Feeling the Heat? Heat Stress Impairs Landmark but Not Route Knowledge in a VR Navigation Task

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Abstract

With global temperatures rising due to climate change, heat stress is becoming an increasingly prevalent condition affecting everyday navigation. Acute heat stress is known to impair complex human cognitive functioning, including memory, attention, and executive functioning. Yet, the influence of heat stress on spatial learning during navigation remains unexplored. Therefore, we conducted a VR navigation study to assess the influence of heat stress on landmark and route knowledge acquisition. Forty-six healthy adults followed a predefined route through a VR urban environment featuring intersections with and without visually salient landmarks, under either heat stress (36–38°C) or a control condition (24.5°C). We found that heat stress significantly impaired overall landmark knowledge, especially at intersections without salient landmarks, where performance failed to exceed chance level. Route knowledge, however, remained unaffected by heat stress regardless of landmark presence. These findings provide novel empirical evidence that acute heat stress selectively impairs spatial learning, highlighting the need for further research into how rising temperatures may affect human spatial cognition during navigation.

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1 Introduction

Imagine exploring an unfamiliar city on a sweltering summer day, as many of us do as tourists. Later that day, you tell your friend about your exciting visit by trying to recall the route you walked – which landmarks you saw along the way, and which direction you turned at each intersection. Would the heat you experienced during your walk have compromised your ability to encode and retain this spatial information? Acute heat stress is known to impair complex cognitive functions, including memory, attention, and executive functioning [8, 9, 25]. With global temperatures rising due to climate change, heat stress is becoming an increasingly prevalent environmental condition affecting not only tourists in novel environments but also everyday navigation. Yet, whether and how heat stress affects spatial learning during navigation remains unexplored.

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Navigation is a complex daily activity, during which we continuously acquire spatial knowledge, broadly categorized into landmark, route, and survey knowledge [19, 23]. Landmark knowledge refers to the recognition of discrete salient features or scenes, route knowledge is knowledge about associated turning directions at landmarks or scenes, and survey knowledge integrates landmarks and routes into a common reference frame with metric information [12, 19, 23]. Landmarks serve as cognitive anchors that support the mental representation of space [5, 6, 28]. Past research has shown that wayfinders' spatial learning improves when navigating environments with visually salient landmarks compared to environments devoid of landmark information [13, 22, 27]. This benefit is attributed to modulations in attentional mechanisms whereby salient landmarks that are selectively prioritized during visual encoding are directly represented in the resulting spatial memory [10, 14, 15].

Spatial learning is also sensitive to disruption by physiological and behavioral changes induced by exposure to various stressors that can interfere with the encoding and retention of spatial information [3, 4, 21]. Acute stress has been shown to shift spatial learning from flexible, hippocampal-dependent strategies toward more rigid, habit-based stimulus-response strategies [3, 4, 21], suggesting that different components of spatial knowledge acquisition may be affected differently by stress. Acute stress can arise from psychosocial stressors, which pose a threat to the social self, such as social-evaluative or interpersonal demands, or physiological stressors of internal origin, such as illness or injury, or external origin, such as exposure to cold or hot environments [3, 25]. However, most navigation research has relied predominantly on psychosocial stressors (e.g., social-evaluative tasks) and physiological stressors such as noxious cold or physical exertion [3, 4], whereas the effects of heat stress on spatial learning remain largely unexplored. This gap is particularly relevant given rising global temperatures, especially as the effects of heat stress on cognitive functioning are well established [8, 9, 25], yet remain unknown regarding spatial learning during navigation.

Therefore, in the present study, we aimed to investigate the effect of heat stress on wayfinders' incidental spatial learning, specifically on landmark and route knowledge. Participants followed a predefined route marked by arrows that appeared on approach in a VR urban environment along 15 intersections with navigation decisions (see Figure 1). Nine of the intersections featured visually salient landmarks (e.g., churches, shops, temples), while the remaining six did not. In line with previous research on the impact of heat on cognitive performance, we hypothesized that (H1) heat stress would impair spatial learning and that (H2) the presence of salient landmarks would mitigate this negative effect on spatial learning.

2 Methods

2.1 Participants

We recruited 46 healthy adults aged 18–40 years (22 female; M age = 23.93 ± 2.36 years) with normal or corrected-to-normal vision and no history of neurological or cardiovascular disease. An a priori power analysis in G*Power for a single-predictor linear model [7], assuming a medium effect size ($f^2 = 0.20$) and a power of 0.80, estimated a minimum required sample size of $N = 42$. The sample was extended to $N = 46$ to account for potential data loss. The study was registered with the Ethics Committee of the University of Zurich (no. 25.05.14). Participants provided written informed consent and received no monetary compensation.

2.2 Design

We employed a between-subjects design with heat stress (heat vs. control) as the independent variable. Participants were evenly distributed across conditions, matched for age and gender (heat: $n = 23$, 11 female, M age = 23.91 ± 2.47 years; control: $n = 23$, 11 female, M age =

23.96 ± 2.31 years), self-reported spatial abilities (heat: $M = 3.94 \pm 0.33$; control: $M = 3.98 \pm 0.39$), and thermal sensitivity (heat: $M = 4.89 \pm 0.90$; control: $M = 4.91 \pm 1.14$), with no significant differences between conditions on any of these variables (all ps $> .770$). In each condition, participants were instructed to follow the predefined VR route and were not informed that their spatial knowledge would be tested afterward, thus ensuring incidental spatial learning. The dependent variables included performance on intersection recognition and route direction recall tasks, visual attention, electrodermal activity, and self-reported thermal comfort. In this paper, we only focus on the effect of heat stress on spatial learning (i.e., landmark and route knowledge). The remaining measures are reported in the procedure section for reproducibility purposes and will be analyzed in future work.

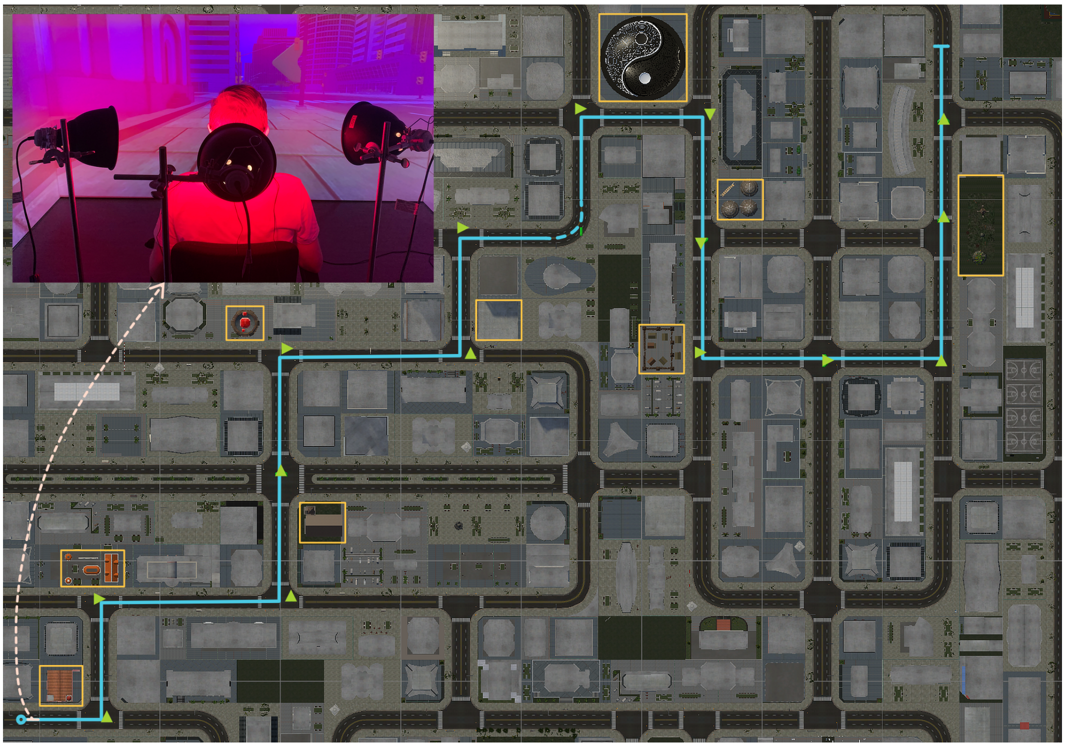

Figure 1 Overview of the VR environment depicting the predefined route (blue), the nine task-relevant landmarks (yellow), and arrows indicating the turning directions (green). The inset image shows a participant's view at an intersection enriched with a visually salient landmark.

2.3 Materials and apparatus

The VR environment depicted a city with a grid layout, modified after Bartling et al. [2], and displayed in a room-sized Cave Automatic Virtual Environment (CAVE), navigated via a foot rudder [2]. The predefined VR route comprised five left turns, five right turns, and five straight segments, for a total of 15 intersections. Nine intersections contained visually salient landmarks, such as churches, shops, and temples, whereas the remaining six had only generic high-rise buildings without distinctive visual or architectural features. To visually simulate a walk during a hot summer day, in the heat condition, we used a high midday sun illumination angle with few shaded areas, while for the control condition, the sun illumination angle was set to represent a morning walk with abundant shadows.

The heat stress was induced using three *Philips E27* infrared lamps (150 W, 230 V, 121 × 136 mm diameter) positioned to the left, right, and rear of the participant's head and neck. Each lamp was controlled by a *Ketotek KT3200PRO* thermostat, which monitored air temperature at the center of the lamp's beam. The thermostat sensors were clipped to participants' clothing, with the temperature maintained between 36°C and 42°C, to maintain consistent heat stress and to ensure safety. This resulted in an air temperature of 36–38°C around the participants' head and neck. In the control condition, the lamps remained off, and the air temperature was regulated to 24.5°C. This temperature falls within the thermal comfort ranges for temperate and air-conditioned indoor environments [1] and aligns with control temperatures used in prior heat-stress cognition research [8].

The Thermal Sensitivity Questionnaire (TSQ) was self-developed to assess participants' subjective sensitivity to heat. The TSQ measures perceived discomfort, tolerance, and behavioral and cognitive responses to heat across eight 7-point Likert scale items. Higher TSQ scores indicate higher sensitivity to heat. The TSQ showed good internal consistency in our sample, with overall Cronbach's $\alpha = .879$ and item-level values $\alpha > .852$.

The Santa Barbara Sense of Direction (SBSOD) scale was used to assess participants' spatial abilities [11]. The SBSOD measures self-reported spatial and navigational abilities, preferences, and experiences across 15 items rated on a 7-point Likert scale [11].

The intersection recognition task assessed landmark knowledge acquisition. Participants were shown images of intersections and asked if they recognized them from the traversed route. There were 15 images of intersections encountered along the route (nine with and six without landmarks), and 15 novel intersections (nine with and six without landmarks) from non-visible parts of the VR environment, for a total of 30 randomized trials.

The route direction recall task assessed route knowledge acquisition. Participants were presented with the 15 images of the traversed intersections in random order and were asked to recall the turning direction (i.e., straight, left, or right) at each intersection.

2.4 Procedure

Participants provided demographic information (age and gender) and completed the SBSOD [11] and TSQ questionnaires online, before taking part in the experiment. The responses were used to match participants across the conditions. On the experimental day, participants were welcomed in a temperature-regulated room set at 22°C where they provided written informed consent and acclimatized for 10 min. Next, they were taken to the CAVE lab and were equipped with an electrodermal activity sensor and a mobile eye-tracker. Participants were then instructed on how to use the foot pedal and practiced navigating a training VR environment for 5 min. Following this, they were instructed to walk as they would when naturally exploring a new environment and then completed the main navigation task (approx. 10–15 min). Upon task completion, the sensors were removed, and participants completed the intersection recognition task, route direction recall task, and a self-developed questionnaire on perceived thermal comfort while navigating the VR environment.

2.5 Data analyses

To assess landmark knowledge acquisition, we computed the discriminability index d' from signal detection theory (SDT; [24]) using the *psycho* package [18] in RStudio. Specifically, d' measured participants' ability to distinguish previously navigated intersections from novel distractor intersections not encountered along the VR route [16], computed separately for intersections with (i.e., nine) and without (i.e., six) landmarks. To assess route knowledge acquisition, we used the recall accuracy of turning directions (in percent).

We employed one-tailed t-tests for each condition (heat vs. control) to assess whether participants' landmark and route knowledge – for intersections with and without landmarks – were greater than chance level, i.e., d' = 0 for landmark knowledge and 46.67% for route knowledge, accounting for intersections with two (12 intersections) or three (three intersections) turning options. A Bonferroni correction was applied to adjust the alpha level for multiple comparisons, and significance was accepted at $p < .0063$ ($\alpha/k = .05/8$ chance performance tests across tasks, conditions, and landmark presence). We also employed mixed-design ANOVAs to assess the effects of heat (heat vs. control) and landmark presence (present vs. absent) on landmark and route knowledge acquisition.

3 Results

Landmark knowledge for intersections with visually salient landmarks was significantly above chance under both heat ($t(22) = 8.47,\ p < .001,\ M_{d'} = 1.66$) and control ($t(22) = 13.82,\ p < .001,\ M_{d'} = 2.01$) conditions. For intersections without salient landmarks, performance exceeded chance in the control condition ($t(22) = 7.68,\ p < .001,\ M_{d'} = 1.04$), but did not reach the Bonferroni corrected threshold ($t(22) = 1.85,\ p = .039,\ M_{d'} = 0.26$) in the heat condition (see Figure 2a). The mixed-design ANOVA revealed a significant main effect of heat stress ($F(1, 44) = 10.50,\ p = .002,\ \eta^2_G = .131$), with participants in the control condition showing overall better landmark knowledge than those in the heat condition. We also found a significant main effect of landmark presence ($F(1, 44) = 78.21,\ p < .001,\ \eta^2_G = .396$), where intersections with salient landmarks were recognized better than those without (see Figure 2a). The interaction between heat stress and landmark presence was not significant ($F(1, 44) = 2.61,\ p = .114,\ \eta^2_G = .021$).

Route knowledge for intersections with visually salient landmarks was significantly above chance under both heat ($t(22) = 6.89,\ p < .001,\ M = 70.53\%$) and control ($t(22) = 7.37,\ p < .001,\ M = 69.08\%$) conditions. For intersections without salient landmarks, performance also exceeded chance under both heat ($t(22) = 4.72,\ p < .001,\ M = 63.04\%$) and control ($t(22) = 5.93,\ p < .001,\ M = 68.12\%$) conditions (see Figure 2b). The ANOVA revealed no main effects of heat stress ($F(1, 44) = 0.25,\ p = .619,\ \eta^2_G = .003$) and landmark presence ($F(1, 44) = 1.77,\ p = .190,\ \eta^2_G = .017$), and no significant interaction effect ($F(1, 44) = 1.06,\ p = .310,\ \eta^2_G = .010$), suggesting that neither heat stress nor landmark presence affected route direction recall (see Figure 2b).

4 Discussion

The present study examined the effect of heat stress on spatial knowledge acquisition during a navigation task in an urban VR environment. We found partial support for our hypotheses that heat stress would impair spatial learning (H1) and that the presence of visually salient landmarks in the environment would mitigate this negative effect (H2). Aligning with H1, heat stress impaired overall landmark knowledge. However, while the presence of visually salient landmarks improved overall landmark knowledge, there was no significant interaction with heat stress to support H2. Furthermore, contrary to both hypotheses, route knowledge performance was unaffected by heat stress (H1) or landmark presence (H2).

The impairment of landmark knowledge under heat stress is consistent with prior broader evidence that heat stress impairs complex cognitive functions [8, 9, 25]. Under heat stress, the additional attentional demands of thermoregulation may have reduced the cognitive resources available for encoding spatial information [25]. The resource depletion argument likely accounts also for the reduced performance in recognizing previously encountered intersections devoid of visually salient landmarks, which place greater demands on memory encoding and retrieval, as these locations offer fewer perceptual cues to anchor spatial memories [13, 27]. In contrast, intersections with visually salient landmarks may have provided sufficiently distinctive visual cues to support recognition even under reduced cognitive capacity, consistent with the role of landmarks as cognitive anchors [5, 28] that guide wayfinders' attention to task-relevant information for facilitated spatial memory formation [10, 14, 15].

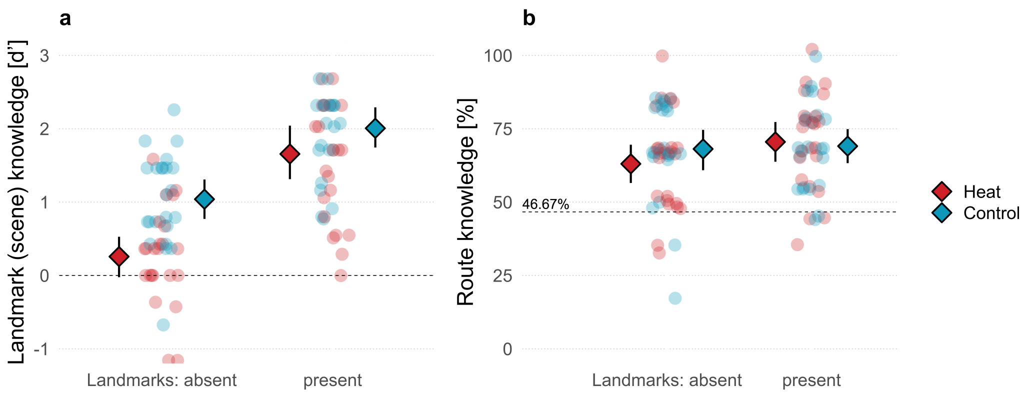

Figure 2 Heat stress impairs landmark knowledge, especially at intersections without visually salient landmarks (a), but does not affect route knowledge (b). *Note: Error bars represent 95% CIs around group means; points indicate individual data and the dashed black line shows chance level.*

The absence of heat stress effect on route knowledge suggests that the encoding of turning directions at intersections is more robust to heat stress than landmark knowledge. These findings extend previous spatial cognition research showing that route-following under psycho-physiological stress relies on habit-based stimulus-response associations that place fewer demands on cognitive resources at the expense of a flexible hippocampal-dependent spatial memory system [3, 4, 21]. Notably, route knowledge acquisition was not affected by the presence or absence of visually salient landmarks. Previous studies have shown that scenes and objects are stored similarly in visual memory [17], suggesting that entire scenes function as landmarks and can be recognized even when visually distinct features are absent [20]. This may be supported by pattern completion, a memory retrieval mechanism that enables the recognition of previously encountered scenes even from partial or degraded visual cues [26]. Additionally, the selective impairment of landmark but not route knowledge is consistent with the findings that heat stress affects cognitive performance differently depending on task type and complexity, exposure duration, and air or core body temperature [8, 9, 25].

Limitations and future work

Given that we present preliminary results on the effect of heat stress on spatial learning, several limitations should be acknowledged. First, heat stress was localized to the head and neck area, which may have resulted in more moderate cognitive effects compared to full-body hyperthermia [8, 9]. Second, we induced heat stress via infrared lamps, increasing the air temperature directly around participants to 36–38°C. Cognitive function is generally unaffected unless heat stress is sufficient to increase core body temperature beyond its homeostatic range, approximately 37°C [8, 25]. Future work should thus investigate whether increased heat intensity impacts spatial learning. Finally, the present study assessed landmark and route knowledge but not survey knowledge. Given that heat stress impairs cognitive tasks disproportionately based on their complexity [25], survey knowledge may be even more vulnerable to heat stress than landmark and route knowledge. This warrants investigation in future research. Next, we plan to analyze the collected electrodermal activity and visual attention data to assess the effect of heat stress on physiological responses, visual attention behavior, and whether visual attention patterns predict spatial learning performance [14, 15].

5 Conclusions

This study provides novel evidence that heat stress selectively impairs landmark knowledge acquisition during navigation, particularly at intersections lacking visually salient features, while leaving route knowledge intact. These findings suggest that heat stress depletes the cognitive resources required for encoding spatial features, while embodied, stimulus-response-based route knowledge remains unaffected. As temperatures continue to rise, understanding how heat stress shapes spatial learning becomes important for designing resilient urban environments and adaptable navigation assistance that supports our daily navigation needs.

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