Threat impairs flexible use of a cognitive map

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Supplementary Information

Supplementary Methods

After completing both navigation tasks (i.e., both the non-Threat and Threat conditions) in each study, participants took part in memory tests in the absence of threat. Participants were not told about these memory tests in advance: they received instructions about these tests only after the navigation portion was completed. First, map recognition memory was tested with a forced-choice task that required participants to select the map layout associated with each condition. Second, an object placement task enabled us to assess how well participants encoded goal objects in relation to other objects and the environment more generally (this task was done only in Studies 2 and 3; in Study 1, participants performed a map drawing task immediately after navigation). Finally, item recognition memory for incidental perceptual details was probed by testing memory for paintings that appeared in the environment but were not relevant for the task. These memory tasks are described in more detail below.

Map Drawing

In Study 1 only, participants were asked to draw the maps they navigated after the navigation portion of the task was completed. They used the custom map editor that generated the maps to estimate the location of walls and objects for each navigation condition, one at a time. Because most participants either claimed the task was too difficult or performed poorly, and creating fair scoring schemes was difficult, this task was replaced with the Object Placement Task for Study 2 and Study 3. The resulting data for map drawing are not reported here.

Map Recognition Memory

Immediately after the navigation component of Study 2 and Study 3 (and after map drawing in Study 1), participants were shown four (4) map layouts, one of which was the actual map used for the condition highlighted in the instructions (**Supplementary Figure 1A**). The participant selected among the four (4) options and then was asked to rate their confidence in the decision on a seven (7) point scale ranging from "Not at all confident" to "Extremely confident". This process was then repeated for the other navigation condition. The lures were unique to each forced choice, i.e., lures for the first decision were different from those for the second decision. The order of testing (i.e., whether the first navigated map was tested first or second) was counterbalanced across participants. Confidence responses for correct and incorrect map recognition judgments are shown in **Supplementary Table 1**, separately for each condition and each study.

	Study 1			**Study 2A**	
	Reward	**Threat**		**Neutral**	**Reward**
	Mean (SD)	**Mean (SD)**		**Mean (SD)**	**Mean (SD)**
Correct	5.18 (1.13)	4.33 (1.97)	**Correct**	4.31 (2.10)	4.47 (1.81)
Incorrect	3.29 (1.14)	3.89 (1.29)	**Incorrect**	3.24 (1.39)	3.27 (1.58)

	Study 2B			**Study 3**	
	Neutral	**Threat**		**Reward-Agent**	**Threat**
	Mean (SD)	**Mean (SD)**		**Mean (SD)**	**Mean (SD)**
Correct	4.78 (1.63)	4.32 (1.62)	**Correct**	4.60 (1.65)	3.68 (1.73)
Incorrect	3.33 (0.98)	2.13 (0.35)	**Incorrect**	3.57 (1.79)	3.08 (1.72)

Supplementary Table 1. Confidence ratings in the map layout memory test, separately for each study and condition. Values are the mean confidence response, with standard deviation in parentheses.

Object Placement Task

In Study 2 and Study 3, participants completed the Object Placement Task, which replaced the Map Drawing Task in Study 1. After completing the Map Recognition Memory task, participants were shown an overhead view of one of the maps used for navigation, with the objects removed from their respective locations. The task required participants to select the six (6) objects associated with that map from among a set of eight (8) total objects, two of which were not associated with either navigation condition. They then had to place the goal objects in the remembered locations on the map. This process was repeated for the other map in which the participant navigated. Map layout presentation was counterbalanced across participants. Scores were tabulated sums based on direct hits and near misses. Direct hits yielded three (3) points, locations within one (1) tile yielded two (2) points, and locations within two (2) tiles yielded one (1) point. Points were awarded only for correct object-location associations, i.e., a correct location with a wrong object yielded 0 points.

In addition to our main analysis, which was designed to capture the precision of memory by awarding more points for direct hits vs. near hits, we conducted an analysis to determine if performance was different from chance. For this analysis, we awarded 1 point for a hit (correct object within 2 tiles of its original position) and 0 points for misses. We then calculated chance performance by simulating 100 test trials for each map. In this simulation, objects were placed randomly on allowable tiles (excluding walls and borders) and awarded 1 point only if they fell within 2 tiles of their original position. Across all studies and conditions, participants' performance was reliably above chance (all *p*s < 0.005). Furthermore, between-condition comparisons yielded the same pattern of results as our main analysis, which is reported below for each study.

Painting Recognition

In Study 1, a set of 144 paintings were displayed sequentially to participants. Old and new paintings were presented in a random order. Paintings were presented one at a time and a self-paced recognition confidence response was collected with a 6-point recognition confidence scale (sure new, maybe new, guess new, guess old, maybe old, sure old; **Supplementary Figure 2A**). 96 of the paintings could have been presented during the navigation portion of the study (half in the Reward condition and half in the Threat condition), and the remaining 48 were entirely new. Of the 96 paintings that could have appeared during navigation, approximately half did appear (because the participant was nearby and facing them). For calculation of d', paintings were treated as 'old' if they were seen during the navigation task, for any duration of time. Unseen paintings and entirely new paintings were both considered 'new'. Confidence responses for seen/old and unseen/new paintings are shown in **Supplementary Table 2**, separately for each condition and each study.

In Study 2 and Study 3, the painting recognition task was similar to Study 1, except that only 96 paintings were presented. This was done to try to improve memory performance (by reducing interference from new items). On average, roughly half of these 96 paintings were presented during the navigation portion (because paintings appeared only when participants were nearby and facing them). The ~50% that did not appear in the navigation test were considered new and used to calculate false alarm rates.

Study 1

	Reward	Threat	
	Mean % (SD) Seen	Mean % (SD) Seen	Mean % (SD) Not Seen
Sure Old	8.0% (5.1%)	4.5% (3.9%)	3.3% (3.4%)
Maybe Old	14.2% (6.6%)	14.7% (6.7%)	14.6% (6.7%)
Guess Old	18.8% (7.4%)	15.4% (6.8%)	17.1% (7.1%)
Guess New	23.1% (8.0%)	24.0% (8.1%)	23.0% (8.0%)
Maybe New	23.1% (8.0%)	24.5% (8.1%)	23.5% (8.0%)
Sure New	12.9% (6.3%)	16.9% (7.1%)	18.5% (7.3%)

Study 2A

	Reward	Neutral	
	Mean % (SD) Seen	Mean % (SD) Seen	Mean % (SD) Not Seen
Sure Old	5.8% (3.0%)	5.9% (3.0%)	5.3% (2.9%)
Maybe Old	18.7% (5.0%)	15.5% (4.7%)	13.6% (4.4%)
Guess Old	19.3% (5.1%)	19.3% (5.1%)	20.6% (5.2%)
Guess New	22.5% (5.4%)	22.3% (5.4%)	24.8% (5.6%)
Maybe New	20.0% (5.2%)	22.7% (5.4%)	21.2% (5.3%)
Sure New	13.7% (4.4%)	14.4% (4.5%)	14.4% (4.5%)

Study 2B

	Threat	Neutral	
	Mean % (SD) Seen	Mean % (SD) Seen	Mean % (SD) Not Seen
Sure Old	4.8% (2.8%)	6.3% (3.1%)	4.2% (2.6%)
Maybe Old	16.6% (4.8%)	17.6% (4.9%)	13.6% (4.4%)
Guess Old	18.9% (5.1%)	20.6% (5.2%)	18.2% (5.0%)
Guess New	24.2% (5.5%)	20.9% (5.2%)	25.3% (5.6%)
Maybe New	20.2% (5.2%)	22.7% (5.4%)	22.2% (5.4%)
Sure New	15.3% (4.6%)	11.9% (4.2%)	16.5% (4.8%)

Study 3

	Reward	Threat	
	Mean % (SD) Seen	Mean % (SD) Seen	Mean % (SD) Not Seen
Sure Old	6.1% (4.5%)	7.3% (4.9%)	4.3% (3.6%)
Maybe Old	11.7% (6.1%)	12.3% (6.2%)	11.3% (5.7%)
Guess Old	18.5% (7.3%)	20.5% (7.6%)	17.6% (6.8%)
Guess New	26.8% (8.4%)	24.0% (8.1%)	25.0% (7.8%)
Maybe New	15.8% (6.9%)	15.4% (6.8%)	18.1% (6.9%)
Sure New	21.1% (7.7%)	20.5% (7.6%)	23.7% (7.6%)

Supplementary Table 2. Confidence ratings in the painting recognition task, separately for each study and condition. Values are the mean percentage of trials that fell in each confidence bin for the condition shown in each column, with standard deviation in parentheses.

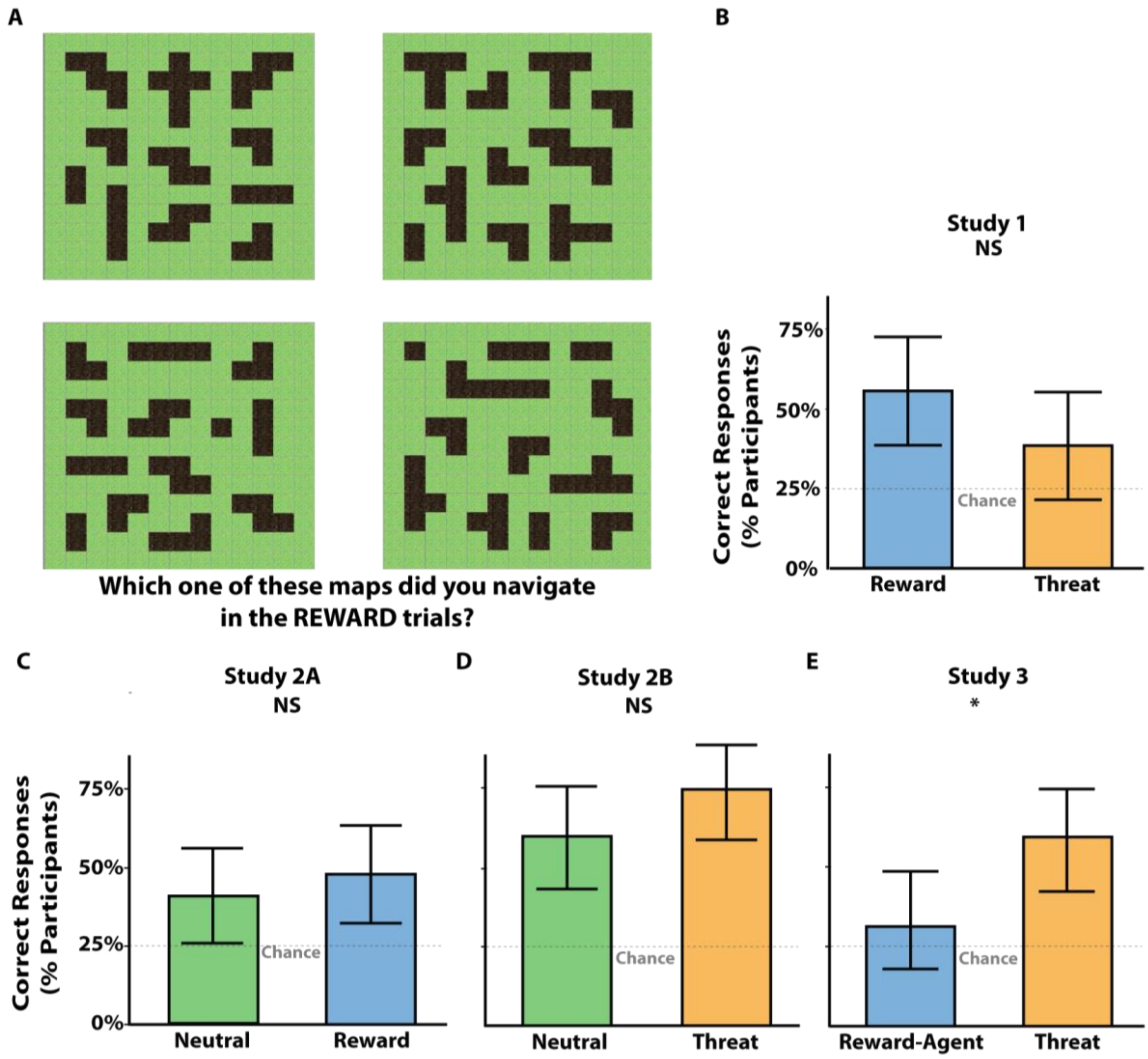
Supplementary Results

Study 1

Map Recognition Memory

The map memory task was a 4-alternative forced-choice recognition test (**Supplementary Figure 1A**), which probed at least some aspects of relational and/or spatial memory. Because map layouts were provided to the participant, effortful free recall of representations was not required and instead each map could be considered and compared with the contents of memory. However, the ability to recognize the correct map layout required relational memory to some extent, e.g., memory for the location and shapes of walls and shapes of open spaces in the environment. (Note that map layout memory is unlikely to be supported by memory for the overhead perspective provided at the start of each trial, because that perspective was entirely occluded except for 1.5 tiles at a time; **Figure 2**).

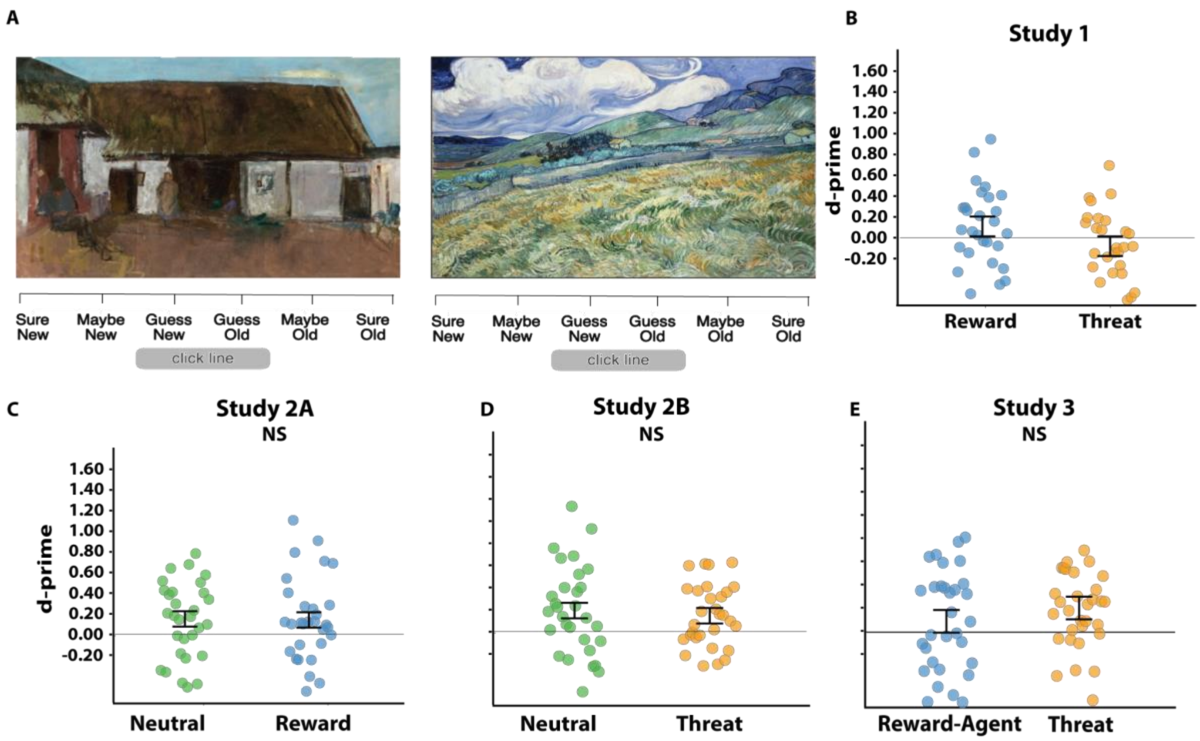
We hypothesized that this form of relational memory may be relatively preserved following threat, because it requires less flexibility than the relational memories needed to support navigation. To test this, we tallied and compared the number of correct responses for the forced-choice map recognition task (**Supplementary Figure 1B**). A logistic regression model with condition (Threat vs. Reward) as an independent variable and participant as a random effect revealed that participants did not score differently on the map recognition task across conditions (beta = -0.65, SE beta = 0.52, 95% CI = [-1.66, 0.36], Odds Ratio (OR) = 0.52, p = 0.21). Thus, the ability to encode a spatially complex environment may be relatively unaffected by this form of threat. Nevertheless, because each participant provided only one memory response for each map, this test may be under-powered relative to our navigation analyses, and this null difference cannot be over-interpreted.



Supplementary Figure 1. Map recognition memory task and results. (A) The map recognition memory task. Participants were prompted to select the correct layout among the four (4) displayed options for the navigation condition provided in the instructions. Map recognition memory was tested for both navigated conditions. **(B)** Results from Study 1 indicated no differences in map recognition between the Reward and Threat conditions, based on the percentage of participants who provided the correct response. **(C)** Results from Study 2A indicated no differences in map recognition performance between the Neutral and Reward conditions. (D) Results from Study 2B indicated no differences in map recognition between the Neutral and Threat conditions. (E) Results from Study 3 indicated that participants were better at identifying the correct map in the Threat vs. Reward-Agent condition. Dashed line represents chance performance, i.e., 1 in 4. NS = not statistically significant. * $p < 0.05$. Error bars represent the binomial proportion 95% confidence interval calculated using the Wilson method.

Painting Recognition

The painting recognition test allowed us to assess item memory for information that was incidental to the primary task goals (**Supplementary Figure 2A**). Many studies report that memory for peripheral details is impaired in stressful situations (Mather, Gorlick, & Nesmith, 2009; Mather & Sutherland, 2011; Steblay, 1992). Alternatively, however, memory for the paintings may be spared in the current study, because the paintings appeared on walls that could be used to guide navigation — including escape from the predator. We first tested whether the number of paintings viewed in each condition was equated, and indeed there was no difference in the number of paintings viewed in the Threat (M = 23.64; SD = 3.20) vs Reward (M = 23.21; SD = 2.75) condition (t(27) = -0.49, 95% CI = [-2.1, 1.33], p = 0.62; Cohen's dz = -0.09, 95% CI = [-0.47, 0.28]) (note that 3 participants were unable to complete the painting task due to software problems or lack of time). We next examined overall performance, measured with d'. Performance was not reliably above chance (M = 0.01, SD = 0.25, 95% CI = [-0.08, 0.11], t(27) = 0.28, p = 0.78; Cohen's d = 0.05, 95% CI = [-0.32, 0.43]). Thus, although there was no statistically significant difference in d' between the Reward (M = 0.11, SD = 0.37) and Threat (M = -0.08, SD = 0.35) conditions (t(27) = 2.00, p = .06, 95% CI = [0.00, 0.38]; Cohen's dz = 0.38, 95% CI = [-0.01, 0.77]), floor effects preclude any conclusions being made. The data are shown in **Supplementary Figure 2B** for transparency. In Study 2, procedural changes were made to try to improve overall memory in the painting task.



Supplementary Figure 2. Painting recognition task and results. (A) Seen and not-seen paintings were displayed sequentially to participants along with a six (6) point scale representing both decision (i.e., seen [old] or not seen [new]) and confidence (sure, maybe, guess). **(B-E)** d′ was not different between any pair of conditions across all three studies. However, performance was not reliably above chance in Study 1; a comparison between conditions is therefore inconclusive due to floor effects. Poor recognition memory was observed across all studies, so the lack of a difference between conditions should be interpreted with caution. Error bars represent ± standard error of the within-participant condition difference. NS = not statistically significant.

Summary of Post-Navigation Memory Tests

In Study 1, we found no evidence that threat affected subsequent recognition of the spatially complex environment that was navigated, although we note that our map recognition test may be under-powered relative to our navigation analyses. Memory for paintings was not reliably above chance, precluding conclusions about how threat affects memory for incidental perceptual features.

Study 2

Map Recognition Memory

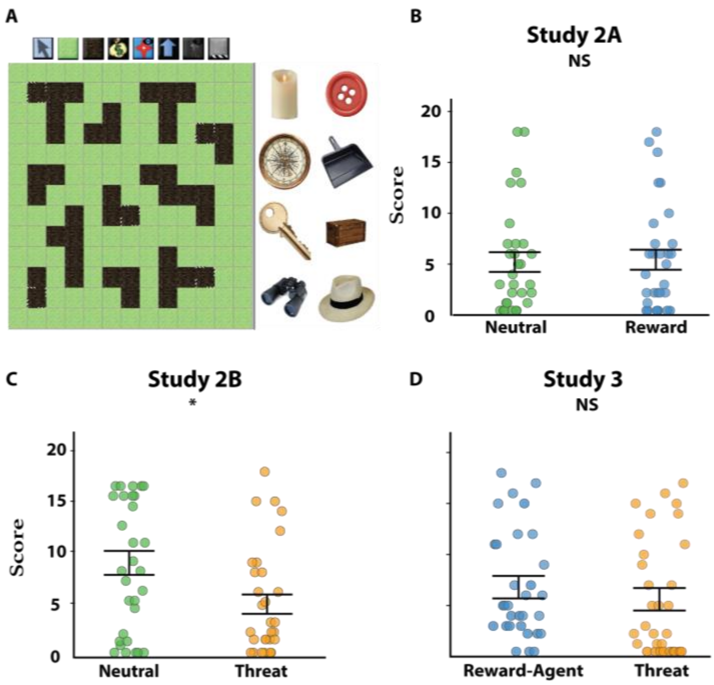
The map recognition task enabled us to determine if participants formed a type of relational, spatial memory that was sufficient to support forced-choice recognition (**Supplementary Figure 1C-D**). To test this, we used a logistic regression model to predict map recognition success, with condition as an independent variable and participant as a random effect. We found no difference in recognition memory for map layouts in the Threat vs. Neutral conditions (beta = 0.61, SE beta = 0.56, 95% CI = [-0.48, 1.70], OR = 1.83, p = 0.28). This replicates our finding from Study 1, in which the Threat condition was compared to a Reward condition. Thus, although threat impaired navigation performance that required flexible, dynamic representations, the ability to encode and subsequently recognize a spatially complex environment may be intact. We again note that this test (with one response per participant per condition) is not as well-powered as navigation analyses, for which there were many observations per participant; thus, the results must be interpreted with caution.

We next tested whether rewards enhance map memory by comparing the Reward vs. Neutral conditions. A logistic regression containing the same parameters used for the Threat vs. Neutral model revealed that memory for the map layout was not significantly different across the Reward and Neutral conditions (beta = -0.28, SE beta = 0.53, OR = 0.76, 95% CI [-1.32, 0.76], p = 0.60).

Object Placement Task

To more precisely assess relational memory, we provided participants with each navigated map layout and asked them to select and place objects collected during the navigation task (**Supplementary Figure 3A-C**). We first compared object placement accuracy scores of the Threat vs. Neutral conditions. Object placement was more accurate in the Neutral condition vs. the Threat condition (Threat: M = 4.9, SD = 5.4, 95% CI = [2.89, 6.91]; Neutral: M = 8.6, SD = 6.6, 95% CI = [6.09, 11.05]; t(29) = 2.38, p = 0.02, 95% CI = [0.52, 6.82]; Cohen's dz = 0.43, 95% CI = [0.06, 0.82]), in line with theories predicting impairment in relational encoding due to threat (Murty & Adcock, 2017). However, this effect must be treated with caution because the difference seems to be driven by unexpectedly high performance in the Neutral condition rather than a performance decrement in the Threat condition (see **Supplementary Figure 3**, compare Study 2A vs. Study 2B).

No differences were observed in the Reward vs. Neutral conditions (Reward: M = 5.2, SD = 5.3, 95% CI = [3.22, 7.12]; Neutral: M = 5.4, SD = 5.4, 95% CI = [3.41, 7.46]; t(29) = -0.18, p = 0.86, 95% CI = [-2.97, 2.50]; Cohen's dz = -0.03, 95% CI = [-0.40, 0.33]).



Supplementary Figure 3. Object placement task and results. (A) Participants used the custom map editor software to select and place objects into an overhead perspective of the navigated environments. **(B)** Scores were not different for the Neutral vs. Reward conditions in Study 2A. **(C)** Scores were higher in the Neutral vs. Threat condition in Study 2B. **(D)** No differences were observed for the Reward-Agent vs. Threat condition in Study 3. Error bars represent ± standard error of the within-participant condition difference. NS = not statistically significant. * $p < 0.05$.

Painting Recognition

We assessed memory for incidental features of the navigation environment by testing recognition of paintings that appeared on the walls. We first compared the number of paintings viewed in the Threat vs. Neutral conditions and the Reward vs. Neutral conditions. Neither comparison yielded statistically significant differences (Threat: M = 25.07, SD = 4.12, 95% CI = [23.53, 26.60]; Neutral: M = 23.3, SD = 3.78, 95% CI = [21.89, 24.71]; t(29) = -1.69, p = 0.10, 95% CI = [-3.91, 0.37]; Cohen's dz = -0.31, 95% CI = [-0.68, 0.06]; Reward: M = 23.93, SD = 4.3, 95% CI = [22.34, 25.52]; Neutral: M = 23.1, SD = 4.13, 95% CI = [21.59, 24.67]; t(29) = 0.99, p = 0.33, 95% CI = [-0.86, 2.46]; Cohen's dz = -0.18, 95% CI = [-0.55, 0.19]).

We next examined overall recognition memory, assessed with d', and found that — unlike Study 1 — performance was now reliably above chance (Threat/Neutral group: M = 0.13, SD = 0.29, 95% CI = [0.02, 0.24], t(29) = 2.50, p = 0.02; Cohen's d = 0.45, 95% CI = 0.08, 0.84; Reward/Neutral group: M = 0.16, SD = 0.33, 95% CI = [0.04, 0.28], t(29) = 2.65, p = 0.01; Cohen's d = 0.48, 95% CI = [0.48, 0.10, 0.87]). We then compared performance across conditions (**Supplementary Figure 2C-D**). No differences were found between the Threat vs. Neutral conditions (Threat: M = 0.11, SD = 0.28, 95% CI = [0.00, 0.21]; Neutral: M = 0.16, SD = 0.40, 95% CI = [0.00, 0.30]; t(29) = -0.67, p = 0.51, 95% CI = [-0.18, 0.10]; Cohen's dz = -0.12, 95% CI = [-0.49, 0.24]). We also found no differences in d' between the Reward and Neutral conditions (Reward: M = 0.15, SD = 0.37, 95% CI = [0.02, 0.29]; Neutral: M = 0.16, SD = 0.40, 95% CI = [0.01, 0.31]; t(29) = -0.15, p = 0.88, 95% CI = [-0.16, 0.14]; Cohen's dz = -0.03, 95% CI = [-0.39, 0.34]).

Thus, we did not find evidence that threat may capture attentional resources, leaving less available for the encoding of peripheral details (Burke, Heuer, & Reisberg, 1992; Christianson, Loftus, Hoffman, & Loftus, 1991). That said, the paintings may not have been regarded as peripheral in the current task: they might have been seen as features of the environment that could potentially aid navigation. Furthermore, the lack of a significant impairment is consistent with findings that threat might not affect memory for individual items (Bisby & Burgess, 2013; Murty & Adcock, 2017). Nevertheless, painting memory was still relatively poor, leaving open the possibility that impairments would be seen if overall accuracy was higher.

Summary of Post-Navigation Memory Tests

We replicated the Study 1 results for map recognition, observing no differences in the number of correct decisions between the Threat and non-threat (here, Neutral) conditions. However, object placement scores were impaired in the Threat vs. Neutral condition, but not different between the Reward and Neutral conditions. This effect, however, was potentially due to unexpectedly high performance in the Neutral condition in Study 2B, rather than a threat-related deficit (see **Supplementary Figure 3**, compare Study 2A vs. Study 2B). We therefore sought to replicate the difference between Threat and non-Threat conditions in object placement in Study 3. Finally, we failed to find differences across conditions in recognition memory for the paintings. This latter finding is consistent with the hypothesis that threat may leave item memory intact (Murty & Adcock, 2017). Nevertheless, painting recognition memory was generally poor, and studies that have higher levels of recognition accuracy may see impairments due to threat.

Study 3

Map Recognition Memory

We assessed recognition of map layouts with the same procedures as Studies 1 and 2 (i.e., a logistic regression model with condition as an independent variable and participant as a random effect). Unlike those studies — in which no differences were observed between conditions — we found that more correct choices were made for the Threat vs. Reward-Agent condition (**Supplementary Figure 1E**; beta = 1.20, SE beta = 0.53, 95% CI = [0.16, 2.25], OR = 1.17, p = 0.02). Also unlike the Reward conditions in Studies 1 and 2, map memory in the Reward-Agent condition was not different from chance (χ-squared(1) = 0.12, 95% CI = [-0.18, 0.32], p = 0.73). Thus, the difference observed between conditions may be due to the unexpectedly poor memory in the Reward-Agent condition. Nevertheless, across all studies, we observed no evidence that threat *impairs* memory for map layouts — despite consistently impairing navigation.

Object Placement Task

We next assessed object placement accuracy within each of the navigated environments (**Supplementary Figure 3D**). While on average higher scores were observed for the Reward-Agent condition (M = 6.80, SD = 5.33, 95% CI = [4.85, 8.76]) vs. the Threat condition (M = 5.61, SD = 5.93, 95% CI = [3.44, 7.79]), the difference did not reach statistical significance (t(30) = 1.09, p = 0.29, 95% CI = [-1.05, 3.44]; Cohen's dz = 0.20, 95% CI = [-0.16, 0.56]) (note that 1 participant was not able to complete the object placement task). These results failed to replicate Study 2B, which suggested that Threat impaired object location memory. Unlike Study 2B, however, the 'safe' context in the current study controls for potential distraction by a navigating agent; thus, object location impairments in the Threat condition in Study 2B may potentially be due to distraction by the predator, or, alternatively, unexpectedly high performance in the Neutral condition in Study 2B (compared to conditions in Study 2A; **Supplementary Figure 3**).

Painting Recognition

We first compared the number of paintings viewed in the Reward-Agent and Threat conditions, and found that more paintings were viewed in the Threat condition (Threat: M = 24.27, SD = 3.35, 95% CI = [23.01, 25.52]; Reward-Agent: M = 21.50, SD = 2.32, 95% CI = [20.63, 22.36]; t(29) = -3.41, 95% CI = [-4.43, -1.11], p = 0.002; Cohen's dz = -0.62, 95% CI = [-1.03, -0.23]). To account for this difference, we conducted additional analyses (described below) to control for the number of paintings viewed.

Painting memory, measured with d', was reliably above chance (M = 0.14, SD = 0.27, 95% CI = [0.04, 0.24], t(29) = 2.77, p = 0.01; Cohen's d = 0.51, 95% CI = [0.12, 0.90]). Comparison between conditions (**Supplementary Figure 2E**) revealed that d' was not significantly different between the Reward-Agent (M = 0.07, SD = 0.42, 95% CI = [-0.08, 0.23]) and Threat condition (M = 0.20, SD = 0.29, 95% CI = [0.09, 0.31]; t(29)=1.53, p = 0.14, 95% CI = [-0.04, 0.30]; Cohen's dz = 0.28, 95% CI = [-0.09, 0.65]) (note that 2 participants were unable to complete the painting task due to software problems or lack of time). To account for the difference in paintings viewed, we used a linear mixed model with d' as the dependent variable, condition and number of images viewed as the independent variables, and participant as a random effect. The model indicated that d′ was not different between conditions controlling for the number of images viewed (beta = 0.09, 95% CI = [-0.09, 0.28], $t(32.5) = 0.99$, $p = 0.33$). These results replicate the Threat vs. Neutral comparison in Study 2.

Summary of Post-Navigation Memory Tests

Painting recognition memory, as measured by d′, replicated results in Study 2, in which no differences between conditions were observed. Memory for map layouts was superior for the Threat condition over the Reward-Agent condition. However, these results should be considered in context of the correct response rates for Studies 1 and 2. Unlike the Reward and Neutral conditions in Studies 1 and 2, map recognition memory in the Reward-Agent condition in Study 3 fell to chance levels. Thus, unexpectedly poor performance in the Reward-Agent condition may have driven the differences observed in map layout memory. Nevertheless, Study 3 concurs with Studies 1 and 2 in finding no evidence for *impaired* map layout memory in the Threat condition. Finally, no differences were observed in the Object Placement Task for the Threat vs. Reward-Agent condition.

Together, the findings from Study 3 suggest that relational details of complex spatial environments may have been acquired in the Threat condition to some extent, evidenced by performance on the map layout and object placement memory tests. Despite the encoding of spatial aspects of the maps, threat impaired the ability to efficiently and flexibly use this information in the service of goals. Nevertheless, null differences between conditions cannot be over-interpreted, and future studies should confirm whether threat-related impairments are specific to online navigation vs. post-test measures of memory.

Summary of Post-navigation Memory Tests Across Studies 1-3

Performance on the post-navigation memory tasks was somewhat inconsistent across studies. Map layout memory was superior for the Threat vs. non-threat condition in Study 3, but not different across conditions in any other study. Furthermore, this test may have been under-powered, because each participant could only give one memory response for each of the navigated maps. Performance on the object placement task was reliably above chance in all conditions and studies, but between-condition comparisons were inconsistent. Object location memory was superior in the non-threat vs. Threat condition in Study 2, but there was no difference between conditions in Study 3. Thus, threat sometimes impairs performance on the object placement task, but not consistently, and threat never impairs (but may improve) performance on the map layout task. The impairment in object location memory in Study 2 may potentially be related to distraction by the predator, because the impairment disappeared when the non-threatening context included an actively navigating agent (the hiker in Study 3). Alternatively, the threat-related impairment in object location memory in Study 2 could have been due to unexpectedly high performance in the Neutral condition in Study 2B (compared to conditions in Study 2A; **Supplementary Figure 3**).

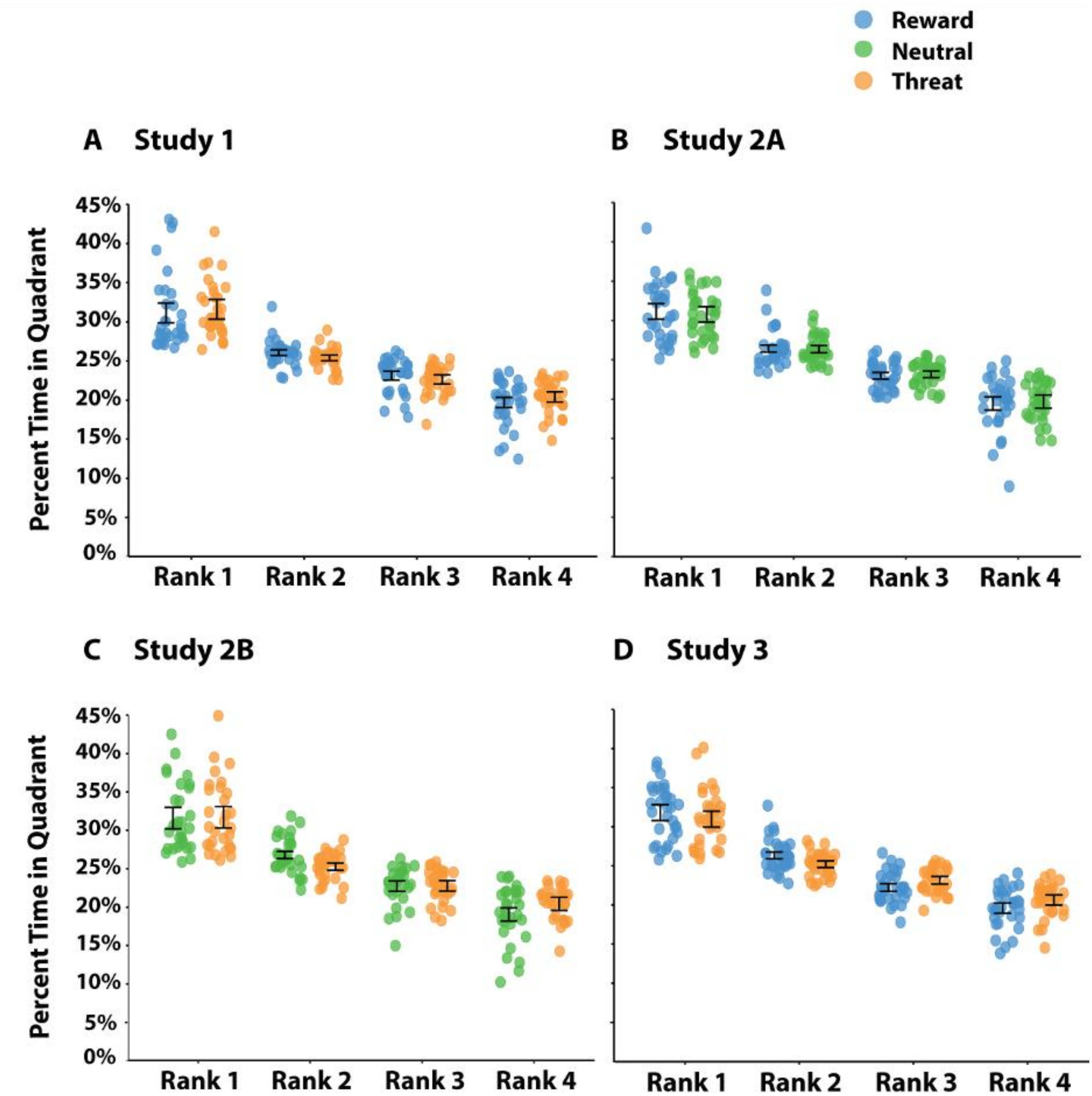
Thus, across studies, we found no consistent evidence that threat impairs relational memory (as assessed after navigation with memory tests for map layouts or object locations within them) or item-based recognition memory for incidental information (as assessed by memory for paintings). However, we caution against over-interpreting the results of these post-navigation memory tests because floor effects (i.e., for painting memory) and lower power (i.e., in map layout recognition memory) may have made it difficult for us to observe condition differences. Future studies that aim to differentiate online navigation from post-navigation memory, with equally powered tests, will be critical. Such studies will have implications for whether threat affects the *use* of relational memories or the *encoding* of these memories (Murty & Adcock, 2017).

Despite the limitations of our post-navigation memory tests, they raise interesting questions for future research that can tie together work on emotional memory and navigation. A relevant line of research comes from studies that have used emotional images to investigate how valence and arousal influence memory for central vs. peripheral details (Mather & Sutherland, 2011; also see Bisby & Burgess, 2013). For example, one study tested how the presence of emotionally arousing images affects memory for other nearby images as well as background patterns (Mather et al., 2009). This study found that emotionally arousing images led to poor memory for background details, but did not affect memory for nearby neutral images. This accords with the current study, in which recognition memory for paintings was not impaired under imperative motivational states — i.e., the presence of a threat did not affect memory for nearby, neutral images. This may be because encoding the paintings into memory is not likely to detract from performance, and under typical real-world circumstances, may indeed be useful for navigation. Painting memory was generally poor, however, leaving open the possibility that more sensitive tests with higher levels of memory performance may yield differences between threat and non-threat conditions. Future studies testing memory for central vs. peripheral details during navigation under dynamic threats vs. safety will be important for addressing this question.

The memory tasks used in our studies could also be improved in future work. For example, in the current studies, item memory was probed by assessing recognition of paintings viewed once and for a relatively brief amount of time. Other methods to probe this category of memory could include both permanent and intermittent peripheral features. Paintings could potentially be used as landmarks, making memory for them valuable if one needs to escape from threat. Such changes could also improve recognition memory overall, because memory for paintings in our studies was generally poor, and indeed not above chance in Study 1. Improving painting memory may make it more likely that impairments will be observed in the threat condition by eliminating floor effects.

Finally, the extent of overlap in memory representations and computations needed to perform the navigation task, the map recognition task, and the object placement task are unclear. We speculate that they depend on at least partly overlapping representations of spatial configuration. Nevertheless, it is certainly possible to encode relatively inflexible, piecemeal memories that are sufficient for above-chance map recognition and recall of a few object locations, while failing to encode cohesive memories that allow flexible navigation.

Supplementary Analysis: Time in Map Quadrants



Supplementary Figure 4. Time spent in different map quadrants. We conducted an exploratory analysis to determine if individuals were more likely to stick to one portion of the navigated map in the Threat vs. non-threat (Reward [Reward-Agent in Study 3] or Neutral) conditions; if so, avoidance of some map locations may contribute to poor learning and navigation. We assigned each tile (of the 13 x 13 tile maps) to one of four regions (quadrants) of roughly equal size, enabling us to assess the extent to which participants preferred to occupy specific areas of the map. We opted to do this at a quadrant rather than tile level because we felt that 169 tiles was too granular of an analysis, and that pooling data over more space might give us more power to see differences between conditions. We extracted the x, y coordinates of the participant at each sampling period (roughly 130ms) and assigned a tile number to each pair of coordinates. This allowed us to tabulate how many sampling periods were spent in each tile and quadrant, and summarize these values in terms of the percentage of time spent in each quadrant for each map. For each individual, we then sorted the quadrants from most to least preferred (i.e., most to least amount of time spent), averaged these data across participants, and finally compared the Threat vs. Reward **(A)**, Neutral vs. Reward **(B)**, Neutral vs. Threat **(C)**, and Reward-Agent vs Threat **(D)** conditions. Individuals did not explore all four quadrants equally: there were biases, such that individuals tended to spend more time in some quadrants than others (note that our analysis was designed to pick up on such a bias, because quadrants were sorted by the amount of time spent in them). However, the amount of time spent in the 'preferred' quadrant did not differ across conditions in any experiment. Thus, navigation impairments in the Threat conditions are unlikely to be due to navigational persistence in one quadrant over others. Note that participants navigated a different map in each condition (e.g., Reward vs. Threat), and quadrants are sorted by time spent in them — the identity of the preferred quadrant (e.g., Northwest) could change across participants and conditions. Error bars represent ± standard error of the within-participant condition difference.

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