proposed by Sexton & Dugas (2009). Factor one, the behavioral factor, delineates the extent to which past experiences with intolerance of uncertainty influence one's behavior and self-perception. Factor two, the cognitive factor, characterizes distress towards general unpredictability and represents an individual's inability to cope with a lack of control over future experiences with uncertainty. In order to explore how individual differences in the IUS are associated with arousal-based memory across contexts, subject-specific random slopes between HR and perceptual memory bias were extracted and separately related to IUS behavioral and cognitive factors. To examine how individual differences in future uncertainty management affect memory and arousal under threat, difference scores across contexts were calculated and related to the cognitive factor. Difference scores were calculated by subtracting mean arousal and memory scores in the haunted house from those in the baseline context.

All statistical tests were conducted using R Studio (R Core Team, 2020). Paired *t* tests were separately run to investigate how the proportion of internal details recalled and perceptual bias scores were affected by context (baseline versus threat). In a chi-squared test, memories for perceptual detail types in the haunted house were compared to baseline rates, which were computed as the proportion of perceptual detail categories recalled at baseline. Linear mixed-effects models were performed using the *lme4* package (Bates, Mächler, Bolker, & Walker, 2015) to examine the relationships between memory, arousal, arousal-memory bias, and IUS scores. For each model analysis, we ran full models using HR or IUS scores as fixed effects. We then ran model comparisons between the model of interest and a null model that did not include the fixed effect of interest. All models included participant as a random effect to account for within-subjects variation in the data. Linear models were used to examine the relationship between differences in memory across contexts, differences in arousal across contexts, and IUS scores. All tests were considered significant when $p < .05$.

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Open Practices Statement

The experiment in this article was not formally preregistered. De-identified data and data analysis scripts are posted on Open Sciences Framework at https://osf.io/v2n9p/. A preprint is available on PsyArXiv.