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Evaluating Navigation Behavior in Urban Heat: A VR-Based Study on Pedestrian Spatial Learning and Thermal Comfort

GEO 511 Master's Thesis

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Abstract

With increasing urban heat exposure driven by climate change, understanding how thermal stress affects spatial cognition is ever more critical for designing climate-resilient cities and navigation systems. While thermal stress impairs various cognitive domains, its specific effects on landmark-based spatial memory formation during navigation remain unexplored. This thesis addresses this gap by presenting a study that investigates how thermal stress (36-38°C) affects the development of landmark-based spatial memory, visual attention allocation, and physiological arousal during urban navigation in a controlled virtual reality environment.

The present study used a between-subject design (N = 46: 23 per condition) in a CAVE environment with infrared lamps as thermal manipulation. Participants traversed a uniform 15-intersection urban route under either control conditions (24.5°C, morning lighting) or heat stress (36-38°C, noon lighting). Spatial memory performance was assessed using signal detection theory (SDT) measures for intersection recognition and route direction recall. Visual attention was measured with eye tracking, assessing participant gaze on four regions of interest: Landmarks, Intersections, Navigation Arrows, and Environment. Electrodermal activity measured the participant's physiological arousal on baseline, experiment trials, and road decision points.

Results revealed a selective dissociation: thermal stress significantly impaired landmark-based intersection recognition (discriminability d' reduced by 0.63 units, p = .002; false alarm rate elevated by 13.3%, p = .006), while route direction memory remained intact (Heat: 67.54% vs. No-Heat: 68.70%, p = .751). Analyses of eye-tracking data demonstrated that the memory impairment was accompanied by an overall reduction in attention to all landmarks, with a 35.7% reduction in fixation on landmarks under heat (p < .001). Crucially, fixation duration on landmarks predicted the sensitivity of intersection recognition performance (r = .62, p < .001) but not the accuracy of route direction memory (r = .15, p = .33), highlighting the attention-related specificity of memory performance. Contrary to arousal-based hypotheses, electrodermal activity showed no significant elevation under thermal stress at baseline, trial-level, or intersection-specific decision points, suggesting that cognitive resource depletion rather than physiological arousal drives the observed deficits.

These findings advance the understanding of spatial cognition by demonstrating that different parts of spatial knowledge acquisition react differently to environmental stressors: While recognition-based, attention-engaged memory declines during thermal load, procedural route memory remains unaffected. The cognitive resource competition model proposed here refines existing thermal stress frameworks by identifying visual attention as the limiting factor and identifying what aspects of cognition are most affected. There are numerous application levels for this research in the field of urban geography, GIScience, and public health, ranging from the implementation of heat-aware navigation systems to designing climate-resilient cities and occupational safety protocols that support cognitive resilience in warming cities.

Keywords: thermal stress, spatial memory, landmark-based navigation, visual attention, eye-tracking, electrodermal activity, virtual reality, urban heat island, climate adaptation

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Chapter 1

Introduction

1.1 Motivation

With the exponential global rise in temperature and rapid urbanization, people in urban areas find themselves increasingly exposed to extreme thermal environments in their daily lives. This is further intensified by Urban heat islands (UHI), which transform routine outdoor activities into challenges and limit urban accessibility (United Nations 2018). While heat-related health issues such as heat exhaustion or dehydration are widely recognized, the relationship between thermal stress and cognitive functioning is not clearly established, especially in active mobility tasks of navigation (Hancock, Ross, and Szalma 2007). Safe and independent wayfinding is a fundamental need that relies on directed attention, spatial encoding, and memory-guided decision-making, which may be weakened under thermal stress (Taylor et al. 2016).

This research gap is becoming increasingly critical, since navigation itself is more than just physical relocation and must also include the cognitive process of learning and interpreting the environment. Current research literature on thermal stress has largely focused on general cognitive domains like working memory or sustained attention, often in static laboratory settings. Conversely, spatial cognition research typically assumes neutral, comfortable environments, neglecting the reality that real-world navigation often occurs under significant physiological strain. Thus, there is no current understanding of how thermal stress affects the cognitive mechanisms underlying spatial learning during navigation.

This issue is addressed for the application of both public good and scientific purposes, in support of the United Nations Sustainable Development Goals (SDGs) (United Nations 2015). SDG 11 (Sustainable Cities and Communities) aims to provide safe, inclusive, and accessible green public spaces, yet rising urban temperatures threaten the accessibility of these spaces for pedestrians (Deilami, Kamruzzaman, and Liu 2018). SDG 3 (Good Health and Well-being) aims to improve mental and cognitive health, which are directly challenged by environmental stressors. Finally, SDG 13 (Climate Action) calls for urgent measures to combat climate change and its impacts; understanding the cognitive cost of heat is essential for designing resilient adaptation strategies that go beyond physical infrastructure. If thermal stress depletes the attentional resources needed for spatial navigation, then pedestrians, especially vulnerable groups, may have increased risk of disorientation and wayfinding errors during heatwaves. This study addresses this motivation by isolating the effects of heat on spatial memory formation and investigating the underlying attentional and physiological pathways, providing empirical evidence to inform safer, climate-resilient urban mobility.

1.2 Goals

The main goal of this study is to explore the impact of thermal stress with temperatures of about 36-38°C on the development of landmark-based spatial memory in navigation tasks in a virtual urban environment. Moreover, it tries to clarify whether heat-related deficits in navigation are caused by impairments in the processing of landmarks or memory loss of route instructions with regard to turns. By distinguishing between these factors, this study clarifies whether thermal stress causes global cognitive impairment or selectively affects attention-related spatial cognition.

To achieve this, the study employs a multimodal experimental design with a controlled immersive virtual reality setup. In addition to measuring memory performance through behavioral data, this study also aims to understand the underlying cognitive mechanisms by measuring both visual attention using eye tracking and autonomic arousal using Electrodermal Activity (EDA). This combination allows for a precise investigation into whether performance decrements are driven by a strategic reallocation of visual attention, a general depletion of attentional capacity, or an increase in autonomic stress arousal. Ultimately, this research seeks to propose a cognitive resource mechanism that explains how environmental heat constrains human wayfinding capabilities, providing a foundation for designing heat-aware navigation systems that support cognitive resilience in warming cities.

1.3 Research Questions and Hypotheses

Based on the motivation and the overall goal, this thesis is structured around one overarching research question and three sets of more specific subquestions. Together, these address how thermal stress in a virtual urban environment affects landmark-based spatial memory and how any such effects are reflected in patterns of visual attention and physiological arousal.

1.3.1 Main Research Question

How does thermal stress, relative to neutral thermal conditions, during navigation in an urban virtual reality environment shape the development of landmark-based spatial memory and the associated patterns of visual attention and physiological arousal?

This overarching question is unpacked into three thematic clusters: spatial memory, visual attention (eye tracking), and physiological arousal (electrodermal activity).

Spatial Memory

RQ1a – Landmark Recognition (Intersection Memory)

How does thermal stress impact intersection recognition performance for the previously navigated route in a post-navigation recognition test, as quantified by signal detection theory measures (discriminability d', hit rate, false alarm rate)?

RQ1b – Route Direction Memory

What differences emerge in route direction accuracy at intersections between thermal stress and neutral conditions, and how do these differences depend on landmark presence?

From these questions, the following working hypotheses are derived:

- **H1a – Intersection Recognition Under Heat**
  Thermal stress reduces intersection recognition sensitivity, reflected in lower discriminability (d'), lower hit rates, and higher false alarm rates compared with neutral thermal conditions.
- **H1b – Route Direction Accuracy Under Heat**
  Compared with neutral thermal conditions, thermal stress reduces route direction accuracy, although performance in both groups remains clearly above the weighted chance baseline.
- **H1c – Landmark Buffer**
  Intersections with salient landmarks show higher route direction accuracy than non-landmark intersections in both conditions, with this landmark buffer being larger under thermal stress.

Visual Attention

RQ2a – Visual Attention Allocation

How does navigation under thermal stress change visual attention allocation within different Areas of Interest (Landmarks, Intersections, Navigation Arrows, Environment) during navigation in the virtual urban environment?

RQ2b – Attention-Performance Relationship

How does visual attention to landmarks and intersections relate to performance in intersection recognition and route direction accuracy, and how do these relationships vary across thermal conditions?

From these questions, the following working hypotheses are derived:

- **H2a – Reduced Attention to Spatial Anchors Under Heat**
  Thermal stress reduces visual attention towards spatial anchors, which is reflected in lower normalized fixation duration on Landmark and Intersection Areas of Interest compared with neutral thermal conditions.
- **H2b – Shift Towards Navigation Aids Under Heat**
  Thermal stress increases visual attention to navigation aids, reflected in higher normalized fixation duration on the Arrow Area of Interest compared with neutral thermal conditions.
- **H2c – Visual Attention $\leftrightarrow$ Memory Association**
  Higher visual attention to landmarks, seen as higher normalized fixation duration on the Landmark Area of Interest, relates to better intersection recognition sensitivity and higher route direction accuracy for both thermal conditions.

Physiological Arousal

RQ3a – Trial-Level Arousal Under Thermal Stress

How does thermal stress change overall physiological arousal during the navigation trial, indexed by tonic skin conductance level and skin conductance response rate, compared to neutral thermal conditions?

RQ3b – Intersection-Level Arousal

How does physiological arousal, indexed by tonic skin conductance level and skin conductance response rate within decision windows, change at intersections based on thermal condition and landmark presence?

RQ3c – Temporal Dynamics of Arousal

How do patterns of physiological arousal evolve across different navigation phases at intersections (baseline approach, decision phase, execution phase), and how are these temporal dynamics affected by thermal conditions and the presence of landmarks?

From these questions, the following working hypotheses are derived:

- **H3a – Trial-Level Arousal Under Heat**
  Navigation under thermal stress results in higher tonic skin conductance levels than navigation under neutral conditions.
- **H3b – Intersection-Level Arousal**
  At intersections, thermal stress increases mean skin conductance level and skin conductance response rate, with higher arousal for landmark intersections than for non-landmark intersections in both conditions.
- **H3c – Temporal Dynamics of Arousal**
  Thermal stress leads to stronger cue reactivity (larger increases in skin conductance from baseline to decision) and reduced action settlement (less return towards baseline from decision to execution), with these dynamic changes being more pronounced at landmark intersections.

Chapter 2

Related Work

The related work section of this thesis focuses on the theoretical foundations and methodological concepts necessary to understand thermal stress effects on landmark-based spatial memory formation during navigation.

2.1 Spatial Learning and Navigation

Spatial learning refers to the cognitive process of individuals acquiring, encoding, and storing knowledge about the layout of an environment, typically while navigating in the environment. This fundamental cognitive function enables humans to navigate efficiently through both familiar and novel environments, forming the basis for successful wayfinding (Chrastil and Warren 2012; Hegarty, D. R. Montello, et al. 2006; Wolbers and Hegarty 2010).

2.1.1 Frameworks of Spatial Knowledge Acquisition

Classic frameworks such as Siegel and White (1975) proposed that spatial learning progresses through three sequential hierarchical stages: landmark knowledge, route knowledge, and survey knowledge. Initially, individuals identify and memorize landmarks (defined as salient, recognizable environmental features serving as reference points and cognitive anchors). Subsequently, navigators will develop route knowledge by remembering the sequence of movements, turning directions, and landmark-direction associations that connect multiple locations. Finally, individuals form survey-knowledge as they develop a comprehensive, integrated understanding of the spatial layout of an environment. This hierarchical progression from landmark recognition to survey knowledge formation has been the backbone of spatial cognition research for decades.

However, newer research challenges the strictly sequential model, suggesting instead that different types of spatial knowledge may be acquired simultaneously rather than in discrete stages (Ishikawa and D. Montello 2006). D. R. Montello (1998) argued that the distinction between route and survey knowledge exists on a spectrum, rather than categorically different forms of representation, and therefore both may be developed in parallel during exploration. This parallel acquisition is further supported by recent empirical evidence. Kim and Bock (2021) found that route and survey knowledge emerged already during a navigation task, contradicting the assumption of hierarchical stage-based learning. Similarly, a study examining landmark, route, and survey knowledge acquisition during wayfinding tasks demonstrated that participants developed multiple forms of spatial knowledge simultaneously. This evidence suggests that individual differences are the key determining factor of the relative strength of each type, rather than their temporal order (Weisberg et al. 2014).

The shift from a strict sequential to a parallel framework has important theoretical implications. With the newer framework, landmarks and routes can be conceptualized as complementary and simultaneously accessible forms of spatial information (Wolbers and Hegarty 2010). Consequently, reliance on specific spatial information depends on individual preferences, task demands, personal spatial abilities, and environmental characteristics (Ishikawa and D. Montello 2006). This newer perspective is also of particular interest when trying to understand how environmental stressors, such as heat, might differentially affect the parallel acquisition, storage, and retrieval of multiple spatial knowledge types.

2.1.2 Spatial Learning in Wayfinding: Importance of Landmarks

As established in the previous section, landmarks serve as fundamental elements in spatial cognition, providing a reference point to anchor spatial representations and facilitate route learning (Caduff and Timpf 2008). For landmarks to be effective, they must be salient and recognizable features, as they help to segment the route into manageable units and reduce decision uncertainty at critical navigation points, such as intersections where a direction choice is required (Karimpur, Röser, and Hamburger 2016). Furthermore, research also shows that the position of these landmarks relative to the decision point can critically influence the encoding and subsequent retrieval of the turning direction information. These positional effects are explored in detail in the following subsections.

Landmark Positioning

Karimpur, Röser, and Hamburger (ibid.) investigated in detail how landmark positioning at intersections affects route memory, revealing that landmarks positioned along the line of travel in the route, particularly at or immediately before an intersection, are encoded and retrieved differently compared to landmarks at other positions. Their findings also demonstrated a significant directional asymmetry in path-related memory. Participants showed a better memory for landmarks encountered during their initial route learning when compared to the return journey, suggesting that the perspective, relative to the landmark, influences the landmark salience and encoding mechanism. This finding reflects what is termed structural landmark salience, which is a result of the visibility of landmarks at intersections, making certain environmental features more effective as navigational cues than others.

Landmark-Based Navigation

These laboratory findings from above have been extended to real-world studies, which demonstrated that landmark-augmented navigation instructions resulted in better incidental spatial knowledge acquisition. Wunderlich and Gramann (2021) showcased that including landmark information in turn-by-turn navigation instructions significantly improved participants' ability to recognize set landmarks and reproduce routes more easily without assistance in real-world urban environments, compared to standard GPS-style direction instructions (ibid.). Furthermore, this effect extends to work across multiple modalities as established through two separate experiments: in the first, participants watched a first-person video of the route, while in the second, they physically walked the same route in the actual urban environment. In both conditions, landmark-augmented instructions led to consistently enhanced landmark recognition and route knowledge, indicating that the cognitive benefits of landmark-based guidance persist whether the environment is experienced via video simulation or physical navigation.

The long-term retention of landmark-augmented spatial learning has been demonstrated through subsequent retention studies. Wunderlich, Grieger, and Gramann (2023) showed that the inclusion of landmark information in turn-by-turn navigation instructions stimulated lasting route knowledge that persists up to three weeks after the initial navigation. Participants who received landmark-based navigation instructions exhibited superior performance in free recall of landmarks, cued recall tasks, and route reproduction compared to the participants receiving standard instructions, even when tested several weeks after the initial navigation (ibid.). These findings underline that small modifications in navigation assistance, in this case, auditory augmentation of salient landmarks at intersections, can fundamentally enhance the depth and persistence of incidental spatial learning.

Attentional Mechanism during Landmark-Based Navigation

The findings above were then expanded on by employing mobile eye-tracking during real-world navigation, which revealed the underlying attentional mechanisms behind landmark-based spatial learning. Kapaj, Hilton, Lanini-Maggi, et al. (2024) demonstrated that the landmark visualization style on mobile maps affects not only visual attention allocation but also subsequent spatial learning processes in outdoor environments. When the landmarks were depicted in a realistic 3D texture rather than an abstract 3D model, participants with low spatial ability had an increased fixation duration on the actual landmarks in the environment, which allowed them to have better knowledge of directions between the landmarks (ibid.).

Furthermore, similar research examining landmark presence and quantity in virtual environments found that increasing the number of landmarks during route learning improved the memory performance of participants (Cheng, Wunderlich, et al. 2022). This relationship, however, showed diminishing results beyond an optimal threshold of landmarks per distance, suggesting that there might be a cognitive saturation point, where additional landmarks no longer benefit spatial learning without taxing further cognitive resources. This inverted-U relationship between landmark density and learning performance reflects fundamental constraints in attentional capacity and working memory resources. When landmark load exceeds cognitive capacity, resources become fragmented, reducing the encoding quality of individual landmarks and their spatial relationships.

Collectively, research on landmark positioning, landmark-based navigation assistance, and visual attention mechanisms has a consistent finding: landmarks at decision points function as cognitive anchors that structure route knowledge and support navigation performance. The resulting theoretical framework from this research, therefore, suggests that landmark direction associations formed at intersections create the fundamental building blocks of route knowledge (Karimpur, Röser, and Hamburger 2016; Wunderlich, Grieger, and Gramann 2023). This framework has direct implications when trying to understand how environmental stressors, such as thermal stress, might impact navigation. Specifically, if environmental stressors, such as thermal stress, compete for cognitive resources needed for environmental processing, then strategically positioned landmarks may serve a compensatory role. By providing perceptually salient, easily encoded spatial information, strong landmark cues at structurally salient intersections could maintain navigation performance even when overall cognitive capacity is compromised by heat stress.

2.2 Thermal Stress and Cognition

To understand how landmarks might function under thermal stress, first, it has to be established what thermal stress is and how it affects cognition more broadly. Environmental stressors significantly influence cognitive performance across multiple domains. Thermal stress can be defined as elevated ambient or radiant temperatures sufficient to induce physiological strain. It has been demonstrated to impair various cognitive functions, including attention, working memory, executive function, and decision-making (Hancock, Ross, and Szalma 2007; Taylor et al. 2016). While both heat and cold represent thermal stressors, the present work focuses exclusively on the effects of heat exposure; cold-induced thermal stress is not examined here. These cognitive impairments have important implications for individuals navigating warm or hot environments, as discussed in the sections below.

2.2.1 Thermal Comfort Standards and Measurements

Thermal stress can be conceptualized as the combination of physiological and cognitive load that competes against task-specific allocated resources. Modern standards such as the ASHRAE Standard 55 (2017) define thermal comfort zones for humans and establish temperature baselines against which thermal stress can be evaluated. For seated indoor activities, the ASHRAE55 standard suggests an acceptable temperature range from approximately 20°C to 26°C. This range, however, can vary depending on various factors, including clothing, metabolic rate, air movement, and individual acclimatization differences (ibid.). Deviations from these "neutral" conditions toward thermal stress activate thermoregulatory responses that impose metabolic and attentional demands, potentially interfering with concurrent cognitive tasks. For outdoor tasks, the wet bulb globe temperature (WBGT) developed by Yaglou and Minard (1957) for the United States military remains the foundational standard metric for quantifying occupational thermal stress. WBGT combines ambient temperature, humidity, and radiant heat into a single composite measure, enabling predictions of physiological strain and performance decrements (ibid.).

2.2.2 Thermal Stress Effects in Occupations

Understanding thermal stress effects from occupational research provides important context for navigation studies. Occupational contexts (military, firefighting, outdoor labor) represent high-stakes environments where thermal stress effects on cognition have been rigorously studied because performance failures have direct safety consequences. Military personnel and firefighters exemplify this population, as both are routinely exposed to extreme thermal conditions while performing cognitively demanding

tasks that require sustained attention, decision-making, and executive function. Studies of firefighters following a realistic training exercise, which involved temperatures exceeding 200°C, revealed mixed but generally negative effects on cognitive performance (Thompson et al. 2024). A systematic meta-analysis across 528 effect sizes from thermal stress studies also confirmed the substantial negative effects on performance, with cognitive tasks being less severely impaired than psychomotor and perceptual tasks (Hancock, Ross, and Szalma 2007). Furthermore, there is also research on how to limit these cognitive deficits. Parsons, Stacey, and Woods (2019) demonstrated how military personnel use heat acclimation protocols, which involve repeated exposure to elevated temperatures over consecutive days, suggesting adaptive neuro-physiological changes that enhance thermal tolerance. The findings from the above high-stress occupational studies establish that thermal stress leads to cognitive challenges even for physically fit and trained individuals, supporting the ecological relevance of investigating heat effects on civilian navigation tasks.

2.2.3 Thermal Stress in Pedestrian Navigation

Research on outdoor thermal comfort has identified high temperatures as causing both perceived discomfort and behavioral responses that impact mobility behavior. Lai et al. (2014) conducted extensive field studies in northern China, which have demonstrated that outdoor thermal stress, evaluated by indicators such as physiological equivalent temperature (PET), can have a considerable effect on pedestrians' route choice, walking speed, and intention to stay outdoors. As thermal stress increases, individuals exhibit marked behavior changes, including reducing walking duration, taking routes that pass through shaded areas despite increased distance, and avoiding outdoor exposure during peak heating times (ibid.).

The effect of thermal stress on navigation is further increased by the Urban Heat Island (UHI) effect, which has direct consequences for health and mobility in urban environments. Deilami, Kamruzzaman, and Liu (2018) and Deilami, Rudner, et al. (2020) documented how higher urban temperatures are associated with reduced vegetation and increased impermeable surface exposure and therefore create spatial patterns of heat exposure. This UHI leads to systematic navigation behavioral change and alters the paths taken by individuals. Their research further revealed that this is disproportionately the case for heat-vulnerable populations, which alter their travel timing, reduce their walking trips, and shift toward motorized transportation to minimize heat exposure (Deilami, Kamruzzaman, and Liu 2018; Deilami, Rudner, et al. 2020). These behavioral responses reflect a standard cost-benefit analysis in which the cognitive and physiological burden of heat exposure outweighs the benefits of active travel.

Heat-Aware Route Navigation

Recent work has developed and assessed heat-aware navigation systems, which take thermal considerations into account, and represent a significant step towards addressing the gap between observed behavioral adaptations and actionable guidance for pedestrian navigation. Feng et al. (2024) developed a shadow-focused navigation tool that combines manually corrected OpenStreetMap pedestrian paths with 3D city models. With the use of ray tracing technology, they simulated real-time shadow distribution and variation over time and computed optimized routes to avoid heat exposure as much as possible. This approach's primary strength lies in its dynamic simulation of shadow conditions at a high spatial resolution, enabling detailed route-level shade quantification. However, this strength also presents scalability challenges, particularly regarding computational resources. The manual correction of the pedestrian network and the shadow modeling are too resource-intensive to scale to large geographic areas. Additionally, while the system can identify shadow paths, it omits other environmental factors which also contribute to thermal stress, such as wind speed or radiant heat exposure from surfaces (ibid.).

Neset et al. (2022) employed a different approach by using satellite-derived land surface temperature data (LST) in combination with pedestrian routing algorithms to create their "WayfinderHeat" prototype. The tool uses thermal data gathered from satellite imagery to determine UHI and cooler spots, and based on the information, it suggests to the user the route with the least amount of heat exposure. The primary advantage of this prototype is its data accessibility, solely relying on open-access data which covers the majority of the globe, enabling deployment across diverse geographic contexts (ibid.). However, the system's critical limitation is its exclusive reliance on static LST data, which cannot account for real-time environmental changes, such as the movement of shadows or heat distribution throughout the day. The tool was assessed in two Swedish cities (Norrköpping and Linköping) and Porto, Portugal, where the summer temperatures were relatively mild, with 20-22 °C in the Swedish cities and 26°C in Porto. These

conditions are not representative enough for extreme heat conditions, which are faced by many in urban areas already globally today (Neset et al. 2022; United Nations 2018).

Both studies (Neset et al. 2022 and Feng et al. 2024), however, face the same methodological limitations, as both lack consideration of demographic factors or spatial learning discrepancy between the participants. Both studies focused more on functionality and usability evaluations, as opposed to testing any potential effects of age, gender, sensitivity to heat, sense of direction, or individual physiological parameters on navigation preferences. For instance, older adults or individuals with medical conditions may prioritize routes with accessible resting points despite increased distance or heat exposure, whereas younger, healthier individuals might prioritize speed over comfort (Deilami, Rudner, et al. 2020). Despite these issues, however, these two studies mark significant milestones towards incorporating thermal environment information into more sustainable urban mobility systems, marking fulfillment of United Nations Sustainable Development Goal number 11 (United Nations 2015), dedicated to sustainable cities and communities.

2.3 Virtual Reality as a Controlled Platform for Thermal Manipulation

Virtual reality (VR) provides a powerful methodological approach for creating controlled environments to investigate spatial cognition and navigation while ensuring ecological validity (Loomis, Blascovich, and Beall 1999; Wolbers and Hegarty 2010). The systematic manipulation and isolation of specific visual environmental factors that might influence spatial learning make VR particularly valuable, as it eliminates confounding variables that would be present in real-world studies. The conceptual foundation for such immersive systems can be traced back to Sutherland (1965), who proposed a framework referred to as the "Ultimate Display", a system which would be so powerful that it could control the existence of matter. The idea of the Ultimate Display has provided a foundation for modern-day research in the areas of virtual reality, highlighting the need for controlled but believable environments. The advancements achieved today, starting from head-mounted systems to projection systems, can be considered as a step towards this concept of fully interactive virtual environments.

Of particular relevance for spatial navigation research is the Cave Automatic Virtual Environment (CAVE) system. CAVE systems surround participants with either three (Caverns) or six large projection surfaces (full immersive system), providing a wide field of view without requiring cumbersome headgear that might induce additional discomfort (Cruz-Neira et al. 1992). The open architecture of CAVE systems facilitates multiple integrations, particularly the integration of thermal stimuli (i.e., heat lamps or fans) positioned to affect participants uniformly without obstructing their movements or vision. In this sense, the CAVE represents a practical realization of Sutherland's original vision, a controllable, multisensory virtual environment that merges perceptual realism with experimental precision.

2.3.1 Thermal Virtual Reality

Hülsmann et al. (2014) pioneered the approach of combining virtual reality with thermal perception research in a CAVE system by incorporating infrared heat lamps and airflow generators in a CAVE system. They further demonstrated that thermal stimuli could be delivered synchronously with visual scenes without compromising tracking accuracy or sense of presence. Their system used ceiling-mounted infrared heat lamps to provide radiant heat and adjustable fans to modulate convective heat transfer, enabling precise control over participants' thermal experience while they navigated virtual environments. Crucially, their systems also demonstrated that the heating system did not meaningfully interfere with the optical tracking systems used in the CAVE system, allowing for a wide range of usability. Further, their study also showcased user acceptance and indicated a strong positive influence of wind warmth stimuli on the perceived presence.

Physiological and Perceptual Validity of Thermal VR

The ecological validity of thermal perception in VR has been empirically validated through comparative studies, which examined the physiological and subjective responses in virtual compared to real environments. Yeom, J. H. Choi, and Kang (2019) tested the thermal perception of participants in VR, measured through thermal sensation votes and physiological indicators such as skin temperature and heart rate,

and matched them to values from participants in real-world spaces, which indicated comparable patterns. Most importantly, they found a slight amplification in thermal sensation for the VR participants, which might be the result of the absence of thermal feedback. Nevertheless, this research established the foundation for further thermal virtual reality studies, as it demonstrated that when appropriately implemented, virtual environments can provide authentic thermal experiences that engage similar physiological and perceptual mechanisms as real-world thermal exposure.

Further studies showed similar evidence for physiological coupling between virtual scenes and thermal responses. Z. Lin et al. (2024) examined how the visual characteristics of virtual environments modulate thermoregulatory responses and found that virtual scenes depicting vegetation, shade, and water features extracted measurable changes in participants' heart rate variability and skin conductance, even when ambient temperature remained constant. These findings, therefore, suggest strong coupling between visual cues associated with thermal properties and actual physiological responses. These responses can be traced back to learned associations between environmental features and thermal states (ibid.). This coupling of visual scene content with physiological arousal further underlines that VR can engage the same perception-physiology linkages that operate in real environments.

Beyond direct perceptual validity, other research has confirmed that thermal manipulations in VR have the same cognitive consequences similar to those observed under real-world thermal stress. Erkan (2021) analyzed this connection by focusing on ambient temperatures on architectural liking. Their study found a clear connection, as participants experiencing thermal stress also expressed lower architectural liking, compared to the baseline group. Although it is not directly related to navigation, the study further established the principle that thermal conditions in VR environments exert measurable effects on cognitive processing, attention allocation, and performance, which are comparable to those in real-world studies.

2.4 Visual Attention and Cognitive Load During Navigation

Recent spatial cognition research has increasingly used multimodal measurement approaches that combine behavioral, physiological, and neural indices to provide comprehensive insights into the complete navigation process. As spatial information acquisition happens in large parts through the visual sense, studying the visual attention and its connection to cognitive processes has been the interest of many research efforts in spatial cognition over the years (Kiefer, Giannopoulos, Raubal, and Duchowski 2017). Eye-tracking technology offers easy and direct access to visual attention allocation, revealing crucial information necessary to understand how individuals select and process environmental information during route learning and wayfinding.

2.4.1 Pupil Diameter and Blink-Related Neural Activity as an Index of Cognitive Load

Pupil diameter has emerged as a particularly sensitive physiological measurement for cognitive load during spatial tasks. Kiefer, Giannopoulos, Duchowski, et al. (2016) found significant evidence that pupillary response systematically increases with increasing task demand, connecting higher cognitive load with larger pupil dilation. To come to these findings, their study tested participants on six different map-based tasks: free exploration, search, route planning, focused search, line following, and polygon comparison. The results indicated low cognitive load for free exploration, medium cognitive load for search, polygon comparison, and line following, and high cognitive load for route planning and focused search (ibid.). This significant correlation between pupil diameter dilation and cognitive load enables real-time assessment of workload during navigation without the need for subjective self-reported questionnaires and therefore allows for measurement with no interference.

In addition to pupil diameters, measures such as spontaneous eye blinks, which are not fixation-based, have also been proven to reflect cognitive processes. Research has found that spontaneous eye blinks are associated with cognitive load, particularly during the processing of complex visual scenes (Cheng, E. Lin, et al. 2023; Valtchanov and Ellard 2015; Wascher, Heppner, and Hoffmann 2014). In detail, eye blinks are found to increase with a higher frequency following a blink suppression period (e.g., after attentional focus) or after a mode switch (e.g., attention shift re-allocation) and are thus identified to represent attentional allocations (Wascher, Arnau, et al. 2022). When combined with synchronized electroencephalography (EEG), blink-related brain potentials (bERPs) can be measured and show the connection between blinks and cognitive load Cheng, E. Lin, et al. (2023).

2.4.2 Areas of Interest Analysis and Gaze Fixation Patterns

The analysis of Areas of Interest (AOI) provides a clear, structured framework for quantifying attention allocation across functionally relevant categories of visual information during navigation. By defining AOIs that correspond to specific environmental features (i.e., landmarks, environment, navigation aids), related metrics such as fixation duration, fixation frequency, and gaze sequences can be computed, which can unveil strategic patterns of visual attention (Kiefer, Giannopoulos, Raubal, and Duchowski 2017).

Eye movements, in the context of scene viewing, can be broken down into two main basic components: fixations (positions on which the eye is paused for an extended period) and saccades (rapid movements between fixations). The framework established by Just and Carpenter (1976) suggests that the visual information is only processed during fixations, and that during saccades, the visual system in the human brain is suppressed and unable to process new visual information. Consequently, the human visual system alternates between saccades and fixations to complete the perception of scenes as validated by modern eye-tracking research (Kiefer, Giannopoulos, Raubal, and Duchowski 2017; Orquin and Holmqvist 2019). This process can be used to identify the regions responsible for cognitive processing by analyzing the fixations, as they are tied to visual attention and cognitive state (Kiefer, Giannopoulos, Raubal, and Duchowski 2017).

Further research has demonstrated that strategic attention allocation during navigation depends critically on both the navigational context and the cognitive demands imposed by the task. Liao et al. (2017) examined the visual attention difference between 2D maps vs 3D geo-browsers in three different processes of pedestrian navigation (self-localization, spatial knowledge acquisition, and decision-making) in digital environments. Their study revealed that participants using 3D geo-browsers had extensive visual search patterns, resulting in significantly longer response times for initial spatial knowledge acquisition compared to 2D map users. This inefficient knowledge acquisition was attributed to information overload and obstructed views inherent in 3D representations. However, the 3D group showed better and more efficient performance in self-location and orientation at complex decision points, when compared to the 2D group. These findings underscore that fixation patterns during navigation reflect the underlying cognitive processes of spatial information encoding, and quantitative metrics such as scanpath length, fixation duration, and saccade count provide complementary insights into both search efficiency and processing depth (ibid.).

2.4.3 Eye-Tracking in Navigation

Eye-tracking technology has been extensively applied in navigation research to investigate visual attention distribution during navigation and wayfinding, particularly under different cognitive demands. Multiple studies have demonstrated that participants trained for different orientation strategies will also have different distributions of visual attention, with eye movements in scenes containing salient 3D landmarks tend to focus strongly on those features (Gunzelmann, Anderson, and Douglass 2004; Peebles, Davies, and Mora 2007). Kiefer, Giannopoulos, and Raubal (2014) conducted a landmark-based self-localization real-world study, where they examined visual attention differences between participants. Their study identified that successful participants focused on helpful map symbols and correctly identified corresponding landmarks in the environment. During route monitoring, humans visually search for landmarks to confirm their expectations, particularly at decision points where directional choices must be made (Spiers and Maguire 2008).

The combination of eye-tracking with physiological measures of cognitive load enables a detailed assessment of how environmental stressors affect navigation performance. While pupil diameter dilation reflects moment-to-moment cognitive demands (Kiefer, Giannopoulos, Duchowski, et al. 2016), and blink-related neural activity indexes attentional shifts (Cheng, E. Lin, et al. 2023), combining these metrics with gaze patterns reveals when and where attention breakdowns occur under stress. While research has examined the effects of thermal stress on cognitive load and its impact on attention, working memory, and decision-making (Hancock, Ross, and Szalma 2007), the specific mechanisms by which heat affects visual attention allocation during navigation remain underexplored. Understanding whether thermal stress alters visual attention away from environmental landmarks towards navigation aids, or whether strong landmark cues at decision points compensate for heat-induced cognitive deficits, is critical for designing resilient navigation systems for increasingly warm urban environments.

2.5 Electrodermal Activity as a Physiological Index of Arousal

Electrodermal activity (EDA) captures the change in the skin's electrical conductance driven by sweat gland activity. The change can be attributed to the sympathetic nervous system's control and is widely used as an objective index of arousal and stress in applied cognitive research (Boucsein 2012). EDA is usually split into two components: 1) tonic skin conductance level (SCL) and 2) phasic skin conductance responses (SCR). SCL describes the tonic component, therefore, the slowly varying baseline level of arousal. SCR refers to the rapid, event-related fluctuations in conductance based on the tonic level, reflecting moment-to-moment reactions to specific stimuli or task events.

2.5.1 EDA in Heat Exposure

EDA recordings can be influenced by various internal and external factors, including environmental ones such as temperature. Qasim, Bari, and Martinsen (2022) analyzed tonic and phasic EDA across different ambient temperature ranges from 22°C–25°C to 40°C–45°C and demonstrated that tonic SCL increases substantially with rising temperature, while phasic SCRs remain unaffected by thermal conditions. This discrepancy between the tonic and phasic components shows their underlying nature, as tonic EDA serves as a direct physiological marker of thermal load, while phasic responses mainly index task-related events regardless of ambient temperature. This is especially important in studies where thermal exposure represents the independent variable. Consequently, tonic EDA should be interpreted as a measure of thermal stress, while phasic responses can provide reliable information about cognitive and attentional processes (ibid.).

2.5.2 EDA as an Index for Cognitive Load

Beyond thermal exposure, EDA has also been shown to capture variation in cognitive load during demanding tasks reliably. Khan et al. (2019) demonstrated this capability by showing that phasic EDA correlates with task difficulty during an engineering exam and that it can predict performance variations. Their results, even if weak, showed a significant positive correlation with exam question difficulty, indicating that more demanding questions showed stronger electrodermal responses. Furthermore, a multiple regression model including EDA, skin temperature, and a difficulty index yielded a moderate statistically significant relationship, suggesting an interplay between physiological arousal, thermoregulation, and cognitive demands. These findings can be seen as evidence for a physiological connection between cognitive load and electrodermal activity, supporting EDA's utility as an objective measure of task-related arousal in performance contexts.

From a methodological perspective, recent validation studies demonstrated that EDA measurements for research purposes can be successfully captured using low-cost wearable systems such as BITalino (Batista et al. 2019; Guerreiro et al. 2013). This accessibility allows for easy integration of physiological measures into multimodal experimental designs to use the data as an additional index of overall arousal and cognitive load.

2.6 Synthesis and Research Gap

The preceding sections have established the theoretical foundation for investigating thermal stress effects on landmark-based navigation. Section 2.1 demonstrated that landmarks, particularly when positioned at structurally salient decision points (Section 2.1.2), serve as critical cognitive anchors for route learning and spatial memory encoding. Further research on landmark-based navigation (Section 2.1.2) and attention mechanism (Section 2.1.2) has established that landmarks at intersections create the fundamental building blocks for route knowledge (Karimpur, Röser, and Hamburger 2016; Wunderlich, Grieger, and Gramann 2023), with visual attention allocation allowing for predictions of the navigation performance (Cheng, Wunderlich, et al. 2022; Kapaj, Hilton, Lanini-Maggi, et al. 2024).

The Section 2.2 has established clear foundations for how thermal stress impacts and impairs attention, working memory, and executive function-cognitive processes fundamental to navigation. Existing research, however, has primarily examined these effects in non-spatial tasks (Section 2.2.2) or correlational field studies (Section 2.2.3). Although heat-aware navigation systems have been developed (Section 2.2.3), they focus primarily on route optimization rather than on understanding the cognitive mechanisms underlying spatial memory formation under thermal stress (Feng et al. 2024; Neset et al. 2022).

Section 2.3 validated the reliability and ecological validity of CAVE VR systems as a controlled research platform for thermal manipulation. Physiological and perceptual responses in thermally-augmented VR environments (Section 2.3.1) mirroring real-world thermal exposure (Hülsmann et al. 2014; Z. Lin et al. 2024; Yeom, J. H. Choi, and Kang 2019). This methodological foundation enables causal investigation of thermal effects on cognition that would be practically challenging to achieve in outdoor field research.

Finally, Section 2.4 reviewed eye-tracking methodologies capable of measuring real-time visual attention allocation using fixation patterns (Section 2.4.2), pupil diameter dilation (Section 2.4.1), and blink-related neural activity during navigation (Section 2.4.1 and Section 2.4.3). When combined with Section 2.5, which established electrodermal activity as a physiological index of both thermal load and cognitive arousal, with tonic SCL serving as a marker of thermal stress and phasic SCR reflecting task-related cognitive demands, these multimodal metrics enable comprehensive assessment of when and where attention breakdowns occur under stress while distinguishing thermal load from cognitive load through complementary physiological indices (Cheng, E. Lin, et al. 2023; Khan et al. 2019; Kiefer, Giannopoulos, Duchowski, et al. 2016; Kiefer, Giannopoulos, Raubal, and Duchowski 2017; Qasim, Bari, and Martinsen 2022).

While landmark saliency and thermal stress have been studied independently, no prior research has investigated whether thermal stress specifically impairs landmark recognition memory and route direction memory during navigation. Furthermore, no research has examined whether strongly positioned landmarks can buffer against heat-induced cognitive deficits.

The existing thermal stress literature focuses on general cognitive deficits (Hancock, Ross, and Szalma 2007; Taylor et al. 2016) without examining the spatial memory mechanism in a navigation context. Conversely, landmark-based navigation research has not yet considered environmental stressors as modulators of spatial memory encoding and retrieval. This represents a significant theoretical and practical gap, particularly given projections of increasing urban heat exposure globally (United Nations 2018) and corresponding alterations in pedestrian navigation patterns (Deilami, Kamruzzaman, and Liu 2018; Deilami, Rudner, et al. 2020; Lai et al. 2014).

This study addresses this gap by examining how thermal stress affects landmark-based spatial memory formation during a controlled VR navigation task. Specifically, the research investigates whether thermal exposure differentially affects 1) *visual landmark recognition memory* (discriminability of intersections encountered during navigation), measured through signal detection theory metrics, and 2) *procedural route direction memory* (recall of turning sequences at intersections), assessed through directional recognition accuracy. Additionally, by integrating eye-tracking metrics of visual attention allocation and physiological measures of cognitive load (pupil diameter, electrodermal activity), this research examines the attentional mechanisms that may mediate thermal stress effects on spatial memory. Understanding these mechanisms is essential for designing resilient navigation systems and urban environments that support effective wayfinding under increasingly common extreme heat conditions.

Chapter 3

Methods

This chapter describes the methodological framework employed to investigate thermal stress effects on spatial navigation. A between-subjects experimental design (N=46) compared navigation performance, visual attention, and physiological arousal between Heat (36-38°C) and No-Heat (24.5°C) conditions within an immersive virtual urban environment. Section 3.1 details participant recruitment and ethical procedures, Section 3.2 describes the virtual environment and thermal manipulation, Section 3.3 outlines the experimental procedure and data collection instruments, and Section 3.4 presents the statistical analysis framework

3.1 Participants

The recruitment of participants was conducted using personal networks to reach young healthy adults between the ages of 18 and 40 years. Interested individuals completed a brief online prescreening by filling out multiple questionnaires (Demographic, Santa Barbara Sense of Direction & Thermal sensitivity/comfort). There were no special requirements for participation in the study, except that participants needed to have normal or corrected-to-normal vision. Participants using corrective eye-wear were required to wear contact lenses rather than glasses, as the eye-tracking equipment cannot accommodate prescription eyeglasses underneath. Participants also needed adequate language proficiency in English to follow instructions and complete questionnaires. Participants were excluded if they had a history of neurological disorders such as epilepsy or migraines, cardiovascular disease, or severe motion sickness.

3.1.1 Sample Size and Power Analysis

Based on an a priori power analysis in GPower for a linear regression with one tested predictor (Condition: Heat vs No-Heat), assuming a medium effect size (f^2 = 0.20) and $1 - \beta$ = 0.80 at an alpha level of 0.05, the obtained sample size was N = 42. As a simple two-group comparison is mathematically equivalent to a regression with one dichotomous predictor, this power analysis also applies directly to the between-group tests reported below.

The assumed effect size (f^2 = 0.20, equivalent to Cohen's d $\approx$ 0.45) was informed by Hancock, Ross, and Szalma (2007)) meta-analysis of 49 studies, which demonstrated that thermal stressors impair human performance by approximately g = -0.34 overall, with cognition being moderately affected. However, several factors suggested that the effect in this study might be somewhat smaller than the meta-analytic average. First, the participants were young healthy adults with robust thermoregulatory mechanisms that can partially buffer heat stress effects. Second, the exposure duration in the experiment (10-15 minutes) was relatively brief compared to many field studies included in the meta-analysis. Third, while the temperature range (36-38°C) represents genuine heat stress, it falls short of the extreme hyperthermia conditions examined in some previous studies. For these reasons, the effect size of f^2 = 0.20 was used as a conservative but realistic estimate that would provide adequate power to detect meaningful thermal effects on spatial cognition without overly optimistic assumptions.

During the recruitment period, 46 participants signed up for the study, providing a small buffer above the minimum required sample size. All 46 participants completed the experimental session (23 per condition), with no dropouts. However, technical issues resulted in data loss for two individuals: one

participant in the Heat condition was excluded from eye-tracking analyses due to a hardware malfunction, and one participant in the Heat condition was excluded from EDA analyses due to file corruption. The final analytical samples were therefore N = 46 for behavioral analysis (intersection recognition and route direction memory), N = 45 for eye-tracking analysis, and N = 45 for electrodermal activity analysis.

3.1.2 Group Assignment and Blinding

Because enrollment was continuous throughout the recruitment period, group assignment to Heat or No-Heat was balanced manually. Tables maintaining both groups and providing baseline scores (gender, Santa Barbara Sense of Direction scores, and thermal sensitivity scores) were updated with each incoming participant. Importantly, assignment decisions were made before any navigation or physiological data were collected, ensuring that group allocation was prospective and balancing-based rather than outcome-driven. Each new participant was allocated to the condition that best preserved balance across demographic and baseline characteristic distributions.

Blinding to condition was not feasible, as the experimental setup (presence of active infrared lamps) made group assignment immediately apparent to both participants and the experimenter conducting the session. To minimize expectancy and observer bias, all instructions were fully standardized and delivered via written protocols. Additionally, outcome scoring was automated wherever possible to mitigate potential bias: questionnaire responses were recorded digitally through the ArcGIS Survey123 platform; navigation trajectories and intersections were logged automatically by the Unity software; and physiological signals (eye-tracking and electrodermal activity) were recorded continuously without manual intervention during data collection.

3.1.3 Ethical Approval and Compensation

Participation in the study was completely voluntary and had no direct costs for the participants. The experiment lasted around 45-60 minutes, and participants received a small chocolate as compensation. The study was registered by the institutional ethics committee with the number 25.05.14 (see more details in the Appendix C), and all data were stored under pseudonymous IDs with only the consent forms linking the participants' identity with their ID, ensuring participant anonymity during data analysis.

3.2 Virtual Environment & Thermal Exposure

This section describes the virtual environment and the thermal exposure manipulation. All participants navigated a single, standardized route through a virtual urban environment. The two experimental groups differed exclusively in thermal exposure (Heat vs. No-Heat), while all other environmental parameters were held constant.

3.2.1 Visual Environment & Route

The virtual environment used in this study was an altered version of an already used and tested environment by Cheng, E. Lin, et al. (2023) and Cheng, Wunderlich, et al. (2022). The environment mimics a high-density urban setting with predominantly tall modern skyscrapers interspersed with smaller buildings such as cafes, corner shops, and older infrastructure. These distinctive smaller structures were purposefully positioned at intersection corners to serve as landmarks (see Section 3.2.2 for details). Streets formed a simple grid with only orthogonal junctions, whereas the facades, signage, and other objects are all visually coherent across the entire city to minimize unintended salience. Furthermore, the environment was stripped of any traffic or pedestrian agents to avoid distractions and keep the scenes constant among all participants.

The route that the participants followed was a single, standardized path across both conditions, ensuring that any observed differences in spatial learning performance can be attributed to the thermal exposure manipulation rather than environmental variation (see Figure 3.1). To complete the route, participants were expected to need 10-15 minutes under a comfortable walking speed (maximum velocity of 2.3 km/h, controlled via foot pedal input) while passing fifteen intersections. Start and end locations(the same for all participants) were automatically set by the environment while logging the exact time participants entered and left each intersection.

To ensure route adherence and standardize navigation behavior, participants were guided by a visual arrow cue that appeared in advance of each intersection and remained visible above the junction. Additionally, invisible collision boundaries (walls) were placed at all non-target turns to prevent participants from deviating from the intended route. This constraint-based guidance eliminated potential confounds arising from route errors or individual exploration strategies, further strengthening the experimental control by ensuring that the only systematic difference between conditions was the thermal exposure manipulation.

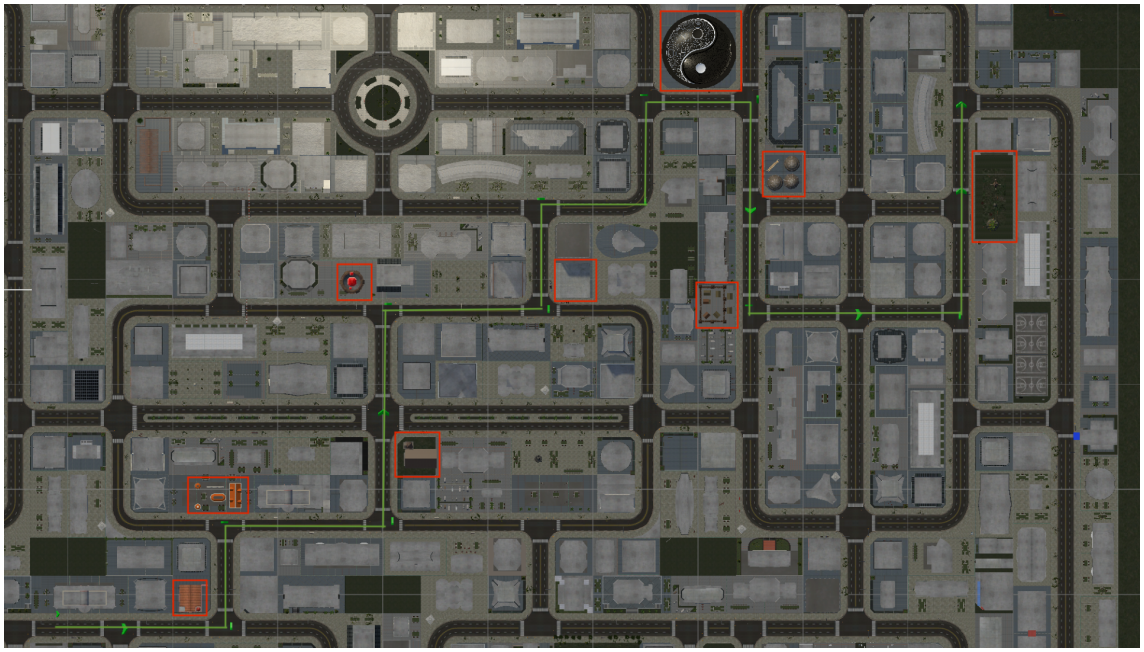

Figure 3.1: Overhead map of the virtual urban environment used in the navigation task. The predefined navigation route is shown in green; landmark locations are indicated in red.

3.2.2 Landmarks

Landmark Selection Criteria

The landmarks used for this study were chosen to be deliberately salient and heterogeneous features when compared to the rest of the buildings and were positioned exclusively at the corners of an intersection to serve as cognitive anchors for spatial learning (see Figure 3.2. The landmarks consisted of different types of buildings, such as churches, corner shops, or buildings with a distinct architectural style that contrasted with the uniform high-rise facades dominating the environment. Following guidelines established in Cheng, E. Lin, et al. (2023), each landmark incorporated multiple features across three dimensions: 1) visual features (e.g., unique color schemes, textures, and architectural details); 2) *spatial features* (e.g., distinctive size, shape, and positioning at decision points); and 3) *semantic features* (e.g., recognizable building functions such as post office, school, or cafe). This multi-dimensional approach ensured that landmarks were sufficiently distinct to support both incidental encoding during navigation and explicit recognition during post-task assessments.

Both experimental groups encountered identical landmarks, and their positioning did not change between the groups, ensuring that any performance differences reflected thermal effects rather than environmental variation. For the purpose of the intersection recognition questionnaire, two sets of landmarks were created: 1) *on-route landmarks*, positioned at intersections along the traversed path and within participants' field of view; and 2) *off-route landmarks*, positioned outside the viewing angles of the navigation route to serve as decoys in the recognition task.

Landmark Intersection-Positioning Strategy

Landmark positioning at the intersections was designed to support both spatial learning and subsequent directional memory assessment. Although positioning landmarks exclusively on the turning side of each

intersection would facilitate spatial learning (Karimpur, Röser, and Hamburger 2016), pilot testing revealed that participants rapidly detected this spatial regularity, making the directional recognition test trivial and unsuitable for the study's objectives. To address this issue, landmark positions at intersections were pseudo-randomized and balanced across the four possible corner locations, ensuring that landmarks did not systematically predict turn direction. This constraint-based randomization maintained the cognitive challenge of the directional memory task while preserving the landmarks' function as salient reference points for spatial encoding.

Image Set Preparation for Recognition Tasks

After finalizing landmark designs and positions, four distinct image sets were created to meet the requirements of the Intersection Recognition Questionnaire (see Section 3.3.2). All images were captured from a standardized camera position with the same image resolution and FOV at the center of the road (reflecting participants' ability to walk on either side) and aligned with the approach direction to each intersection. The four image sets were constructed as follows:

- **Set 1M (Morning, On-Route):** Images of the 15 on-route intersections rendered with morning lighting (shaded), used for the No-Heat group.
- **Set 1N (Noon, On-Route):** Images of the same 15 on-route intersections rendered with noon lighting (sunlit), used for the Heat group.
- **Set 2M (Morning, Off-Route):** Images of 15 off-route intersections rendered with morning lighting, serving as decoys for the No-Heat group.
- **Set 2N (Noon, Off-Route):** Images of the same 15 off-route intersections rendered with noon lighting, serving as decoys for the Heat group.

This design ensured that recognition task stimuli were visually matched to each group's navigation experience, controlling for potential confounds arising from lighting differences between conditions.

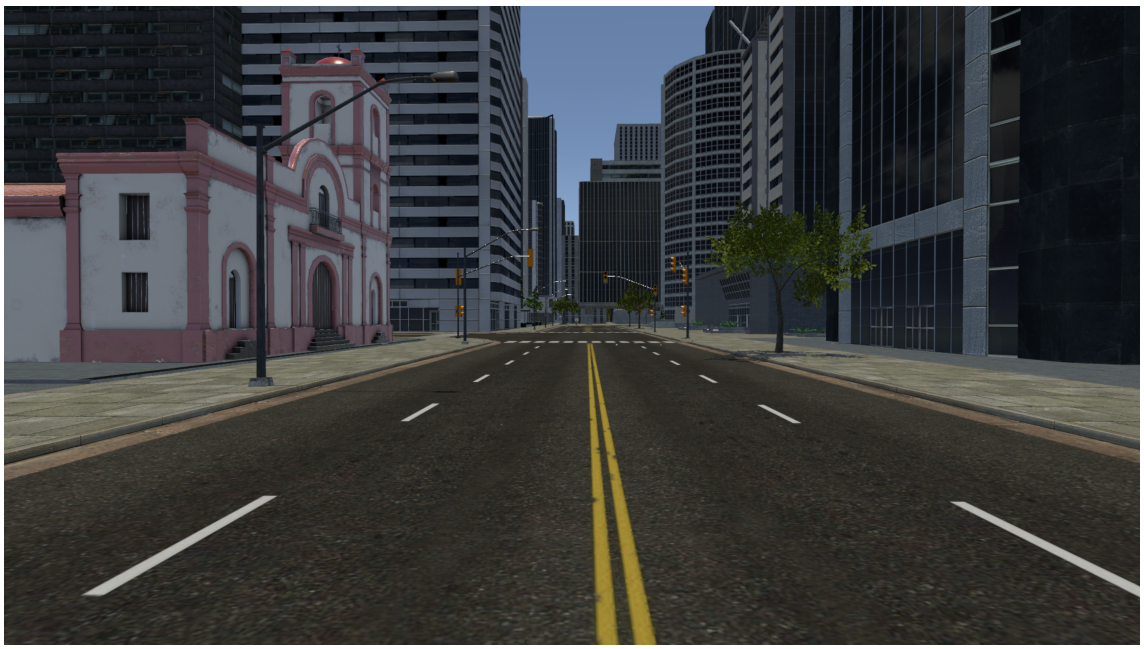

Figure 3.2: First-person view of a representative intersection in the virtual environment illustrating a salient landmark (pink church) used as a spatial anchor during navigation.

3.2.3 Thermal Conditions (Independent Variable)

The study employed a single independent variable: thermal exposure condition, manipulated at two levels to create a between-subjects design.

Condition Definitions

- **No-Heat Control Condition:** Visually shaded urban environment (morning time rendering) combined with comfortable, neutral ambient temperature of 24.5°C, simulating typical indoor conditions without thermal stress.
- **Heat Experimental Condition:** Visually sunlit urban environment (noon time rendering) combined with elevated temperature of 36.0°C to 38.0°C achieved through radiant heat exposure, simulating heat stress conditions.

The temperature range of 36.0°C to 38.0°C was selected to represent moderate heat stress. This range exceeds the ASHRAE thermal comfort zone (approximately 21°C to 25°C for sedentary adults (ASHRAE Standard 55 2017)), yet remains below extreme hyperthermia thresholds, providing a realistic stressor level that induces physiological and cognitive effects in young healthy adults without creating safety concerns.

Physical Heat Manipulation

To achieve the physical heating condition, three identical infrared lamps were positioned around the participant's head and neck area (left, right, and posterior positions) based on a previous study (Hülsmann et al. 2014). Each lamp was a Philips E27 infrared lamp (150 W, 230 V; diameter 121 mm × 136 mm) mounted on a fixed shelf and controlled individually by a Ketotek KT3200PRO thermostat.

Each thermostat monitored ambient temperature at the center of its lamp's beam, positioned directly above the participant's skin. A feedback-controlled safety cutoff was set at 42°C; once this threshold was reached, the thermostat automatically halted heating until the temperature dropped below the cutoff, resuming heating in a continuous cycle. Based on pilot testing, this 42°C cutoff maintained the target temperature range of 36.0°C ± 0.5°C in the surrounding areas of the head and neck while preventing excessive skin exposure. The geometry, mounting positions, and power settings of all three lamps were held constant across all Heat condition participants to ensure standardized radiant heat exposure.

Lamp positioning (left, right, and posterior to the participant) was chosen to avoid obstructing vision during the virtual navigation task. However, head rotations exceeding approximately 45° could misalign the infrared beam with sensor placement, potentially causing minor temperature deviations (±1°C). During the experiment, temperature was continuously monitored (see Section 3.2.4).

Visual Manipulation

To strengthen the ecological validity and immersive quality of the thermal manipulation, the virtual environment's lighting conditions were altered between groups. The No-Heat group navigated a morning-time rendering of the city (predominantly shaded, soft lighting), while the Heat group navigated a noon-time rendering (bright sunlight, minimal shadows). This visual cue is consistent with thermal environmental expectations and has been shown to enhance perception of thermal properties in immersive environments (Erkan 2021; Z. Lin et al. 2024; Yeom, J. H. Choi, and Kang 2019). The time-of-day manipulation provided a coherent multisensory experience, strengthening participants' implicit association between environmental context and thermal experience (see Figure 3.3.

Figure 3.3: Experimental setup in the CAVE displaying the thermal apparatus: three Philips infrared lamps (left, right, posterior) positioned around the participant's head and neck, controlled by independent thermostats to maintain target heat exposure (36-38°C). The virtual urban environment is projected on the surrounding screens.

3.2.4 Manipulation Checks

The thermal manipulation was mainly verified through subjective self-report and procedural compliance checks, supplemented by objective physiological measures. This multi-method approach ensured that participants in the Heat condition experienced genuine thermal stress while No-Heat controls remained in neutral conditions.

Objective Physiological Measures

Electrodermal activity (EDA), recorded continuously via the BITalino sensor throughout the navigation task (see Section 3.3.2), provided an objective measure of sympathetic nervous system arousal (Batista et al. 2019; Benedek and Kaernbach 2010a; Boucsein 2012; Greco, Valenza, Lanata, et al. 2016; Guerreiro et al. 2013). Elevated skin conductance levels (SCL) and increased phasic skin conductance responses (SCRs) indicate physiological stress response (Boucsein 2012). Between-group comparisons of EDA metrics (mean tonic SCL, SCR rate, median SCR amplitude; see Table 3.1) were planned as objective indices that the Heat condition induced greater physiological arousal than the No-Heat condition. EDA data was processed and analyzed as described in Section 3.4.5.

Procedural Temperature Verification

In the Heat condition, the three infrared lamps were activated immediately after participants were equipped with thermal sensors and before task instructions were provided. This timing allowed lamps to reach the target temperature range during the 5-minute familiarization phase with the navigation controls. Prior to initiating the main navigation task, temperature readings were visually verified at all three thermal sensors to confirm that the ambient temperature at the measurement sites was within

the target range of 36.0°C ± 0.5°C. The experimenter recorded this pre-task temperature verification on a checklist.

During the main navigation task, temperature was monitored at each of the 15 intersections by checking thermostat readings on the three heat sensors. Any deviations exceeding ±1.0°C from the 36.0°C target were noted in the experiment log along with the intersection number, timestamp, and any corrective actions taken (e.g., lamp repositioning, re-verification of sensor placement). No-Heat control participants underwent the identical procedural steps, including the same pre-task interval duration, but without temperature sensors or lamps, ensuring equivalent experimental timing across conditions.

Subjective Thermal Comfort Assessment

Immediately after the navigation task concluded, participants were asked to complete the Thermal Comfort Questionnaire (TCQ; see Section 3.3.2), which captured their subjective thermal experience during navigation (ASHRAE Standard 55 2017). The TCQ was identical for both groups, providing a direct manipulation check: participants in the Heat condition were predicted to report significantly higher thermal discomfort ratings than those in the No-Heat condition. Results are presented in Section 4.1.4.

Compliance Summary

Across all 46 participants, pre-task temperature verification confirmed that all Heat condition participants (n = 23) began the main task within the target temperature range. During-task temperature monitoring revealed no systematic deviations or safety concerns. All participants completed the post-task Thermal Comfort Questionnaire, and complete EDA data was recorded for all participants during navigation. These convergent manipulation checks (objective physiological arousal (EDA) (Benedek and Kaernbach 2010a; Greco, Valenza, Lanata, et al. 2016), procedural temperature verification, and subjective thermal perception (TCQ) (ASHRAE Standard 55 2017)) collectively confirm that the thermal manipulation was successfully implemented and perceived as intended.

3.2.5 Operational Safety

The main risks during the experiment were related to severe thermal discomfort or motion sickness. No adverse events occurred during any experimental session. Nevertheless, multiple preventive measures and monitoring protocols were implemented to ensure participant safety and well-being.

Thermal Apparatus Safety Measures

The three installed infrared lamps (see Section 3.2.3) were all mounted on a shelf positioned behind the participant's seated location. Each lamp was secured with multiple tapes to the shelf to prevent any displacement or falling. Prior to each experiment, the mounts and tape were checked visually for stability, and any electrical cable was secured out of the participant's way to eliminate tripping hazards.

Each lamp was equipped with a Ketotek KT3200PRO thermostat that enforced an automatic safety cutoff at 42°C, measured at the center of the infrared beam (Hülsmann et al. 2014). This threshold had a higher temperature than desired in the center of the beam; however, it allowed for maintaining the target ambient temperature of 36.0°C ± 0.5°C in surrounding areas, as validated through pilot testing. The thermostats were operating in continuous measuring mode, where the individual heat lamps were automatically turned on once the temperature dropped below the cutoff, and turned off again upon reaching the temperature threshold. This automation eliminated the need for manual intervention and ensured consistent, safe thermal exposure throughout the experiment.

To minimize any risk of direct skin contact with the heat lamps, their positioning was carefully calibrated to direct radiant heat toward the head and neck area without obstructing the participant's field of view or allowing contact with lamp surfaces. Participants were instructed to remain seated and to avoid any sudden movements during the task.

During the 5-minute acclimatization phase (see Section 3.3.1, participants also received safety instructions. This included:

- The purpose and nature of the thermal manipulation (Heat condition only)
- Expected sensations (warmth around the head and neck, similar to sun exposure in summer)
- The participant's right to withdraw from the study at any time without penalty
- How to signal discomfort or request task termination (verbal communication or raising a hand)
- The location and function of the foot pedal controller, emphasizing the importance of remaining seated to avoid tripping or damaging the equipment

Participants were asked to verbally confirm their understanding of these instructions and to ask any clarifying questions before proceeding. All participants provided written informed consent, which included explicit disclosure of heat exposure (for Heat condition participants) and potential risks, including thermal discomfort and mild motion sickness.

Continuous Monitoring During the Experiment

While the participants were conducting the main navigation task, their well-being was continuously monitored to watch out for signs of severe distress or discomfort. The monitoring consisted of these main steps:

- **Temperature readings:** Thermostat displays were visually checked at each of the 15 intersections to verify that the temperature remained within the target range of 36.0°C ± 0.5°C. Any deviations exceeding ±1.0°C were immediately noted, and corrective actions (lamp or sensor repositioning) were taken if necessary.
- **Participant signs of distress:** Signs of too high distress in the form of verbalization of discomfort or hand signal were monitored. If any signs of severe distress were noted, the physical well-being of the participants was checked verbally. No participants reported severe discomfort.

Post-Experiment Procedures and Cool-Down

Immediately after the main navigation task was completed, the following procedures were executed:

1. All data recording streams were stopped simultaneously via the LabRecorder software.
2. For the Heat condition participants, all three infrared lamps were immediately powered off.
3. Thermal sensors (Heat condition only), eye-tracking glasses, and the BITalino EDA sensor were removed from the participant.
4. Participants were invited to move to the adjacent climate-controlled acclimatization room (22°C) if desired, or to remain in the CAVE room (24.5°C ambient temperature) to complete post-task questionnaires. No participant used this option.
5. The participants were asked if they felt well and if they experienced any lingering discomfort effects.

Safety Outcomes

In all 46 subjects (23 Heat and 23 No-Heat), there were no adverse occurrences. None of the subjects experienced severe thermal discomfort, feelings of hyperthermia, or motion sickness severe enough to terminate tasks. Temperature values all operated within acceptable limits with no failures of equipment. These outcomes confirm that the thermal manipulation was both effective for experimental purposes and safe for participants.

3.3 Experimental Design

This section will explain the experimental design in three parts. The Procedure section 3.3.1 will focus on the timeline of an experimental session and describe what the participants go through when participating in the study. Secondly, the Materials & Tools section 3.3.2 specifies the thermal apparatus, software, sensors, and questionnaires used. Lastly, the Data Handling & Pre-processing section documents how the data streams were recorded, synchronized, cleaned, and transformed for the outcomes analyses later.

3.3.1 Participant Procedure

The participant procedure in this study is designed to ensure consistency of experimental conditions and precise measurement of thermal and navigational variables. Below is the procedure each participant goes through in sequential phases. The exact instructions given to the participants can be found in the Appendix A.

Recruiting Phase
When signing up for the study, participants choose their desired time slot using an online scheduling system and receive confirmation, including their participant number. Using this ID, the participants are asked to fill out three questionnaires before the on-site experiment: a) Demographics, b) Santa Barbara Sense of Direction (SBSOD; (Hegarty, Richardson, et al. 2002)), and c) Thermal Sensitivity Questionnaire (TSQ). Baseline scores were used for subsequent manual balancing of Heat/No-Heat conditions as described previously.

Arrival and Acclimatization
Participants were greeted and could leave all their belongings in the CAVE room before proceeding to the acclimatization phase. For that, all participants, regardless of their group, spend 10 minutes in a temperature-controlled room, which is set to 22°C. (ASHRAE Standard 55 2017) During this time, participants are asked to read the consent form, read through the participant procedure, and ask questions if something is unclear. The acclimatization period served to stabilize physiological variables before thermal intervention.

Familiarization with environment controls
Following the acclimatization phase, the participants are seated and equipped with all necessary sensors: eye-tracking glasses, BITalino, and heat sensors for the experimental group. Participants are then given a maximum of 5 minutes to become familiar with the controls of the virtual environment by completing a quick training session. They navigate around a mock intersection using the foot paddle controller and familiarize themselves with the environment, aesthetics, and how to move in it. Note that the environment used in the training session is the same one used in the experimental environment; however, during the training session, participants are restricted to only one intersection, which is also not part of the main navigation task. The training session ensures that participants feel comfortable navigating the environment and gives time to set up all necessary data collection streams. Lastly, the participants are given the instructions for the main navigation task.

Main Navigation Task
Each participant completed the main task, navigating a pre-defined urban route in the CAVE environment as described in Section 3.2.1. Participants received identical on-screen route cues, with task instructions instructing them to navigate “as you would in a real city: take your time, observe the surroundings, do not rush.” Navigation was designed to last approximately 10–15 minutes. Both experimental groups traversed the identical route; only the heat manipulation and lighting differed between groups.

Post-Navigation Task
Upon completion, participants filled out three post-task online questionnaires: (a) the Thermal Comfort Questionnaire (TCQ; as a manipulation check (ibid.)), (b) the Landmark Recognition Questionnaire, and (c) the Route Recognition Questionnaire (see 3.3.2 for tools). Participants were shown images of landmark-containing and non-landmark intersections, indicating which were encountered, and, for route recognition, identified turn directions. All questionnaires were administered via ArcGIS Survey123, and submission integrity was checked in real time.

Post-Experiment Debrief
Subsequent to the questionnaires, the participants received a short debriefing in text and verbal form. The debrief explains the study's objectives and gives the participants the possibility to ask further questions. This ensures transparency of the study and the research process. Additionally, participants get their promised small token of appreciation in the form of a chocolate bar.

3.3.2 Materials & Tools

This subsection summarizes the technical setup and tools used in the study. It first described the VR hardware and tracking infrastructure (CAVE system, Unity implementation, and data streaming), then details the thermal apparatus used to manipulate heat exposure, followed by the sensors for eye tracking and electrodermal activity. Finally, it outlines the questionnaires and environmental controls that complemented the behavioral and physiological measurements.

VR Hardware & Tracking

The study used the GIVA CAVE multi-projection system at the University of Zurich for the visual representation of the environment. The CAVE was configured using MiddleVR, and the environment was built in Unity Version 2021.3.11f1. Participants were seated centrally between the projections and controlled their movement using a foot pedal controller, which allowed for seamless "walking" in the environment. This pedal was chosen for its efficacy in minimizing simulator sickness while providing intuitive forward/backward locomotion in sedentary VR (Cheng, E. Lin, et al. 2023). Head position was not tracked to maintain standard visual alignment for all participants.

The participants' position (3D virtual camera coordinates) within the environment was recorded within the Unity software every 10 seconds (*Unity_pose*) and every time a participant entered and exited an intersection (*Unity_POI*). These event triggers were timestamped and streamed to the LabReader via the Lab Streaming Layer. Five primary data streams (see Section 3.3.3) were synchronized using the shared LSL time-base, including Unity, NEON eye-tracking (Section 3.3.2), and BITalino EDA (Section 3.3.2) outputs.

Thermal Apparatus

Thermal exposure in the Heat condition was achieved using three Philips E27 infrared heat lamps (150 W, 230 V each, 121 mm × 136 mm diameter). Lamps were mounted on a fixed shelf at the left, right, and posterior positions surrounding the participant's head and neck (Figure 3.4). Each lamp was independently controlled by a Ketotek KT3200PRO thermostat that monitored air temperature at the center of the lamp's beam. The thermostats enforced an automatic safety cutoff at 42°C, which maintained a local ambient temperature of 36.0–38.0°C during operation without exceeding safe limits for skin exposure, based on pilot testing and current VR safety guidelines (Hülsmann et al. 2014; Jin et al. 2023; Park 2025). Lamps cycled automatically between heating and cooling to maintain the target range. Infrared radiant heating was chosen for its efficiency in generating rapid skin-surface heat perception, closely mimicking solar heat load in urban settings, while allowing precise control and safety cut-off compared to convective methods (Park 2025).

All physical mounting points were checked before each session for stability, and all electrical cables were tucked away and secured to prevent interference with the participant or with data acquisition devices. Lamps were positioned in a way that no participant could accidentally touch the bulbs, and the geometry was held constant across all sessions.

Figure 3.4: Thermal manipulation apparatus components and mounting geometry, including Philips infrared lamps, thermostats, and safety sensors.

Sensors

NEON Eye Tracking

The study used mobile eye-tracking glasses, which allowed for unrestrained head movement while recording participants' gaze behavior during navigation (see Figure 3.5). The specific model was NEON, which are head-mounted mobile eye-tracking glasses from Pupil Labs (2025). Neon is a video-based pupil-corneal reflection eye tracker, which does not require any calibration and offers a gaze precision accuracy of 1.8°, independent of lighting conditions and participant-specific factors (Baumann and Dierkes 2023). The glasses contain a front-facing scene camera with a field of view of 132° x 81° and a resolution of 1600 x 1200 pixels, which records at 30 Hz. The eye movements were recorded using the NEON companion application on a smartphone and are uploaded to Pupil Cloud at a sampling rate of 200 Hz. To connect the glasses to the LabRecorder data stream, the smartphone, which was connected to the glasses and tucked away in a pouch attached to the participant's seat, was linked to a private network to stream the recorded data.

BITalino EDA

Electrodermal activity (EDA) was measured using the BITalino (r)evolution platform, which has been extensively validated as a low-cost, reliable open-source system for biosignal acquisition in laboratory and mobile scenarios (Guerreiro et al. 2013). The EDA sensor was attached with pre-gelled Ag/AgCl electrodes to the non-dominant hand's index and middle fingers (see Figure 3.5). The data was collected using the OpenSignals (r)evolition software, which is also recommended by PLUX (PLUX 2020) for physiological signal recording. The BITalino is connected via Bluetooth to the software and therefore allows for continuous data collection. The incoming data stream was also further streamed to the LabRecorder software to allow for synchronization of the EDA data with the other data streams.

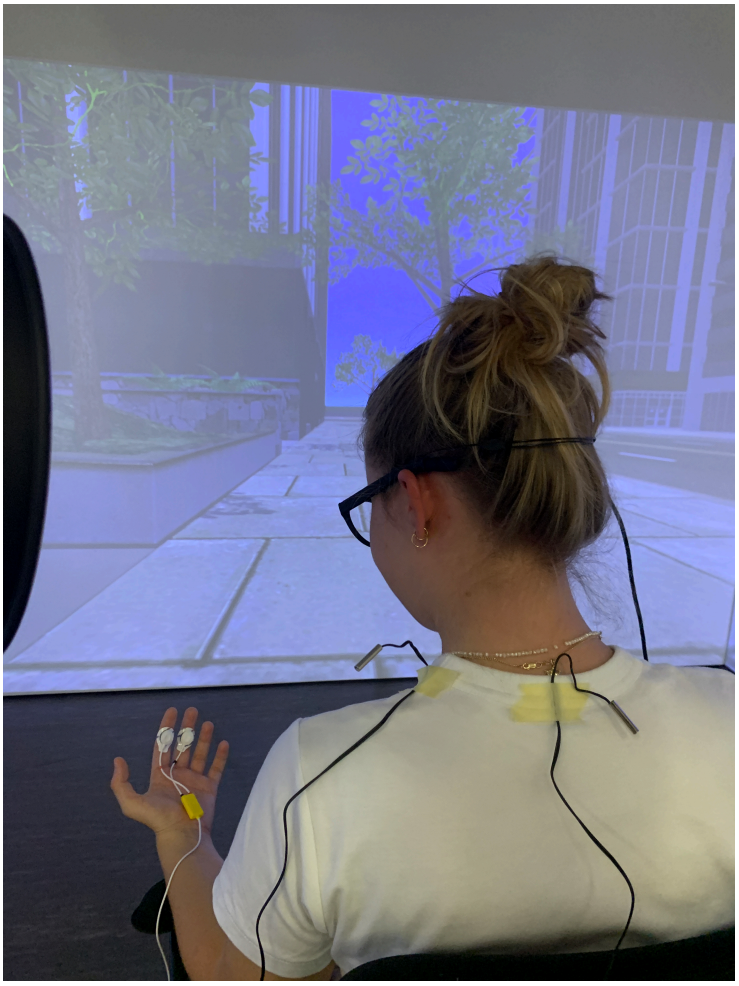

Figure 3.5: Participant wearing eye-tracking glasses, BITalino EDA sensor, and thermostat measurement instruments during the navigation.

Questionnaires

The following questionnaires were used to balance the participants between the two groups based on their scores (Demographic Survey, Sense of Direction Questionnaire, and Thermal Sensitivity Questionnaire) and to assess the participants' performance during the task (Thermal Comfort Questionnaire, Landmark recognition Questionnaire, and Route recognition Questionnaire). All questionnaires were created with the ArcGIS Survey123 tool. Each questionnaire can be found in the Appendix B.

Demographic Survey
The demographic survey was used to collect the participants' gender, age, and educational background, and was filled out by participants before conducting the on-site experiment. Only the gender and age were used to balance the participants across the control and experimental groups.

Sense of Direction Questionnaire
To assess the baseline spatial ability, the study used the standardized instrument of the Santa Barbara Sense of Direction (SBSOD) questionnaire developed by Hegarty, Richardson, et al. (2002). The SBSOD is a 15-item questionnaire where participants self-report on a 7-point Likert scale on their spatial and navigational abilities, preferences, and experiences. The participants also completed this questionnaire before conducting the on-site experiment and were grouped based on their mean of all items. Items 1, 3, 4, 5, 7, 9, and 14 are positively worded (e.g., "agree") and were reverse-scored; therefore, a Likert response of 1 was recoded as 7 (2→6, 3→5, 4→4), and vice versa.

Thermal Sensitivity Questionnaire
The Thermal Sensitivity Questionnaire (TSQ) aimed to capture the self-reported sensitivity to heat. The TSQ also uses a 7-point Likert scale and partial reverse scoring (Items 2, 4, and 6) similar to the SBSOD. Together with the SBSOD score, the score obtained from the TSQ was used to balance the participants across both groups and was therefore filled out by the participants before attending the on-site experiment.

Thermal Comfort Questionnaire
The Thermal Comfort Questionnaire (TCQ) captured the post-task subjective heat exposure and was mainly used for a manipulation check and is based on the ASHRAE Standard 55 (2017) and Lai et al. (2014). The TCQ uses a 7-point Likert scale, with one reverse-scored item (Item 4) and one bipolar item (Item 8).

Intersection Recognition Questionnaire
The Intersection Recognition Questionnaire assessed the participants' ability to remember the encountered intersections on the route. The task was based upon previous implementations by Kapaj, Hilton, Lanini-Maggi, et al. (2024), which is built on Wunderlich and Gramann (2021) and Wunderlich, Grieger, and Gramann (2023). To assess the memory, the participants were shown an image of an intersection and asked if they remembered seeing this intersection as part of their route. The participants were shown 30 images of intersections and landmarks: 15 depicted on-route intersections (9 with a landmark and 6 without), and the remaining 15 depicted off-route locations (9 novel landmarks and 6 novel intersections), for a total of 30 trials. The images were created twice, once for each group, with the correct lighting per group and presented in the same random order for all participants as explained in the Landmark section 3.2.2.

Route Recognition Questionnaire
The Route Recognition Questionnaire was used to assess the participants' memory for associated route directions and was also built on Kapaj, Hilton, Lanini-Maggi, et al. (2024), which was built on Wunderlich and Gramann (2021) and Wunderlich, Grieger, and Gramann (2023). For each traversed intersection alongside the route, the participants were shown the image, regardless of whether they had previously recognized the intersection, and were asked to determine the turn they had taken (left / straight / right). The 15 on-route items comprised 9 intersections with a landmark and 6 without a landmark. The distribution of correct directions was balanced within each condition: with landmarks, there were 3 left, 3 straight, and 3 right turns; without landmarks, there were 2 left, 2 straight, and 2 right turns.

Environmental Controls

Environmental conditions were standardized across all sessions to isolate the independent variable of thermal manipulation. All participants underwent a 10-minute acclimatization phase in a separate, climate-controlled room maintained at 22°C (ASHRAE Standard 55 2017). The main navigation room, in which the experiment took place, was also maintained at 24.5°C for both conditions, as the heat was only provided by the heat lamps. Both rooms were climate-controlled with a centralized ventilation system.

Lighting within the CAVE was also held constant, as during the study, only the projection was kept on, whereas all other lights were turned off. The only visual difference between conditions was the in-engine time-of-day appearance (morning/shaded for No-Heat; noon/sunlit for Heat), as specified in the Virtual Environment & Thermal Exposure section 3.2. In Heat sessions, the infrared lamps emitted a faint visible (red) component; because the units were shelf-mounted behind the participant's head, a small amount of spill light could be visible on the projections, but this was minimal and consistent across heat sessions.

Acoustic conditions were kept quiet and consistent for all participants. During the experiment, no communication, except for any questions, with participants took place. To ensure standardized cutaneous exposure, participants wore light indoor clothing (e.g., T-shirt) and removed any outerwear before study entry; those with longer hair were asked to tie it up, ensuring infrared exposure to the neck.

These controls ensured that differences in navigation performance and subjective comfort reflected only the experimental manipulation rather than other environmental or social variables.

3.3.3 Data Handling & Pre-processing

The following subsection explains how the raw data streams were modified to result in analysis-ready variables. The thermostat display readings for Heat compliance were procedural only and not ingested as data (see Manipulation Checks 3.2.4).

Streams & Synchronization

For all sessions, the signals were recorded into a single XDF container using the Lab Streaming Layer (LSL) time base. Five data streams were expected per session.

1. *Unity_pose*: Virtual camera position sampled every 10 seconds.
2. *Unity_POI*: Marker when player enters and leaves an intersection.
3. *NEON_Gaze*: Gaze data of participants.
4. *NEON_Video*: Video recording of what the participants saw.
5. *BITalino_EDA*: Electrodermal activity at 100 Hz, sampled at the non-dominant hand.

Responses from all questionnaires (Demographics, SBSOD, Thermal Sensitivity, Thermal Comfort, Intersection Recognition, and Route Recognition) were exported from ArcGIS Survey123 as a CSV file. As all questions were mandatory, no item-level manipulation was required. Before conducting the experiment, the completion of the questionnaires and the presence of the five LSL streams were confirmed. Post experiment, an integrity check ensured each stream was present and non-empty.

Cleaning & Quality Control

Questionnaires
All questions were mandatory to fill out before being able to submit each questionnaire, which omitted any item-level missingness. Submissions were checked before each session to confirm the correct participant ID and the submission of all three pre-experiment questionnaires (Demographic, SBSOD, Thermal Sensitivity). After the experiment, the other three post-experiment questionnaires (Thermal Comfort, Intersection Recognition, and Route Recognition) were checked for completion as well.

Navigation Logs
Post-experiment, the event sequences were validated for order and completeness: route start $\rightarrow$ intersection entry $\rightarrow$ intersection exit (repeat for all intersections) $\rightarrow$ route finish. As the recording already started during the warm-up and training phase, any segments that were not within the main navigation task had to be removed in further analysis. There were no missing markers or missing data for all participants.

Eye-Tracking
Raw recording and gaze samples were visually checked post-experiment for completeness with the Pupil Labs Cloud software. Before categorizing the participants' eye fixation data (see more in Section 3.4.4), fixations that were shorter than 150 ms were discarded as express fixations, and fixations longer than 2000 ms were removed as outliers; the remaining fixations were retained for analysis. The thresholds were based on previous implementation in Kapaj, Hilton, Lanini-Maggi, et al. (2024). More details can be found in Section 3.4.4

Electrodermal activity (BITalino)
Recorded signals were inspected visually post-experiment for completeness with the OpenSignals software. Detailed steps for cleaning and quality control can be found in Section 3.4.5.

Derived Metrics

Table 3.1: Derived analysis metrics across behavioral, visual attention, and physiological modalities. All metrics follow established protocols in spatial navigation and psychophysiological research (Benedek and Kaernbach 2010a; Horvers et al. 2021; Kapaj, Hilton, Lanini-Maggi, et al. 2024).

Modality	Metric	Definition
Questionnaires		
Intersection Recognition	Sensitivity (d')	Discriminability index from SDT; separates true memory from response bias (Tanner and Swets 1954).
	Hit rate	Proportion of on-route intersections correctly recognized as "seen".
	False alarm rate	Proportion of decoy intersections incorrectly recognized as "seen".
	Response criterion (c)	Response bias index; $c > 0$ = conservative, $c < 0$ = liberal.
Route Recognition	Route accuracy	Proportion of correct directional turns across 15 intersections.
Eye-Tracking (Pupil Labs Cloud)		
Visual Attention	Normalized Fixation Duration (nFD)	Percentage of trial time spent fixating each AOI (Landmark, Intersection, Arrow, Environment).
	Trial duration	Total active navigation time (first to last AOI fixation).
Electrodermal Activity (BITalino)		
Trial-Level	Mean SCL	Average tonic arousal across navigation task (μS).
	SCL Corrected	Trial SCL minus baseline SCL; isolates task-related arousal (μS).
	SCR Rate	Frequency of phasic responses (peaks/min).
Intersection-Level	Mean SCL (intersection)	Tonic arousal during decision and crossing sequence (μS).
	SCR Rate (intersection)	Phasic response frequency within intersection window (peaks/min).
Temporal Dynamics	Cue Reactivity	SCL change from Baseline to Decision phase (μS).
	Action Settlement	SCL change from Decision to Execution phase (μS).

3.4 Statistical Analysis

This section describes the statistical procedures used to evaluate the effects of thermal stress on spatial navigation performance, visual attention allocation, and physiological arousal (Figure 3.6). The analysis framework proceeds in five stages. First, baseline measures and manipulation checks (Section 3.4.1) verify that the two experimental groups were comparable and that the thermal manipulation was effectively perceived by the participants. Second, intersection recognition performance (Section 3.4.2) is analyzed using signal detection theory to separate memory sensitivity from response bias. Third, route direction memory (Section 3.4.3) is assessed by examining both overall performance and the influence of landmark presence. Fourth, visual attention patterns (Section 3.4.4) are analyzed with eye-tracking metrics to understand gaze allocation across different environmental features. Finally, physiological arousal (Section 3.4.5) is indexed through electrodermal activity, decomposed into tonic and phasic components at multiple temporal scales. All analyses were conducted in R (version 4.3.1), with specific packages noted where relevant.

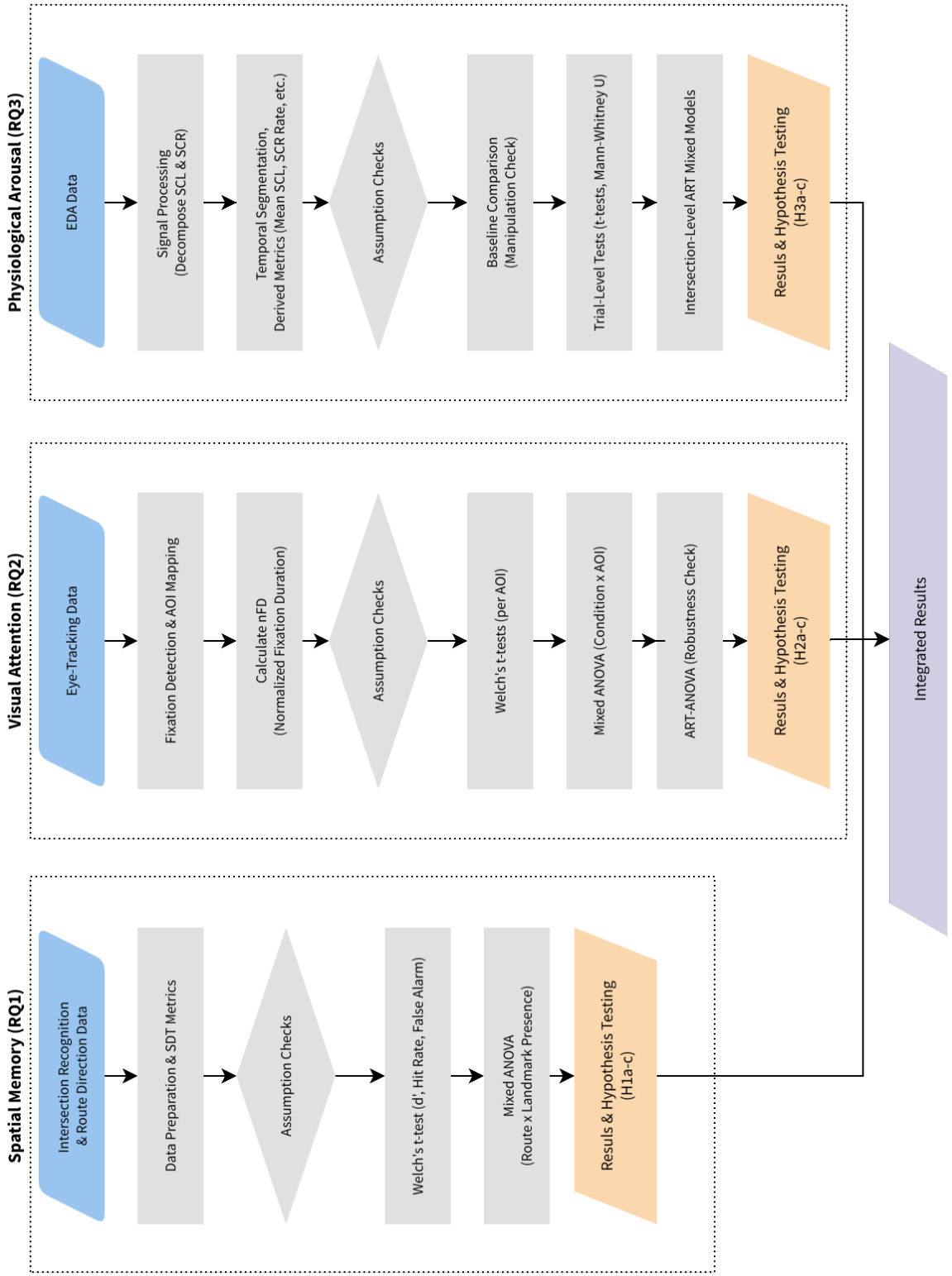

Figure 3.6: Summary of statistical analysis workflows for intersection/route data, eye-tracking, and EDA

3.4.1 Baseline Measures and Manipulation Check

To ensure that observed group differences in the main outcomes (intersection recognition sensitivity measured by d', route direction accuracy, visual attention allocation to environmental features, and physiological arousal indexed by electrodermal activity) reflect the thermal manipulation rather than pre-existing differences in demographic or psychological characteristics, baseline comparability was assessed across multiple dimensions. Specifically, age, gender distribution, spatial ability (Santa Barbara Sense of Direction), thermal sensitivity, and post-task thermal comfort were compared between the Heat and No-Heat conditions.

Age differences between conditions were tested using Welch's independent-samples *t*-test. Gender distribution was compared using a χ^2 test of independence. For all questionnaire scores (SBSOD, TSQ, TCQ), normality within each condition was evaluated with Shapiro-Wilk tests, homogeneity of variance with Levene's tests, and group differences tested using Welch's *t*-tests. Effect sizes were quantified as Cohen's d based on pooled standard deviations. These baseline comparisons confirm whether any differences in spatial navigation outcomes can be attributed to the thermal manipulation itself rather than confounding group characteristics established prior to the intervention.

3.4.2 Intersection Recognition

To assess the participants' ability to recognize intersections during the navigation trial, Signal Detection Theory (SDT) (Tanner and Swets 1954) was applied, following principles established by Kapaj, Hilton, Lanini-Maggi, et al. (2024). SDT provides independent estimates of sensitivity (d') and response bias (c), thereby separating true discrimination ability from overall response tendencies. This approach is better suited than analyzing raw recognition accuracy alone because raw recognition accuracy conflates memory strength with decision criteria. A participant might have a strong memory but still use a conservative response strategy when answering the questionnaire (or the other way around). SDT allows to separate these two processes.

Data Preparation and SDT Metrics

Raw yes/no responses from the Intersection Recognition Questionnaire were first coded according to standard SDT categories. The questionnaire consisted of 30 items: 15 on-route intersections that participants had actually navigated, and 15 off-route decoy intersections that were novel.

For each participant, responses were scored such that correctly identifying a previously seen intersection as "seen" counted as a *hit* (H), while incorrectly identifying a novel decoy intersection as "seen" counted as a *false alarm* (F). This yielded two counts per participant: hit count (out of 15 possible on-route items) and false alarm count (out of 15 possible decoy items).

To handle extreme hit and false alarm rates that would otherwise produce undefined z-scores (e.g., when $H = 0$ or $H = 15$), log-linear continuity correction was applied (Hautus 1995):

$$\hat{H} = \frac{H + 0.5}{S + 1}, \qquad \hat{F} = \frac{F + 0.5}{N + 1}$$

where $S = 15$ (number of targets) and $N = 15$ (number of decoys). The discriminability index was then computed as:

$$d' = z(\hat{H}) - z(\hat{F})$$

where $z(\cdot)$ denotes the inverse cumulative standard normal distribution. Higher values of d' indicate greater ability to discriminate old from new items, with $d' = 0$ indicating chance-level performance.

The response criterion, indexing response bias, was computed as:

$$c = -\frac{1}{2}\left[z(\hat{H}) + z(\hat{F})\right]$$

A criterion of $c = 0$ indicates no response bias (unbiased), $c > 0$ indicates a conservative bias (tendency to respond "not seen"), and $c < 0$ indicates a liberal bias (tendency to respond "seen"). These calculations were performed using the `psycho::dprime()` function in R, with the `adjusted = TRUE` parameter to implement log-linear correction.

Assumption Checking

Before conducting any statistical analysis, all dependent variables (d', hit percentage, false alarm percentage, and c) were assessed to ensure they met the assumptions for parametric tests.

First, the normality of the distributions for each variable was evaluated within each condition (Heat and No-Heat). This was accomplished through a combination of quantitative and visual methods: 1) *Shapiro-Wilk tests* provided a statistical test for normality, while 2) *Q-Q plots* and 3) *histograms* allowed for visual inspection of the distribution shape and deviation from theoretical normality.

Second, homogeneity of variance between the Heat and No-Heat groups was tested using *Levene's test*, which is robust to deviations from normality, supplemented by an inspection of variance ratio F-tests (A. Field, Miles, and Z. Field 2012).

Finally, for the ordinary least-squares (OLS) regression models used for complementary analysis and residual diagnostics, a standard 4-panel residual diagnostic plot was generated and visually inspected for each model. This comprehensive check included:

1. **Residuals vs. Fitted plot** to check for non-linearity and heteroskedasticity.
2. **Q-Q plot of residuals** to confirm the normality of residuals.
3. **Scale-Location plot** to verify the homogeneity of variance (homoscedasticity).
4. **Residuals vs. Leverage plot** to identify influential cases using Cook's distance contours.

These diagnostic procedures collectively informed the decision to proceed with parametric tests or to employ non-parametric alternatives where assumptions were violated.

Between-Group Comparisons

The primary hypothesis, that thermal stress impairs intersection recognition sensitivity, was tested by comparing d' values between the Heat and No-Heat conditions using Welch's independent-samples *t*-test. Welch's test was selected because it does not assume equal variances and remains robust to moderate violations of normality (ibid.). To understand the specific aspect of recognition where a difference was observed, d', hit rates, and false alarm rates were also compared between the two groups through the same testing.

Effect sizes for all between-group comparisons were quantified using the point-biserial correlation coefficient (r), which is appropriate for dichotomous predictors and continuous outcomes. According to the guidelines by Cohen (1988), an (r) of 0.10, 0.30, and 0.50 is considered a small, medium, and large effect size, respectively.

In addition to the primary sensitivity analysis, the response criterion (c) was examined as a secondary analysis to determine whether thermal stress altered participants' overall response strategy (i.e., their willingness to respond "seen"). One-sample *t*-tests within each condition tested whether c differed significantly from zero (which would indicate biased responding), and an independent-samples *t*-test compared c between the Heat and No-Heat conditions.

Note on OLS Regression Models: In order to keep consistent with other spatial navigation studies that commonly report regression coefficients, and to enable thorough residual diagnostics through 4-panel diagnostic plots, ordinary least squares (OLS) regression models were fitted in parallel with the *t*-tests. The regression models used d', hit rate, and false alarm rate as dependent variables, each regressed onto the factor Condition (coded as No-Heat = 0, Heat = 1). The model specification was:

$$Y_i = \beta_0 + \beta_1 \cdot \text{Condition}_i + \varepsilon_i$$

where Y_i represents the dependent variable, β_0 estimates the mean for the No-Heat group, and β_1 estimates the difference in means (Heat-No-Heat).

However, since OLS regression with one dichotomous predictor is mathematically equivalent to an independent samples t-test when equal variances are assumed, and because Welch's *t*-test is a more robust alternative when equal variances are not guaranteed. Both of these OLS regressions confirmed satisfaction of assumptions (as described in Section 3.4.2), although these coefficients are not reproduced here in order to avoid redundancy.

Rationale for Not Using ANOVA: A repeated-measures ANOVA was not conducted for d' because d' is inherently a participant-level aggregate index. Specifically, d' pools all 15 target intersections (on-route) with a single set of 15 decoy intersections (off-route) across the entire recognition task. Attempting to apply a repeated-measures ANOVA to d' would require either 1) reusing the same decoy set across multiple within-subject conditions, which violates the statistical independence assumption, or 2) arbitrarily splitting the decoy set into subsets and pairing them with target subsets, which undermines the principled coupling of targets and decoys that is fundamental to the SDT framework. Neither approach is methodologically sound. Therefore, between-group comparisons of d' are appropriately restricted to independent-samples tests (*t*-tests or equivalent OLS regression), which correctly treat d' as a single summary measure per participant (Kapaj, Hilton, and Fabrikant 2024).

3.4.3 Route Direction Accuracy

To assess participants' memory for the specific turns taken during navigation, route direction accuracy was measured using forced-choice recognition at each of the 15 on-route intersections. This measure captures participants' memory for the spatial actions performed at each decision point, thereby linking location memory to route-specific procedural knowledge (Kapaj, Hilton, Lanini-Maggi, et al. 2024).

Data Preparation and Scoring

The raw turning direction responses from the Route Recognition Questionnaire were normalized to L (left), R (right), or S (straight) and compared against the correct answer key. The response choices varied between each intersection, as not all of them offered the same turning possibilities (across the 15 Recognition items, there were 12 binary-choice and 3 ternary-choice intersections).

For each participant, route direction accuracy was computed as the proportion of correctly recalled turns:

$$\text{Route Accuracy} = \frac{\text{Number of correct turns}}{\text{Number of answered items}} \times 100$$

A weighted chance baseline was computed across the 15 items to account for varying numbers of response options. For each intersection i, chance accuracy is $1/n_i$, where n_i is the number of response options (2 or 3). The overall weighted chance baseline was:

$$\text{Chance\%} = \left(\frac{1}{15} \sum_{i=1}^{15} \frac{1}{n_i} \right) \times 100, \qquad n_i \in \{2, 3\},$$

Which evaluates to 46.67%, accounting for the mixture of 2-choice and 3-choice items.

Assumption Checking

Prior to statistical testing, the route accuracy scores were assessed for normality and homogeneity of variance following the same diagnostic procedures described in Section 3.4.2. Specifically, normality of route accuracy within each condition (Heat, No-Heat) was evaluated using Shapiro-Wilk tests, Q-Q plots, and histograms. Homogeneity of variance between groups was tested using Levene's test.

For the mixed ANOVA, an additional assumption check was performed on the within-subject difference scores (Landmark accuracy minus NoLandmark accuracy for each participant), as the normality of these difference scores is critical for valid repeated-measures inference. This was assessed using Q-Q plots and Shapiro-Wilk tests.

Statistical Analyses

Between-group differences in route direction accuracy were assessed using an independent-samples *t*-test with Condition (No-Heat vs. Heat) as a between-subjects factor, and participants' percentage of correctly recalled turns (across all 15 intersections) as the dependent variable.

To assess whether performance in each group exceeded what would be expected by random guessing, one-sample *t*-tests were conducted within each condition, testing the null hypothesis that mean accuracy equals the weighted chance baseline ($H_0 : \mu = 46.67\%$) against a two-tailed alternative.

Effect sizes were quantified using the point-biserial correlation coefficient (r), following the conventions described in Section 3.4.2.

Mixed ANOVA: Landmark Presence

To test whether the landmark presence at intersections influenced the route direction accuracy (and whether this influence differed by thermal condition), a 2 x 2 mixed ANOVA was conducted using the `ez` package. The ANOVA was built in the following way:

- **Between-subjects factor:** Condition (No-Heat vs. Heat)
- **Within-subjects factor:** Landmark Presence (Landmark vs. NoLandmark)
- **Dependent variable:** Proportion of correct turns (0 to 1)

The intersections were categorized into two groups: "Landmark" if a landmark building was present at the intersection (9 intersections) or "NoLandmark" if no landmark was present (6 intersections). For each participant, route accuracy was aggregated separately for the two landmark categories, yielding two within-subject observations per participant.

The ANOVA was performed using the `ezANOVA()` function, which computed sums of squares and reported generalized eta-squared (η^2_G) as the effect size measure (A. Field, Miles, and Z. Field 2012). Additionally, there was no need to compute a Mauchly's test of sphericity, as the within-subject factor only had two levels.

3.4.4 Eye-Tracking Analysis

To understand whether thermal stress alters visual attention allocation during spatial navigation, eye-tracking data were collected continuously during the main navigation task. The methods for this section followed closely the framework established by Kapaj, Hilton, Lanini-Maggi, et al. (2024), focusing on eye movements to quantify attention related to navigation-related environmental features. This subsection describes the data processing pipeline, quality control procedures, metric operationalization, assumption testing protocols, and statistical analyses employed.

Data Processing and Area of Interest Definition

The collected fixation data were exported from Pupil Labs Cloud and consisted of three main data files: raw fixations with timestamps (fixations.csv), aggregated metrics per AOI per recording session (AOI metrics.csv), and participant metadata linking recordings to experimental conditions (sections.csv). The following data processing was performed in R.

Four Areas of Interest (AOIs) were manually defined to capture the participants' attention to navigation-related features: 1) *Landmark* (salient buildings positioned at intersection corners, as described in Section 3.2.2), 2) *Intersection* (road junctions and the buildings immediately at intersection corners), 3) *Arrow* (the directional arrow cues that guided participants' route), and 4) *Environment* (background urban scenery, including non-landmark buildings, sky, and distant structures). These AOIs were manually annotated fixation-by-fixation in Pupil Labs Cloud for all participants. If a fixation was outside any of the AOIs (for example, within the real environment when adjusting the foot pedal), the fixation was classified as not being on any of the AOIs. Figure 3.7 shows an example of the manual AOI annotation procedure, displaying how the four regions were systematically mapped within the Pupil Cloud software.

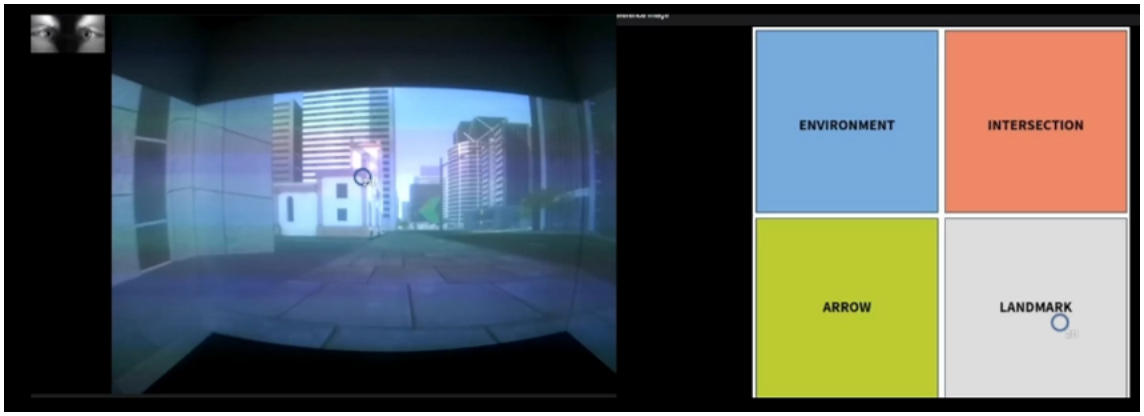

Figure 3.7: Manual area-of-interest (AOI) annotation workflow in Pupil Cloud. Left: example first-person video frame at an intersection during navigation. Right: corresponding AOI map with four mutually exclusive regions: Landmark (salient corner building), Intersection (junction area and corner buildings excluding the landmark), Arrow (directional guidance cue), and Environment (background scenery, non-landmark buildings, and sky). AOIs were manually annotated using the same spatial mapping across participants to enable AOI-based gaze metrics.

Fixation Detection and Filtering

The raw gaze data was automatically processed within the Pupil Labs Cloud software by applying their fixation detection algorithms. Their software uses a velocity-based threshold algorithm (I-VT) with optic-flow-based head-motion compensation, following recent advances in fixation detection for head-mounted eye trackers (Drews and Dierkes 2024). This approach accounts for gaze-stabilizing eye movements, which can occur during head movement. Without head-motion compensation, these compensatory movements would be misclassified as saccades by standard velocity thresholds, artificially inflating saccade counts and deflating fixation durations.

Following the example given by Kapaj, Hilton, Lanini-Maggi, et al. (2024), detected fixations were filtered to retain only those with durations between 150 ms and 2000 ms, reducing the dataset by 21.8%. The minimum duration threshold excluded saccadic eye movements and transient gaze shifts, while the maximum duration threshold removed outliers caused by tracking errors or extended gaze drift. Further, only the fixations that were mapped as being within an AOI were kept for further analysis, resulting in the removal of an additional 17.2% of all raw fixations. In total, 64.8% of all raw fixations were used for further analysis.

Trial duration was defined as the time interval from the first AOI fixation to the last AOI fixation. This definition excludes any pre-trial setup periods and post-trial time, ensuring that only the active navigation time contributes to the analysis. Trial duration was computed in nanoseconds from raw timestamps and converted to minutes for the statistical analysis.

The main dependent variable for the eye-tracking analysis was the *normalized fixation duration (nFD)*. It was calculated for each individual participant and each Area of Interest (AOI) and represents the percentage of total trial time spent fixating within a given AOI:

$$\text{nFD}_{\text{AOI}} = \left(\frac{\sum \text{Fixation Duration}_{\text{AOI}}}{\text{Trial Duration}} \right) \times 100$$

By normalizing fixation durations relative to each participant's total trial time, nFD controls for individual differences in navigation speed and allows meaningful comparisons across participants, conditions, and AOIs. Note that nFD values across all four AOIs do not sum to 100% because participants also spend time in saccadic movements, blinks, and fixations outside the defined AOIs.

Data Quality Controls and Participant Exclusion

Only one participant (Heat group) had to be excluded from all eye-tracking analyses due to missing data caused by technical recording failure. No other participants were excluded. The final sample size for eye-tracking analyses was therefore: Heat = 22 participants, No-Heat = 23 participants (N = 45 total).

Assumption Checking

Prior to conducting any statistical tests, the nFD values for each AOI were assessed for normality and homogeneity of variance following the assumption procedures described in Section 3.4.2. Specifically, normality within each condition (Heat, No-Heat) was evaluated using Shapiro-Wilk tests, Q-Q plots, and inspection of skewness and kurtosis statistics for each of the four AOIs (8 tests total: 4 AOIs × 2 conditions). Homogeneity of variance between conditions was tested using Levene's test, with variance ratios below 3:1 considered acceptable (A. Field, Miles, and Z. Field 2012).

Statistical Analyses

The primary analysis consisted of the between-group differences in nFD for each AOI (Landmark, Intersection, Arrow, Environment), which were tested using Welch's independent-samples t-test. Welch's test was chosen as it does not assume equal variances and is robust to moderate violations of normality (ibid.). The effect sizes were quantified using Cohen's d based on pooled standard deviations.

As a validation check to ensure that any observed nFD differences reflected genuine attention allocation changes rather than confounding factors, trial durations (in minutes) were compared between conditions using Welch's *t*-test. Additionally, the comparability of fixations was evaluated through between-group contrasts on average fixation duration, fixation count per participant, and the proportion of trial time spent fixating outside AOIs.

To test whether thermal stress affected attention allocation differently across AOI, a 2 (Condition: Heat vs. No-Heat; between-subjects) × 4 (AOI: Landmark, Intersection, Arrow, Environment; within-subjects) mixed-model ANOVA was performed using the `ez` package. The ANOVA tested three hypotheses: 1) main effect of Condition (overall attention differences between thermal conditions), 2) main effect of AOI (differential attention across feature types), and 3) Condition × AOI interaction (whether heat affects attention to some features more than others). The sums of squares were computed, and partial eta-squared (η^2_G) was reported as the effect size measure. Furthermore, a Mauchly's test of sphericity was applied to the within-subjects factor, and the Greenhouse-Geisser corrections were applied if sphericity was violated ($p < .05$).

As a robustness check, an Aligned Rank Transform (ART) ANOVA was conducted using the `ARTool` package. This approach gives an alternative that does not assume normality or sphericity, making it suitable for data with distributional violations. Both results from the parametric and non-parametric ANOVAs are reported for completeness and transparency.

To explore the relationship between gaze allocation and task performance, Pearson correlations were computed between nFD and behavioral outcomes (e.g., between landmark nFD and d', and between environment/intersection nFD and route accuracy). The results were displayed as a correlation matrix heatmap to visualize the associations among all eye-tracking and behavioral variables.

3.4.5 Electrodermal Activity Analysis

To understand whether thermal stress also modulates physiological arousal during spatial navigation, continuous electrodermal activity (EDA) was recorded during the main navigation task. EDA provides a direct index of sympathetic nervous system activation, reflecting the body's autonomic response to cognitive load, environmental stressors, and emotional states (Benedek and Kaernbach 2010a; Boucsein 2012). The analysis decomposes EDA into its *tonic* (slowly varying baseline arousal) and *phasic* (rapid responses to discrete events) components (Greco, Valenza, and Scilingo 2016), which allows for a more detailed analysis of potential arousal both at trial and intersection levels. The analysis framework consisted of four sequential levels: 1) pre-task baseline extraction, 2) manipulation check comparing baseline arousal between groups, 3) trial-level analysis with baseline correction, 4) intersection-level analysis examining arousal at decision points, and 5) temporal dynamics analysis of arousal trajectories at intersections.

Data Acquisition and Signal Processing

The EDA was recorded using the BITalino (r)evolution device, as it is a low-cost, easy-to-use, and also demonstrated to be reliable in comparison to established EDA recording devices (Batista et al. 2019). The system samples EDA signals continuously at a rate of 100 Hz throughout the main navigation task, providing adequate temporal resolution for detecting both tonic and phasic electrodermal components

(Moos 2025). The recording began immediately after sensor attachment and was stopped after completing the main navigation task, yielding continuous EDA.

Raw EDA data was processed with a custom R script to decompose the EDA into its tonic and phasic components following established psychophysiological methods (Benedek and Kaernbach 2010a; Boucsein 2012; Moos 2025). The tonic component (SCL) was extracted through double-pass moving average smoothing: a 5-sample (50 ms at 100 Hz) moving average filter was applied twice in succession, reducing high-frequency noise while preserving slow-wave tonic variations and removing phasic responses (Benedek and Kaernbach 2010a).

The phasic component (SCR) was isolated by applying a second-order Butterworth high-pass filter with a 0.05 Hz cutoff frequency to the tonic SCL signal, using zero-phase forward-reverse filtering to avoid phase distortion. This 0.05 Hz cutoff falls within the standard range of time constants (0.5–5 s) recommended for separating phasic from tonic electrodermal activity (Horvers et al. 2021). The filtered phasic signal was then normalized to a 0–100 scale for each participant to account for individual differences in baseline conductance range, and negative values (artifacts of filtering) were rectified to zero.

Individual SCR peaks were detected using the `pracma::findpeaks()` function. To distinguish genuine phasic responses from baseline noise, a minimum peak height of 10 units was applied, given the normalization of the data. Furthermore, a 2-second inter-peak interval was enforced to prevent any double-counting of multi-peaked responses.

Temporal Segmentation and Synchronization

To align the physiological data with the navigation events, the trial start and end times were extracted from the Lab Streaming Layer marker streams using the `pyxdf` Python library interfaced via R. Three temporally distinct periods were defined for analysis:

1. Pre-Task Baseline Period: All EDA data recorded before the "StartGame" marker, representing participants' resting arousal state before the main navigation task. Critically, for participants in the Heat condition, this baseline period occurred *after* infrared lamp activation-lamps were turned on immediately following sensor attachment and remained active throughout the 5-minute familiarization phase. Therefore, the pre-task baseline captured participants' arousal during passive heat exposure (Heat group) versus neutral ambient temperature (No-Heat group) before any navigation demands. This baseline period duration varied naturally across participants (M = 153.6 s, range = 24.5–425.6 s), depending on sensor setup time and familiarization duration. For each participant, baseline SCL was computed as the mean tonic level across this pre-task period, providing an individual reference value for subsequent baseline correction.

2. Trial Period (Main Navigation Task: EDA data from the "StartGame_ENTER" LSL marker to the final Point of Interest (POI) timestamp, capturing the complete 15-intersection navigation sequence. This period represents active navigation under either heat or neutral conditions. Note: This approach worked for almost all participants, except for one, as the XDF file was corrupt and therefore the complete BITalino recorded time was used as the trial period in the analysis.

3. Intersection Periods: To understand arousal dynamics at the intersections, EDA signals were further segmented into the intersection-specific epochs using the DirectionTrigger markers from the Unity environment. Each of the 15 intersections was defined by an entry timestamp (`DirectionTrigger[N]_ENTER`), which was triggered when the navigational arrow cue appeared (upon entering the detection zone before the physical intersection), and lasted until 8 seconds after the (`DirectionTrigger[N]_EXIT`) marker. This window ($\sim$12 seconds total) captures the complete navigation sequence: cue detection, decision making, and the physical crossing of the intersection.

   To account for the slow kinetics of tonic SCL (Benedek and Kaernbach 2010b), the temporal dynamics of each intersection was decomposed into three distinct functional epochs: 1) Baseline approach, the 8 seconds before the navigation cue (pre-ENTER), 2) Decision Phase, the $\sim$4-second window between `ENTER` and `EXIT` (cue visible) and 3) the 8 seconds immediately following `EXIT` and therefore crossing the intersection.

Figure 3.8 illustrates how baseline-corrected SCL isolates task-related arousal changes.

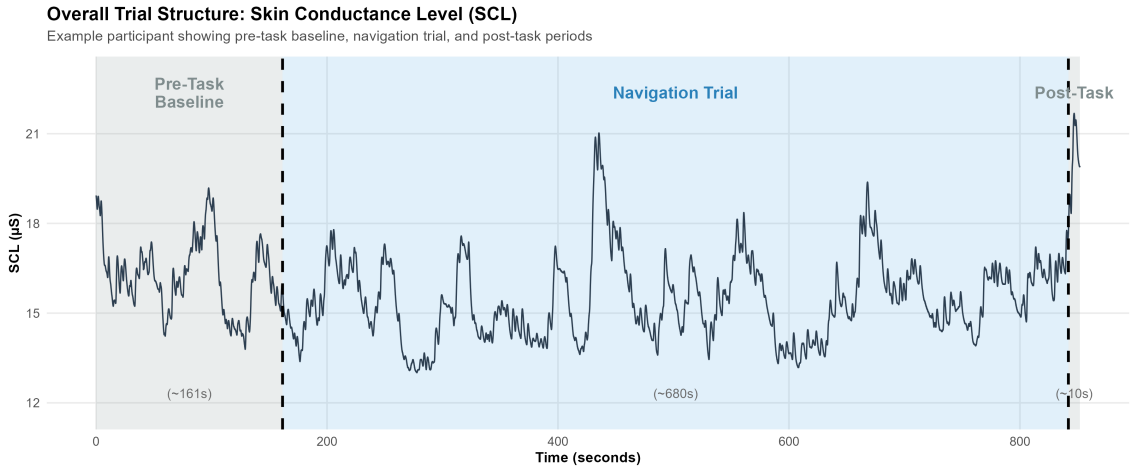

Figure 3.8: Trial-level EDA temporal segmentation and baseline correction. Skin conductance level (SCL) was baseline-corrected as the difference between the mean navigation-trial SCL and the mean pre-task baseline SCL. For participants in the Heat condition, the baseline period was recorded after lamp activation during the familiarization phase to quantify passive heat effects independent of navigation demands.

Figure 3.9 defines the two arousal transition indices derived from intersection-level phase segmentation.

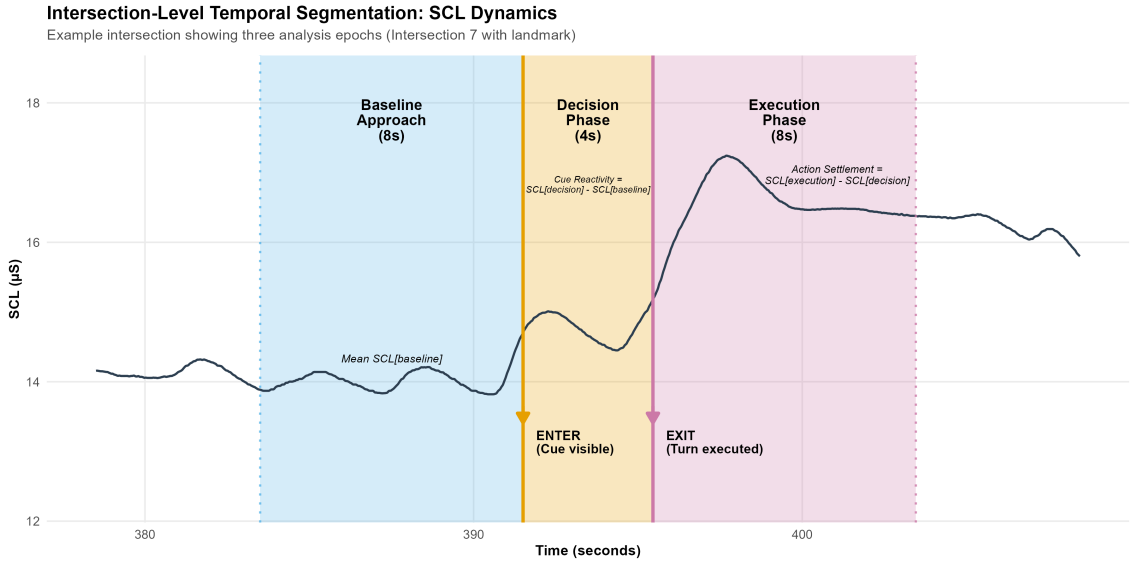

Figure 3.9: Intersection-level EDA temporal segmentation into three functional phases. Two arousal transition indices were derived: Cue Reactivity (Decision SCL - Baseline SCL), reflecting the immediate physiological response to cue appearance, and Action Settlement (Execution SCL - Decision SCL), reflecting whether arousal is sustained or diminishes during intersection crossing. This three-phase structure was applied to all 15 intersections for each participant.

Derived Metrics from EDA analysis

Following established EDA analysis frameworks (Horvers et al. 2021), the following arousal indices were computed to capture different aspects during the task:

Trial-Level Metrics:

- **Mean SCL** (μS): Average tonic arousal level across the trial.
- **SCL Corrected** (μS): Mean trial SCL minus pre-task baseline SCL, isolating task-related arousal changes.
- **Percent Change from Baseline** (%): Proportional change from baseline to trial SCL.
- **SCR Rate** (peaks/min): Frequency of phasic responses normalized to events per minute.

Note: The baseline-corrected SCL served as the primary outcome measure for trial-level analyses, as it accounts for pre-existing arousal differences and isolates stress-induced changes. Raw (uncorrected) Mean SCL was computed for completeness and quality assurance, but is not reported separately in the Results section to avoid redundancy; the pattern of findings was consistent across corrected and uncorrected metrics. Auxiliary indices (standard deviation of SCL and total SCR count) were also derived to support quality checks and exploratory inspection of variability and peak frequency, but are not reported in detail as they did not provide substantively different information from the primary metrics.

Intersection-Level Metrics:

- **Mean SCL during intersection** (μS): Tonic arousal during the decision and crossing sequence.
- **Mean SCL Corrected** (μS): Intersection SCL minus Pre-Task Baseline SCL.
- **SCR Rate at intersection** (peaks/min): Phasic response frequency within the intersection window.

As with trial-level metrics, raw (uncorrected) intersection SCL was computed but not separately reported in the Results. Further intersection-level descriptors (within-intersection SD of SCL and the raw number of SCR peaks) were calculated for exploratory purposes and data-quality inspection, but are not used as main dependent variables in the inferential analyses.

Temporal Dynamics Metrics:
To understand how arousal changed when approaching and leaving an intersection, EDA was analyzed across the three functional epochs defined above (Baseline approach, Decision, Execution). For each epoch, Mean SCL and a linear SCL slope (in μS/s) were estimated to capture the level and rate of change in tonic arousal. On this basis, two transition metrics were defined as the main indices of dynamic change:

- **Cue Reactivity** (μS): Change in Mean SCL from Baseline to the Decision phase (Decision $-$ Baseline), indexing the immediate physiological response to the navigational instruction.
- **Action Settlement** (μS): Change in Mean SCL from the Decision phase to the Execution phase (Execution $-$ Decision), reflecting whether arousal is sustained or settles once the motor action is initiated.

In addition, an exploratory SCL slope metric was computed as the change in the linear SCL slope between phases (e.g., Decision $-$ Baseline), assessing whether the rate of arousal generation accelerated or decelerated upon seeing the cue. This slope metric is used descriptively and in a global profile test, but is not central to the mixed-model analyses.

Statistical Analyses

Manipulation Check: Pre-Task Baseline Comparison

To assess whether thermal exposure *alone* (independent of navigation) elevated sympathetic arousal, pre-task baseline SCL and SCR rate were compared between Heat and No-Heat conditions. Critically, this baseline period occurred after thermal lamp activation for the Heat group: infrared lamps were turned on immediately after sensor attachment and remained active throughout the 5-minute familiarization phase. Therefore, the pre-task baseline captured participants' arousal state during passive heat exposure (Heat group) versus neutral temperature (No-Heat group) before initiating navigation. This comparison serves as a pure thermal manipulation check: if heat exposure increases physiological arousal independent of cognitive task demands, this should manifest as an elevated baseline SCL or SCR rate in the Heat group during this pre-navigation period.

Normality of baseline metrics within each condition was assessed using Shapiro-Wilk tests. For metrics violating normality ($p < .05$), non-parametric Mann-Whitney U tests were conducted. For metrics meeting normality assumptions, independent-samples t-tests were used with Welch's correction applied when Levene's test indicated unequal variances. Effect sizes were quantified using Cohen's d.

Trial-Level Comparisons

Between-group differences in baseline-corrected SCL (primary outcome) and SCR rate during the navigation task were assessed using independent-samples *t*-tests. Baseline-corrected SCL was computed as:

$$\text{SCL}_{\text{corrected}} = \text{SCL}_{\text{navigation}} - \text{SCL}_{\text{baseline}}$$

where $\text{SCL}_{\text{baseline}}$ represents mean tonic arousal during the pre-task period (including familiarization with lamps active for the Heat group), and $\text{SCL}_{\text{navigation}}$ represents mean arousal during the main 15-intersection navigation task. This correction isolates task-related arousal changes from each participant's pre-task baseline. For the Heat group, this reflects arousal change from passive heat exposure to active navigation under heat; for the No-Heat group, it reflects arousal change from passive neutral conditions to active navigation.

This correction isolates the task-related arousal changes from each participant's pre-task baseline. For the Heat group, this reflects arousal change from passive heat exposure to active navigation under heat; for the No-Heat group, it reflects arousal change from passive neutral conditions to active navigation. This approach allowed for the detection of thermal effects on navigation arousal responses.

Intersection-Level Mixed-Effects Models

To account for the repeated-measures structure of the data (15 intersections per participant) and strong deviations from normality in intersection-level SCL and SCR rate, Aligned Rank Transform (ART) mixed models were fitted. ART is a non-parametric approach that applies a preprocessing step to align and rank data separately for each effect before conducting a mixed-effects ANOVA, thereby enabling factorial analysis of non-normal data. The models included thermal condition (Heat vs. No-Heat) as a between-subjects factor, landmark presence (Landmark vs. No-Landmark) as a within-subjects factor, and random intercepts for participants to account for between-person variability and non-independence of repeated observations:

$$\text{art}(\text{EDA}_{\text{metric}}) \sim \text{Condition} \times \text{Landmark} + (1 \mid \text{Participant})$$

Temporal Dynamics

The temporal dynamics of arousal across the intersection sequence were analyzed in two steps. First, overall changes in SCL (Cue Reactivity, Action Settlement, and the SCL slope difference between phases) were assessed with one-sample *t*-tests across all intersection events to establish the general physiological response profile. Second, to examine whether these dynamic responses differed by thermal condition and landmark presence, ART mixed models were fitted for the Cue Reactivity and Action Settlement change scores, using the same fixed-effect structure as above (Condition, Landmark Presence, and their interaction, with random intercepts for participants). As with the intersection-level analysis, consistent deviations from normality in the change scores motivated the use of non-parametric ART models.

Chapter 4

Results

This chapter presents the empirical findings of the study, structured to address the three overarching research questions defined in Section 1.3. First, Section 4.1 analyzes baseline measures to ensure group comparability and validates the thermal manipulation. Section 4.2 addresses the impact of thermal stress on spatial memory (RQ1a), specifically intersection recognition performance. Section 4.3 examines route direction accuracy (RQ1b) and the role of landmark presence (RQ1c). Section 4.4 reports on visual attention allocation (RQ2) and its relationship to memory performance. Finally, Section 4.5 analyzes physiological arousal (RQ3) at the trial and intersection levels.

4.1 Baseline Measures and Manipulation Check

To ensure that any observed group differences reflect the thermal manipulation rather than any pre-existing differences, participant characteristics, baseline navigation ability, and thermal sensation were assessed. Furthermore, the post-task thermal comfort questionnaire enables the validation of the effectiveness of the experimental manipulation.

Table 4.1: Participant Demographics, Baseline Measures, and Manipulation Check by Condition (Heat vs No-Heat). Values are mean (SD) unless otherwise stated. Group comparisons use Welch's *t*-tests for continuous variables and χ^2 tests for categorical variables; *df* denotes degrees of freedom and *d* denotes Cohen's *d* effect size.

Measure	**Heat** *M (SD)*	**No-Heat** *M (SD)*	***t* / χ^2**	***df***	***p***	***d***
Demographics						
Age (years)	23.9 (2.5)	24.0 (2.3)	-0.06	43.8	.951	0.02
Gender (M/F)	12/11	12/11	0.00	1	>.99	-
Baseline Measures						
SBSOD Score	3.95 (0.33)	3.98 (0.39)	-0.32	42.6	.751	0.09
TSQ (Baseline)	3.01 (0.85)	2.89 (1.09)	0.43	41.3	.671	0.13
Manipulation Check						
TCQ (Post-Task)	3.74 (0.45)	4.55 (0.28)	-7.34	36.9	<.001	2.16

4.1.1 Participant Characteristics

A total of 46 participants signed up for the study, filled out all questionnaires, and completed the main navigation task. One participant in the Heat condition was excluded from eye tracking analyses due to missing data from a software recording error, resulting in a final eye tracking sample of 45 participants (22 Heat, 23 No-Heat).

As shown in Table 4.1, groups were very well-matched on all baseline characteristics. Age did not differ between the conditions ($t(43.8) = -0.06$, $p = .951$, Cohen's $d = 0.02$), with both groups averaging approximately 24 years old. Gender distribution was identical across conditions (12 males, 11 females per group; $\chi^2(1) = 0$, $p > .99$).

4.1.2 Santa Barbara Sense of Direction Scale (SBSOD)

The SBSOD questionnaire (Hegarty, Richardson, et al. 2002) was used to assess participants' self-reported spatial navigation ability before the experiment.

Assumption tests revealed violation of SBSOD scores in the Heat condition (Shapiro-Wilk: $W = 0.834$, $p = .001$), whereas the No-Heat condition met normality assumptions ($W = 0.938$, $p = .160$). To check the variances, Levene's test was used, which revealed equal variances between groups ($F(1, 44) = 1.01$, $p = .320$).

Due to the non-normal distribution in the Heat group, the robust Welch's t-test was employed for the group comparison. As detailed in Table 4.1, no significant difference was found between the conditions ($t(42.6) = -0.32$, $p = .751$, Cohen's $d = 0.09$). Therefore, the two groups did not differ in their baseline spatial navigation ability, confirming that the participants were well distributed across both groups in this dimension prior to the thermal manipulation.

4.1.3 Thermal Sensation Questionnaire (TSQ) - Baseline

To confirm that both groups did not differ in initial self-reported thermal sensation (how they perceive heat), the TSQ was used.

Both assumption tests were validated with normality being met by both groups (Heat: $W = 0.958$, $p = .424$; No-Heat: $W = 0.964$, $p = .555$), and variances were homogeneous (Levene's test: $F(1, 44) = 2.17$, $p = .147$).

As shown in Table 4.1, baseline thermal sensation did not differ significantly between conditions ($p = .671$). Therefore, participants in both conditions have similar thermal sensations, confirming that any post-manipulation differences reflect the experimental intervention rather than initial group differences.

4.1.4 Thermal Comfort Questionnaire (TCQ) - Post-Task

To validate whether the experimental design worked and the participants perceived the heat as discomforting, the TCQ was used directly after the main navigation task.

Assumption tests revealed that the Heat condition met normality ($W = 0.983$, $p = .955$), whereas the No-Heat condition showed a marginal violation ($W = 0.891$, $p = .017$). Furthermore, the variances were marginally heterogeneous (Levene's test: $F(1, 44) = 3.40$, $p = .072$), justifying the use of Welch's t-test.

Thermal comfort differed highly significantly between conditions (Heat: $M = 3.74$, $SD = 0.45$; No-Heat: $M = 4.55$, $SD = 0.28$), $t(36.9) = -7.34$, $p < .001$, Cohen's $d = 2.16$. The Heat condition reported substantially lower thermal comfort (18% reduction) compared to the No-Heat condition, representing a very large effect size.

Therefore, the thermal manipulation successfully created distinct subjective thermal experiences between conditions, validating the experimental design.

4.2 Intersection Recognition (RQ1a)

To address *RQ1a*, this section examines how thermal stress impacted the specific memory for intersections. Participants' ability to recognize seen versus unseen intersections was assessed using a yes/no recognition task. For this task, participants completed a recognition questionnaire on 30 intersection images: 15 target images that had been encountered during the navigation task and 15 decoy (unseen) intersection images. For each participant, discriminability d' was quantified using signal detection theory (SDT), calculated with a log-linear correction to account for extreme hit and false alarm rates (Hautus 1995). Hit rates and false alarm rates were also calculated as secondary measures. The two conditions (no-heat and heat) were compared using independent-samples t-tests (A. Field, Miles, and Z. Field 2012).

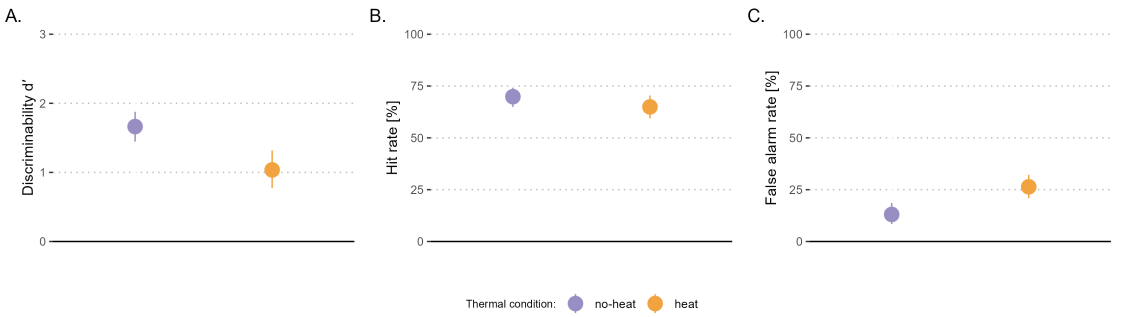

Figure 4.1: Intersection recognition performance by condition. (A) discriminability (d'), (B) hit rate, and (C) false alarm rate for intersections encountered during navigation. Points show group means; error bars indicate 95% confidence intervals.

4.2.1 Discriminability d'

The mean discriminability was higher in the no-heat condition $M = 1.66$, SE $= 0.12$, 95% CI $[1.42, 1.91]$, SD $= 0.57$ compared to the heat condition $M = 1.04$, SE $= 0.14$, 95% CI $[0.74, 1.33]$, SD $= 0.68$.

To test for any violations of normality in d' a Shapiro-Wilk test was used yielding: no heat $W = 0.98, p = .912$ and heat $W = 0.96, p = .486$). Furthermore, Levene's test for homogeneity of variance indicated equal variances between groups ($F(1, 44) = 0.71, p = .403$).

The independent-samples Welch t-test revealed a significant difference in discriminability between the conditions with $t(42.5) = 3.38, p = .002$. The heat condition showed a lower discriminability than the no-heat condition (mean difference $= 0.63$ d' units, 95% CI $[0.25, 1.00]$). This represents a moderate-to-large effect size, $r = .46$.

Therefore, heat exposure significantly impaired participants' ability to discriminate previously seen intersections from novel intersections. This finding supports *Hypothesis H1a*, which predicted reduced discriminability under thermal stress.

4.2.2 Hit Rate

The calculated mean hit rate in the no-heat condition was 69.86% SE $= 2.51, 95\%$ CI $[64.65, 75.06]$, SD $= 12.04$, and 64.93% in the heat condition SE $= 3.03, 95\%$ CI $58.65, 71.21]$, SD $= 14.53$.

Assumption testing revealed that hit rates in the no-heat condition significantly violated normality (showcased with Shapiro-Wilk: $W = 0.79, p < 0.001$), whereas the heat condition met normality assumptions $(W = 0.95, p = .346)$. A further Levene's test indicated equal variances between groups $(F(1, 44) = 1.50, p = .227)$. Given this violation, hit rate results should be interpreted with caution; however, d' (the main outcome) met all parametric assumptions.

Lastly, the independent-samples t-test showed no significant difference in hit rates between conditions, $t(44) = -1.25, p = .217, r = .19$.

Therefore, thermal stress did not significantly impair the ability to correctly endorse previously seen items. This result offers only partial support for *Hypothesis H1a*, as the predicted reduction in hit rates was not statistically confirmed.

4.2.3 False Alarm Rate

The calculated mean false alarm rate in the no-heat condition was 13.04% SE $= 2.70, 95\%$ CI $[7.45, 18.64]$, SD $= 12.95$, and 26.38% in the heat condition SE $= 3.07, 95\%$ CI $[19.74, 33.02]$, SD $= 14.70$.

Similar to the hit rate assumption tests, the Shapiro-Wilk test indicated a violation of normality in the no-heat condition $W = 0.84, p = .002$, whereas the heat condition met normality assumptions $(W = 0.97, p = .694)$. A further Levene's test indicated equal variances $(F(1, 44) = 0.75, p = .393)$.

The independent-samples t-test revealed a significant increase in false alarm rates under heat exposure with $t(44) = 3.27, p = .002$. This represents a moderate effect size $(r = .44)$. The participants in the heat condition incorrectly labeled, on average, 13.33% more unseen intersections as "seen" than those in the no-heat condition.

Therefore, heat exposure significantly increased a participant's tendency to incorrectly identify decoy intersections as having been previously encountered. This aligns with *Hypothesis H1a*, confirming that thermal stress increases false alarm errors.

4.2.4 Response Bias c

To understand whether participants showed a tendency to consistently say "yes" or "no" more often than expected, one-sample t-tests were conducted for each condition. A value of $c = 0$ indicates no bias, whereas positive values indicate that participants were more likely to say "no" (responding "not seen"), and negative values indicate they were more likely to say "yes" (responding "seen").

In the no-heat condition, the response bias c was significantly greater than zero with ($M = .33$, $SE = .07$, 95% CI $[.18, .48]$; $t(22) = 4.57$, $p < .001$), therefore suggesting that participants tended to say "no" more often than expected. For the heat condition, the response bias c was also significantly greater than zero with ($M = .14$, $SE = .06$, 95% CI $[.02, .25]$; $t(22) = 2.46$, $p = .022$), however showing a smaller bias.

The difference in response bias between the conditions was proven to be significantly different with $t(41.2) = 2.13, p = .039$ (mean difference $= .19$, 95% CI $[.01, .38]$). Participants in the no-heat condition showed a stronger tendency to say "no" ($M = .33$) compared to those in the heat condition ($M = .14$).

Therefore, heat exposure affected the response bias by reducing it, meaning that participants from the heat group were more likely to label an intersection as seen, compared to the no-heat group.

4.3 Route Direction Accuracy (RQ1b & RQ1c)

Addressing *RQ1b*, this section assesses whether thermal stress affected the ability to recall the correct turning direction (Left/Right/Straight) at encountered intersections. After completing the Intersection Recognition task, participants completed a 15-item direction recognition task that included all encountered intersections in the route. The route comprised 15 intersections: 12 offering two directional alternatives and 3 offering three alternatives, which resulted in a weighted chance baseline of 46.67%.

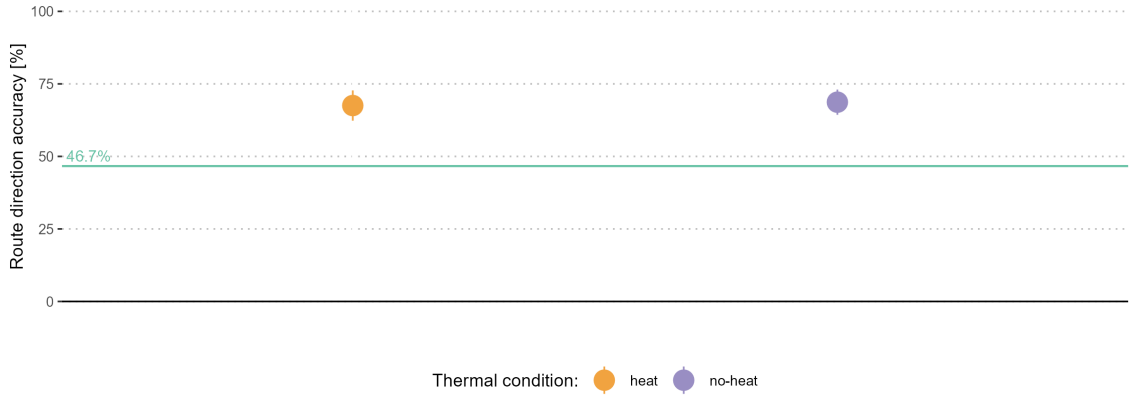

Figure 4.2: Route direction accuracy by condition. Points represent group means; error bars indicate 95% confidence intervals. The horizontal line marks the weighted chance level (46.67%) based on the task's response structure.

4.3.1 Overall Accuracy by Condition

The overall accuracy was high for both groups, with the no-heat condition having ($M = 68.70\%$, $SE = 2.39$, 95% CI $[63.75, 73.65]$, $SD = 11.45$), and the heat condition ($M = 67.54\%$, $SE = 2.73$, 95% CI $[61.88, 73.19]$, $SD = 13.07$).

Shapiro-Wilk tests confirmed that the assumption of normality was met for both the No-Heat ($W = 0.90, p = .20$) and Heat conditions ($W = 0.90, p = .09$). Levene's test confirmed homogeneity of variance ($F(1, 44) = 0.11, p = .74$).

The independent-samples t-test confirmed no significant difference between the two groups with $t(44) = -.32$, $p = .751$, effect size $r = -.05$. The difference in mean accuracy was -1.16 percentage points ($SE = 3.62$) with model fit $R^2 = .002$ and residual SD $= 12.29$.

In addition, both groups performed well above the weighted chance level of 46.67%. One-sample t-tests revealed significantly higher accuracy than chance for no-heat ($t(22) = 9.23$, $p < .001$, 95% CI $[63.75, 73.65]$), and for heat ($t(22) = 7.66$, $p < .001$, 95% CI $[61.88, 73.19]$).

Therefore, contrary to *Hypothesis H1b*, thermal stress did not impair route direction memory. Wayfinding knowledge appears to be robust to the thermal stressor, even when recognition memory is impaired.

4.3.2 Landmark Presence × Condition

To examine whether the presence of distinctive landmarks at intersections influenced recognition accuracy and whether this effect depended on the thermal condition (addressing *Hypothesis H1c*, a two-way mixed ANOVA (within–subject factor: LandmarkPresence [Landmark vs. NoLandmark]; between–subject factor: Condition [no-heat vs. heat]) was run on the per-participant cell means (DV = accuracy proportion).

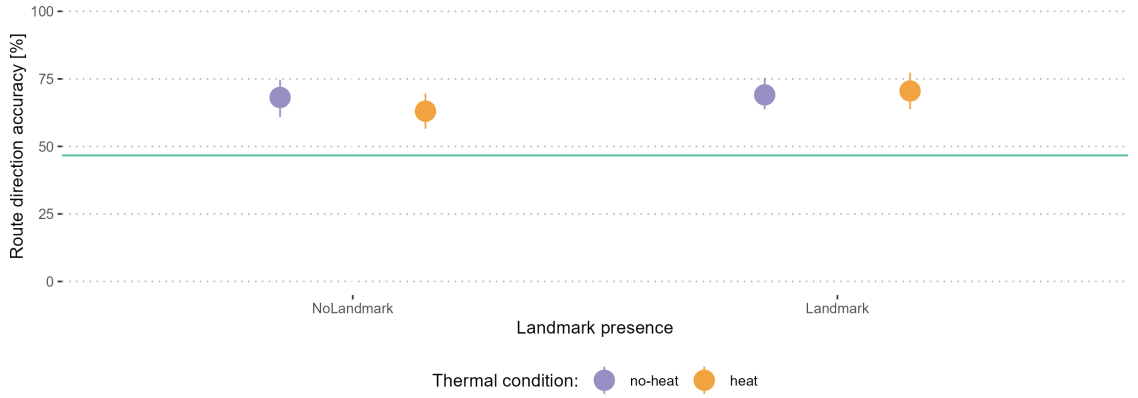

Figure 4.3: Route direction accuracy (%) by landmark presence and condition. Dots = cell means; error bars = 95% CI; horizontal line = chance baseline (46.67%).

The group means for the landmark intersections were $M = .69$, $SE = .03$ for the no-heat group and $M = .71$, $SE = .03$ for the heat group. For non-landmark intersections the no-heat group had $M = .68$, $SE = .04$ and the heat group $M = .63$, $SE = .03$.

The Shapiro-Wilk test for normality assumption testing showed normality for the difference scores ($W = .98$, $p = .42$) and the Levene's test showed variance equality with ($F(1, 44) = .11$, $p = .74$).

The conducted mixed ANOVA showed no significant main effect of the Condition ($F(1, 44) = .25$, $p = .62$), no significant main effect of Landmark Presence ($F(1, 44) = 1.77$, $p = .19$), nor any significant interaction ($F(1, 44) = 1.06$, $p = .31$); all effect sizes (generalized η^2)) were below .02.

The heat group, however, showed a slightly higher accuracy for intersection with landmark presence ($M = .71$) compared to non-landmark intersections ($M = .63$). Nonetheless, this difference did not reach statistical significance.

Therefore, *Hypothesis H1c* is rejected. The presence of salient landmarks did not reliably improve route direction accuracy in either condition, and heat exposure did not modulate this effect.

4.4 Visual Attention (RQ2a & RQ2b)

To address *RQ2*, eye-tracking data were analyzed across two main questions. First, *RQ2a* examines how thermal stress changed visual attention allocation across four Areas of Interest (AOIs: Landmark, Intersection, Arrow, and Environment). Second, *RQ2b* investigates whether visual attention to these features predicted memory performance, and whether this relationship varied by thermal condition. The results for RQ2a are presented in Sections 4.4.1–4.4.6, followed by RQ2b in Section 4.4.7

4.4.1 Data Preparation and Quality Control

The collected eye-tracking data was available from 45 participants (22 Heat, 23 No-Heat), as for one participant, the recording was missing due to a software error. As stated in the method section 3.4.4, only the fixations with durations between 150ms and 2000ms were kept, reducing the dataset from 101'039 to 79'018 fixations (21.8% removed). Furthermore, only the fixations that were within the four

pre-defined Areas of Interest (AOIs: Landmark, Intersection, Arrow, Environment) during the active trial period (defined as the time from the first to the last AOI fixation) were included in the analysis (N = 65'446 fixations).

The trial duration was calculated as the time between the first and last AOI fixation with the mean trial time of 12.5 minutes across both conditions (SD = 1.5, range = 10.9-17.6 minutes) and did not differ significantly between the conditions $t(37) = 0.26$, $p = .795$, $d = 0.08$. Therefore, group differences in fixation patterns are not the result of different task completion times.

4.4.2 Descriptive Statistics

The Table 4.2 presents the normalized fixation duration (nFD; calculated as total fixation duration on each AOI divided by trial duration, expressed as a percentage) for each AOI by condition. To address *RQ2*, eye-tracking data were analyzed across two main questions. First, *RQ2a* examines how thermal stress changed visual attention allocation across four Areas of Interest (AOIs: Landmark, Intersection, Arrow, and Environment). Second, *RQ2b* investigates whether visual attention to these features predicted memory performance, and whether this relationship varied by thermal condition. The results for RQ2a are presented in Sections 4.4.1–4.4.6, followed by RQ2b in Section 4.4.7

Table 4.2: Descriptive statistics for normalized fixation duration (nFD) by area of interest (AOI) and condition. Values are mean (SD). Differences are computed as Heat minus No-Heat; percent change is relative to the No-Heat mean.

AOI	Heat M(SD)	No-Heat M(SD)	Difference	% Change
Landmark	6.93 (3.58)	10.8 (3.11)	-3.85	-35.7
Intersection	20.8 (7.89)	27.6 (7.19)	-6.82	-24.7
Arrow	2.52 (1.71)	4.21 (1.94)	-1.69	-40.1
Environment	35.6 (7.01)	40.2 (5.73)	-4.56	-11.3

Visual inspection revealed that participants in the Heat condition spent less time fixating on all AOIs as compared to the No-Heat condition. The full distributions of nFD by AOI and condition are illustrated in Figure 4.4.

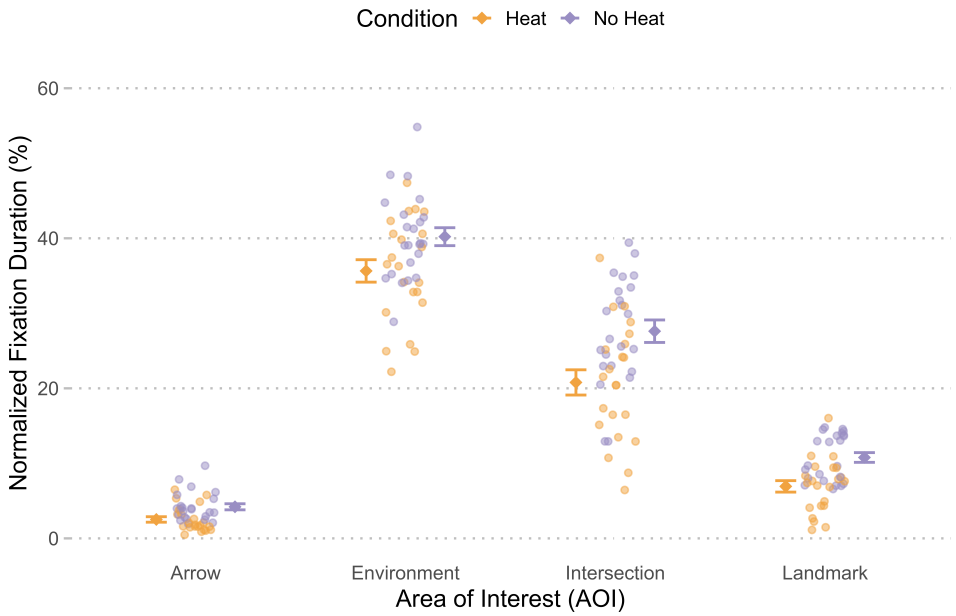

Figure 4.4: Distribution of nFD by AOI and condition (boxplots and individual data points). Thermal stress is associated with a generalized reduction in attention across all categories.

Therefore, thermal stress reduced the time spent fixating on each of the four areas of interest.

4.4.3 Assumption Testing

Before conducting any parametric analyses, the normality of the data was assessed using Shapiro-Wilk tests, and to assess the homogeneity of variance, Levene's test was used for each AOI.

Normality

The data within the Intersection AOI showed normal distributions in both groups (Heat: $W = 0.988$, $p = .993$ and No-Heat: $W = 0.959$, $p = .446$). For the Landmark AOI, only the heat condition met normality assumptions with $W = 0.957$, $p = .427$, whereas the No-Heat condition showed a significant deviation from normality with $W = 0.845$, $p = .002$. The Arrow AOI showed deviation from normality for both conditions with Heat: $W = 0.856$, $p = .004$ and No-Heat: $W = 0.876$, $p = .008$. Lastly, the Environment AOI showed normal distributions for both groups with Heat: $W = 0.961$, $p = .519$ and No-Heat: $W = 0.969$, $p = .659$.

Therefore, given these mixed results and the robustness of ANOVA to moderate violations of normality with reasonably balanced groups, the subsequent analysis used parametric tests but also conducted non-parametric Aligned Rank Transform (ART) ANOVA as a robustness check.

Homogeneity of Variance

Using Levene's test, homogeneity of the variances was assessed across all AOIs which indicated equal variances across all AOIs: Intersection: $F = 0.14$, $p = .712$, variance ratio < 1.3; Arrow: $F = 0.08$, $p = .773$, variance ratio < 1.3; Landmark: $F = 0.08$, $p = .781$, variance ratio < 1.4; Environment: $F = 1.48$, $p = .231$, variance ratio < 1.6.

Therefore, the assumption of homogeneity of variances was met for all AOIs, as all variance ratios were below the threshold of 3:1.

4.4.4 Primary Analysis: Independent Samples *t*-Tests

Independent-samples Welch's *t*-tests were conducted to compare nFD between conditions for each AOI (Table 4.3). Given violations of normality for some variables, Welch's test was chosen for its robustness to unequal variances and non-normality. The results can be seen in Table 4.3.

Table 4.3: Between-condition comparisons of normalized fixation duration (nFD) by AOI using Welch's *t*-tests. The table reports group means, test statistics with degrees of freedom, two-sided *p*-values, and Cohen's *d* effect sizes.

AOI	Heat	No-Heat	*t* (df)	*p*	*d*
Landmark	6.93	10.8	-3.84 (41.6)	$< .001$	1.15
Intersection	20.8	27.6	-3.03 (42.2)	.004	0.91
Arrow	2.52	4.21	-3.10 (42.7)	.003	0.92
Environment	35.6	40.2	-2.38 (40.6)	.022	0.71

Hypothesis Linking: These findings provide strong support for *Hypothesis H2a*, confirming that thermal stress significantly reduces visual attention to spatial anchors (Landmarks and Intersections). However, the results contradict *Hypothesis H2b* (Shift Towards Navigation Aids). Instead of increasing, attention to the Arrow AOI was significantly reduced ($d = 0.92$), suggesting a global suppression of visual processing rather than a strategic reallocation.

To further characterize the attentional differences between conditions, Figure 4.5 presents two complementary analyses of gaze behavior during the trial period. Figure A shows the percentage of trial time allocated to stable fixations on AOIs versus time spent in saccades, blinks, or fixations outside mapped AOIs (computed as the proportion of time between first and last AOI fixation). Figure B shows the mean number of fixations on AOIs versus non-AOI regions during the same period (computed by counting all fixations within the trial timeframe and categorizing them by fixation status).

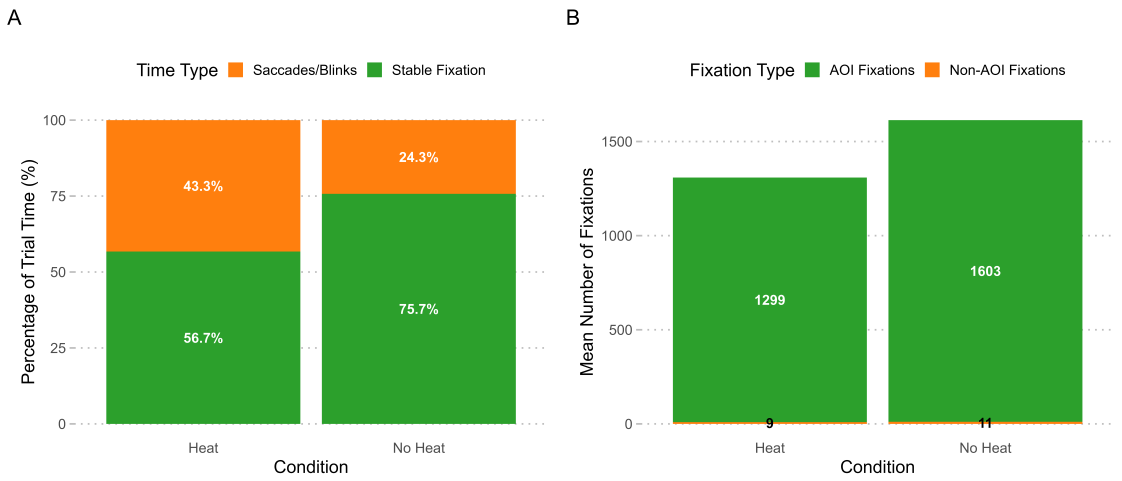

Figure 4.5: Time and fixation allocation by condition. (A) Percentage of trial time spent in stable fixations on AOIs (green) versus saccades/blinks/outside-AOI gaze (orange). Heat participants spent on average 56.7% of time on AOIs versus 75.7% for No-Heat participants. (B) Mean number of fixations on AOIs (green) versus non-AOI regions (orange). Heat participants made an average of 1299 AOI fixations versus 1603 for No-Heat participants, with minimal non-AOI fixations in both groups.

As shown in Figure 4.5A, the heat participants spent an average of 56.7% (*SD* = 16.8) of trial time in stable fixations on the AOIs compared to an average of 75.7% (*SD* = 4.8) for No-Heat participants. Therefore, the heat condition spent an average of 43.3% (*SD* = 16.8) of time in saccades, blinks, or outside-AOI gaze compared to 24.3% (*SD* = 4.8) for No-Heat. Figure B confirms this pattern at the fixation count level: Heat participants made significantly fewer AOI fixations (*M* = 1,299, *SD* = 350) than No-Heat participants (*M* = 1,603, *SD* = 280), $t(40.2) = -3.20$, $p = .003$, $d = 0.96$.

Therefore, thermal stress not only reduces the total time spent fixating but also results in fewer stable fixations and more time spent in unstable gaze patterns such as saccades/blinks/outside-AOI gaze, reducing visual efficiency and stability.

4.4.5 Mixed ANOVA: Overall Effects

To understand whether thermal stress produced a uniform reduction in attention across all AOIs or if specific AOI types are affected differently, a 2 (Condition: Heat vs. No-Heat) $\times$ 4 (AOI: Landmark, Intersection, Arrow, Environment) mixed ANOVA was conducted with condition as a between-subjects factor and AOI as a within-subjects factor. The Mauchly's test for assumption of sphericity indicated violation of sphericity with $W = 0.286$, $p < .001$. Correspondingly, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.672$). The summarized results of the ANOVA can be found in Table 4.4.

Table 4.4: Mixed-design ANOVA results for normalized fixation duration (nFD) with Condition (Heat vs No-Heat) as a between-subject factor and AOI as a within-subject factor. The table reports *F* statistics, degrees of freedom, *p*-values, and partial eta-squared (η_p^2). Where indicated, *p*-values are Greenhouse-Geisser corrected.

Effect	***F***	***df***	***p***	η_p^2
Condition	29.7	1, 43	<.001	.143
AOI	387	3, 129	<.001	.872
Condition $\times$ AOI	1.78	3, 129	.175[a]	.030

[a] Greenhouse-Geisser corrected *p*-value

Main Effect of Condition

Resulting from the ANOVA, a significant main effect of Condition emerged, $F(1, 43) = 29.7$, $p < .001$, $\eta_p^2 = .143$, indicating that overall, participants in the Heat condition spent significantly less time fixating on navigation-relevant AOIs (adjusted mean across all AOIs) compared to the No-Heat condition. This large effect (accounting for 14.3% of the variance) confirms that thermal stress widely reduced the visual attention to AOIs during navigation.

Main Effect of AOI

From the analysis, a highly significant main effect of AOI emerged with $F(3, 129) = 387$, $p < .001$, $\eta_p^2 = .872$. This effect, however, must be interpreted with extreme caution, as the Environment AOI constitutes a residual category that comprises all visual fixations that are not on any other AOI Landmarks, Intersections, or Arrows but still within the environment. Therefore, the finding that participants spent more time looking at the Environment than at specific navigation features is expected and reflects the nested structure of the AOI categories rather than a meaningful attentional preference. However, the main question addressed by this analysis concerns the Condition $\times$ AOI interaction and condition-specific differences for targeted navigation features (examined via independent t-tests in Section 4.4.4).

Condition $\times$ AOI Interaction

The Condition $\times$ AOI interaction was not statistically significant after applying the Greenhouse-Geisser correction with $F(3, 129) = 1.78$, $p_{GG} = .175$, $\eta_p^2 = .030$. Despite having varying effect sizes in the independent t-tests (ranging from $d = 0.71$ for Environment to $d = 1.15$ for Landmarks), thermal stress produced a statistically uniform proportional reduction across all four AOIs. This suggests that thermal stress impaired general attentional capacity rather than selectively disrupting specific feature detection processes. However, the trend toward an interaction in the non-parametric ART-ANOVA ($p = .074$; see Section 4.4.6) suggests that larger effect sizes for Landmarks and Intersections may reflect meaningful differential impairment that needs further investigation.

4.4.6 Robust Analysis: ART-ANOVA

As there were violations of normality (see Section 4.4.3 and sphericity, a non-parametric Aligned Rank Transformation (ART) ANOVA was conducted as a robustness check. The results from the ARTANOVA confirmed the parametric findings for main effects: Condition ($F = 34.8$, $p < .001$) and AOI ($F = 405.3$, $p < .001$). To highlight here is that the Condition $\times$ AOI interaction approached significance ($F = 2.36$, $p = .074$) in the ARTANOVA. Even though the parametric test suggests uniform impairment across all AOIs, the non-parametric test hints at potential differential effects, with the Landmarks AOI showing the largest impairment ($d = 1.15$) and Environment the smallest ($d = 0.71$). This difference might reflect the functional importance of different features for spatial navigation under cognitive stress, though this interpretation requires caution, given the non-significant parametric interaction.

4.4.7 Linking Visual Attention to Memory Performance

To understand if reduced visual attention during navigation was associated with the memory performance differences reported in Sections 4.2 and 4.3, correlations between nFD and behavioral performance measures were calculated across all participants.

Attention and Intersection Recognition

A strong positive correlation was shown between nFD on Landmarks and intersection recognition sensitivity (d' from Section 4.2.1): $r = .623$, $p < .001$ (Figure 4.6). Therefore, participants who spent more time fixating on landmarks during the navigation task also showed better subsequent recognition performance.

Attention and Route Direction Accuracy

In contrast, neither the nFD on Landmarks AOI ($r = .148$, $p = .333$.) nor the nFD on Intersection AOI ($r = -.087$, $p = .571$.) correlated significantly to the route direction accuracy (from Section 4.3.1). Additionally, intersection recognition (d') and route accuracy showed no significant correlation: $r = .229$, $p = .131$. Therefore, visual attention to specific AOIs during navigation was not associated with route direction memory.

The complete correlation matrix between eye tracking measures and behavioral outcomes is presented in Figure 4.6.

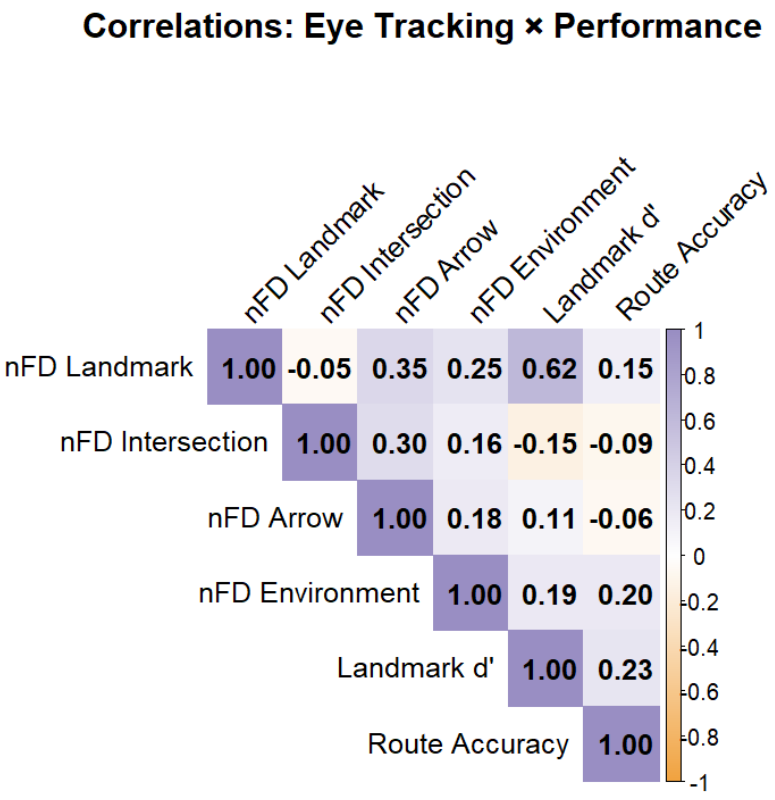

Figure 4.6: Correlation matrix between nFD measures (for each AOI) and behavioral performance. Intersection recognition sensitivity (d'; Section 4.2.1) correlates significantly with Landmark nFD ($r = .62$, $p < .001$), whereas route direction accuracy (Section 4.3.1) shows no significant correlations with any eye tracking measure.

Therefore, *Hypothesis H2c* is only partially supported: visual attention to landmarks is critical for declarative recognition memory but does not appear to determine route wayfinding success.

4.5 Electrodermal Activity Analysis (RQ3)

The previous sections established that thermal stress impaired landmark-based spatial memory (Section 4.2) and altered visual attention allocation patterns (Section 4.4). To understand whether these cognitive deficits were accompanied by elevated physiological arousal, electrodermal activity (EDA) was recorded continuously throughout the experimental session.

This section reports EDA findings across four temporal scales, progressing from coarse to fine-grained: 1) pre-task baseline arousal during passive heat exposure versus neutral conditions (manipulation check), 2) trial-level arousal averaged across the entire 15-intersection navigation task, 3) intersection-level arousal at individual decision points, and 4) temporal dynamics of arousal trajectories before, during, and after navigation decisions. Complete EDA data were available for 45 participants (22 Heat, 23 No-Heat), with one participant excluded due to insufficient baseline data.

4.5.1 Manipulation Check: Pre-Task Baseline Arousal

Pre-task baseline SCL and SCR rates were compared between groups to assess whether passive heat exposure (before navigation began) elevated sympathetic activation.

Baseline Tonic Arousal (SCL)

Shapiro-Wilk tests indicated violations of normality in both conditions (Heat: $W = 0.90, p = .023$; No-Heat: $W = 0.90, p = .024$). Levene's test confirmed homogeneity of variance ($F(1, 43) = 1.11, p = .297$).

A Mann-Whitney *U* test revealed no significant difference between the Heat condition ($M = 4.94\,\mu$S, $SD = 2.19$) and the No-Heat condition ($M = 6.42\,\mu$S, $SD = 3.29$), $W = 175, p = .078, d = 0.53$. Descriptively, the Heat group showed lower baseline SCL than the No-Heat group, despite the presence of the heat stressor.

Baseline Phasic Arousal (SCR Rate)

Baseline SCR rates were elevated across both groups, likely reflecting anticipatory arousal in the VR lab context. Assumption checks indicated a deviation from normality for Heat ($W = 0.85, p = .003$) and No-Heat ($W = 0.91, p = .043$). Variances were homogeneous ($F(1, 43) = 0.04, p = .847$).

A Mann-Whitney *U* test showed no significant difference in baseline SCR rate between the Heat condition ($M = 17.7$ peaks/min, $SD = 6.0$) and the No-Heat condition ($M = 15.1$ peaks/min, $SD = 6.8$), $W = 313, p = .178, d = 0.41$.

Contrary to the expectation that passive heating would elevate arousal, both tonic and phasic measures confirmed equivalent pre-navigation baseline states. This indicates that the thermal manipulation alone (without cognitive load) did not result in a measurable physiological stress response.

4.5.2 Trial-Level Arousal (RQ3a)

Given the absence of baseline arousal differences, the analysis proceeded to examine whether thermal stress elevated arousal during active navigation. The recorded signal was split into its tonic (SCL) and phasic (SCR) parts.

Baseline-Corrected Tonic Arousal

Assumption tests revealed normality in both conditions (Heat $W = 0.92, p = .092$; No-Heat: $W = 0.96, p = .403$), and variances were homogeneous ($F(1, 43) = 0.23, p = .635$). An independent-samples *t*-test revealed no significant effect of thermal stress on tonic arousal change, $t(42.9) = 0.26, p = .793, d = 0.08$. Both groups showed a comparable minimal change in arousal from baseline to task (Heat: $M = +0.098\,\mu$S, $SD = 1.20$; No-Heat: $M = -0.000\,\mu$S, $SD = 1.30$). The percent change from baseline was similarly unaffected ($M_{\text{Heat}} = +3.7\%$, $M_{\text{No-Heat}} = +0.1\%$).

Phasic Arousal (SCR Rate)

Trial-level SCR rates met normality assumptions (Heat: $W = 0.97, p = .655$; No-Heat: $W = 0.93, p = .128$) and homogeneity of variance ($F(1, 43) = 1.63, p = .208$).

An independent-samples *t*-test showed no significant difference in SCR rate during navigation between the Heat ($M = 18.8$ peaks/min, $SD = 6.4$) and No-Heat conditions ($M = 15.3$ peaks/min, $SD = 8.2$), $t(41.2) = 1.59, p = .120, d = 0.47$. Although the Heat group showed a numerically higher rate, the difference was not statistically significant.

Therefore, contrary to *Hypothesis H3a*, the thermal stress did not result in a generalized increase in physiological arousal during the navigation task, neither in tonic levels nor in the frequency of phasic stress responses.

4.5.3 Intersection-Level Arousal (RQ3b)

To understand if the arousal was specifically elevated while traversing an intersection, the EDA metrics were analyzed within the combined window of the decision and execution phases (∼12 seconds per intersection).

4.5.4 Tonic Arousal (SCL)

Assumption testing revealed significant violations of normality for intersection-level baseline-corrected SCL across all sub-groups ($p < .05$), though Levene's test indicated homogeneity of variance ($F(3, 671) = 2.19, p = .088$). Consequently, a non-parametric Aligned Rank Transform (ART) mixed-effects model was fitted.

The ART ANOVA, however, revealed no significant main effect of Condition on intersection SCL, $F(1, 43.1) = 0.20, p = .66$. There was also no main effect of Landmark Presence ($F(1, 628) = 0.15, p = .70$) nor a Condition × Landmark interaction ($F(1, 628) = 0.18, p = .67$)

Phasic Arousal (SCR Rate)

At an intersection level, the assumption tests revealed a violation of normality ($p < .001$) across all sub-groups and homogeneity ($p < .001$). Consequently, the non-parametric ART model was chosen.

The ART analysis revealed no significant main effect of Condition, $F(1, 43.1) = 2.60, p = .11$. Descriptively, SCR rates at intersections (Heat: 18.9 peaks/min; No-Heat: 15.1 peaks/min) were comparable to the overall trial averages (Heat: 18.8 peaks/min; No-Heat: 15.3 peaks/min). This suggests that the decision-making events did not have any significant effect on phasic arousal. Furthermore, landmark presence also did not affect the SCR rates ($F(1, 628) = 0.01, p = .91$), nor was there an interaction ($F(1, 628) = 0.40, p = .53$).

Therefore, *Hypothesis H3b* is rejected. Physiological arousal did not increase specifically at intersections or in response to landmarks, regardless of the thermal condition.

4.5.5 Temporal Dynamics of Arousal (RQ3c)

To split the physiological arousal during the intersection navigation sequence, two dynamic metrics were computed: Cue Reactivity (change in mean SCL from the 8s Baseline to the 4s Decision phase) and Action Settlement (change in mean SCL from the 4s Decision to the 8s Execution phase).

The overall changes in arousal were assessed using paired *t*-tests across all intersection events ($N = 675$) to establish the general physiological response profile. With this analysis, a significant negative cue reactivity effect ($t(674) = -2.01, p = .045$) was found. This indicates that tonic arousal levels slightly decreased upon seeing the navigation cue (arrow) relative to the baseline approach. In contrast, there was no significant Action Settlement effect, $t(674) = -0.13, p = .895$, indicating that arousal levels did not significantly change as participants transitioned from the decision phase to physically crossing the intersection. Similarly, the rate of arousal generation (SCL slope) did not significantly differ between the decision and baseline phases ($t(674) = -0.73, p = .463$).

In the second step, the ART mixed models were used to test if these dynamic responses were altered by the experimental conditions. For Cue Reactivity, there was no significant main effect of Condition ($F(1, 45.6) = 1.26, p = .27$) or Landmark Presence ($F(1, 628) = 0.49, p = .48$), nor any significant interaction ($F(1, 628) = 0.21, p = .64$). For Action Settlement, the Condition $\times$ Landmark interaction approached significance, $F(1, 628) = 3.51, p = .061$. Descriptively, the Heat group showed a tendency toward greater relaxation (larger SCL decrease) at landmark intersections, whereas the No-Heat group showed the opposite trend, though this did not reach the significance threshold.

Therefore, *Hypothesis H3c* is not supported. Thermal stress did not alter the temporal dynamics of arousal (cue reactivity or action settlement), and no significant differences were found in how participants physiologically anticipated or recovered from navigation decisions.

Chapter 5

Discussion

As urban heat intensifies, people are increasingly required to navigate complex city environments under thermal stress. Yet it remains unclear which aspects of spatial memory and attention are most vulnerable in such conditions. This study was guided by a single, overarching research question that examined how thermal stress during navigation in a virtual urban environment influences the development of landmark-based spatial memory and the associated patterns of visual attention and physiological arousal. To provide a comprehensive analysis of the underlying mechanisms, this question was divided into three intertwined domains: 1) spatial memory formation, distinguishing between landmark recognition and route direction recall; 2) visual attention allocation across task-relevant environmental features; and 3) physiological arousal dynamics during navigation phases. Decomposing the research question allowed for a better analysis of the underlying mechanisms and an understanding of how heat impairs general cognitive performance and alters pedestrian mobility and attention behavior in urban environments.

This study fills a critical theoretical and practical gap, as it is the first to analyze how thermal stress selectively affects landmark-based spatial memory during active navigation while simultaneously measuring the underlying attentional and physiological mechanisms. Previous research has focused on how heat affects the broader cognitive domains (Hancock, Ross, and Szalma 2007; Taylor et al. 2016) and landmark-based navigation (Karimpur, Röser, and Hamburger 2016; Wunderlich, Grieger, and Gramann 2023) independently. But no prior work has directly tested whether environmental thermal stress selectively impairs specific components of spatial memory or whether strongly positioned landmarks can buffer against heat-induced cognitive deficits. Furthermore, eye-tracking studies have established that fixation duration on landmarks can predict landmark-based spatial learning (Kapaj, Hilton, Lanini-Maggi, et al. 2024), but no study has examined how thermal stress modifies these attentional mechanisms during navigation. Additionally, while electrodermal activity has been shown to index both thermal load, with tonic skin conductance increasing substantially with increasing ambient temperatures (Qasim, Bari, and Martinsen 2022), and task-related cognitive demands through phasic responses (Khan et al. 2019), the connection between thermal stress, attention, and physiological arousal during navigation has not been systematically investigated. The multimodal assessment in this study, combining eye-tracking metrics of visual attention allocation with electrodermal activity measurements, enables a direct examination of whether observed navigation deficits are driven primarily by attentional mechanisms or thermal load-induced physiological changes.

The core findings of this study revealed a clear dissociation in spatial memory outcomes under thermal stress. Signal Detection Theory measures revealed significant impairment of intersection recognition sensitivity under heat exposure (d': 0.63 units lower; false alarm rate 13.3% higher). Crucially, this impairment was specific: there was no discrepancy in route direction accuracy, which remained well above chance level for both conditions. Importantly, eye-tracking analysis showed a clear uniform reduction in visual attention across all defined Areas of Interest (AOI) (Landmarks, Intersections, Navigation Arrows, and Environment) under thermal stress, with fixation duration reduced by 11%-40% depending on the AOI. These findings suggest a general reduction in available attentional resources under thermal stress, rather than a strategic reallocation of attention across different environmental features. Despite there being a large subjective thermal discomfort difference between the heat and neutral group (Cohen's d = 2.16 for the thermal comfort questionnaire), the physiological arousal paradoxically indexed by electrodermal activity showed no significant increase under thermal stress at all. Together, these findings suggest that navigation performance under thermal stress may not be reliably indexed by physiological arousal

measures, indicating that the primary mechanisms involve attentional and cognitive resource allocation rather than sympathetic system activation. This points to a cognitive resource competition mechanism rather than arousal escalation as the primary pathway through which thermal stress impairs spatial memory.

The following discussion interprets these findings by analyzing each major result area (intersection recognition, route direction memory, eye-tracking-based visual attention, and electrodermal activity) and connecting them to the corresponding sub-research questions and hypotheses. The findings are then positioned within the existing literature to illustrate the novel contributions of this study. Next, the discussion synthesizes the results into the overarching mechanisms, critically reflects on methodological limitations, and outlines future research possibilities. Finally, the broader implications for urban geography, GIScience, and climate adaptation in increasingly warm urban environments are explored, with emphasis on how these findings can inform the design of thermally resilient navigation systems and urban spaces.

5.1 Spatial Memory

The primary finding of this study is that thermal stress produces a significant dissociation in spatial memory outcomes, with landmark-based intersection recognition selectively impaired while route direction memory remained intact. By "selectively impaired," it is meant that thermal stress compromised specific attention-dependent components (landmark encoding) but not others (route direction recall). This dissociation is theoretically important, as it reveals that different components of spatial knowledge have different vulnerabilities. In line with the parallel acquisition framework proposed by Ishikawa and D. Montello (2006) and supported by Kim and Bock (2021), which proposes that landmark recognition and route sequencing develop simultaneously but rely on separate cognitive processes, the present results provide empirical evidence that these systems respond differently under thermal load. Specifically, landmark recognition appears highly sensitive to attentional resource depletion, whereas route direction memory remains comparatively robust. The following subsections interpret each memory outcome in relation to existing literature and showcase what the findings revealed about the underlying mechanisms of thermal stress during navigation.

5.1.1 Intersection Recognition Impairment $d' \downarrow$, False Alarms $\uparrow$

The specific vulnerability of landmark-based memory under thermal stress was most clearly demonstrated by the Signal Detection analysis. In line with *Hypothesis H1a*, which predicted that thermal stress would reduce intersection recognition sensitivity, Signal Detection Theory analysis revealed that thermal stress significantly impaired intersection recognition, with discriminability (d') 0.63 units lower in the heat condition compared to neutral thermal conditions. This impairment resulted from two patterns: lower hit rates (69.86% vs. 64.93%) and substantially higher false alarm rates (13.04% vs. 26.38%). Particularly notable is the 13.3% increase in false alarms, which indicates that heat-exposed participants were more likely to incorrectly identify unseen intersections as previously encountered ones. This specific error pattern suggests deficient encoding rather than pure retrieval failure: while memory loss (a retrieval deficit) would primarily manifest as reduced ability to recognize previously seen intersections (lower hits), it would not systematically increase false identifications of novel intersections. The observed pattern, both lower hits *and* substantially elevated false alarms, indicates that participants could not reliably distinguish new from previously experienced intersections because insufficient discriminative detail was encoded during the navigation phase. Under heat, the visual features necessary for later recognition were never adequately stored in memory.

This encoding deficit contrasts with the robust spatial knowledge formation documented under optimal conditions. Wunderlich, Grieger, and Gramann (2023) demonstrated that landmark-augmented navigation under neutral thermal conditions creates lasting spatial knowledge, with participants retaining detailed landmark and route memory up to three weeks post-navigation. This durability indicates that when attentional resources are available, landmarks are encoded deeply and consolidated effectively. The present findings, however, reveal that thermal stress prevents such robust encoding by depleting the attentional resources necessary for landmark processing during navigation. Consequently, the connection to memory loss becomes clear: if initial encoding is compromised, there is less spatial

information available for subsequent retrieval, producing performance deficits similar to retrieval failures but originating from an earlier processing stage. The immediate recognition test employed here, filled out directly after navigation, minimizes consolidation and long-term retrieval demands, thereby isolating the encoding impairment as the primary locus of thermal stress effects.

This finding extends current thermal stress research by demonstrating that heat-induced cognitive impairments are not uniform across all spatial-memory processes. While Hancock, Ross, and Szalma (2007) established that thermal stress broadly impairs attention and working memory, this study shows that these impairments specifically target attention-dependent incidental memory formation during navigation.

This selectivity aligns with parallel spatial knowledge frameworks (Ishikawa and D. Montello 2006; Kim and Bock 2021), which propose simultaneous but independent acquisition of landmark and route knowledge. As established above, thermal stress selectively impairs the attention-intensive landmark recognition process while sparing more automatic route memory. The discrepancy found in this study (impaired landmark recognition, yet preserved route direction) demonstrates that thermal stress selectively targets the attention-intensive processes of incidental recognition memory, while not affecting the automatic episodic memory for actions. This interpretation is consistent with the visual attention results, which showed reduced fixation duration on landmarks under heat. Additionally, landmark fixation was associated strongly with better intersection recognition sensitivity ($r = .62$, $p < .001$), further supporting the attentional mechanism. Together, these findings indicate that thermal stress disrupts landmark-based recognition memory primarily by reducing the attention resources allocated to landmarks during navigation, rather than uniformly hindering all forms of spatial knowledge.

5.1.2 Route Direction Accuracy Preservation

In contrast to the fragile nature of landmark recognition, the ability to recall route direction proved remarkably resistant. Contrary to *Hypothesis H1b*, which predicted degraded route direction performance under thermal stress, route direction accuracy was not significantly impaired. Both conditions showed statistically similar performance (Heat: $M = 67.54\%$, $SE = 2.73$; No-Heat: $M = 68.70\%$, $SE = 2.39$), with a negligible difference of 1.16% ($t(44) = -.32$, $p = .751$, $r = -.05$). Importantly, both groups performed well above the weighted chance level of 46.67%, as confirmed by one-sample t-tests for the Heat ($t(22) = 7.66$, $p < .001$) and No-Heat ($t(22) = 9.23$, $p < .001$) groups. Thus, even under thermal stress, route direction memory remained robust, and both groups performed better than guessing randomly.

These findings, combined with the impaired landmark recognition documented above, support the proposition that different forms of spatial knowledge rely on partially distinct cognitive resources. As established in Section 5.1.1, parallel frameworks propose that landmark and route knowledge develop simultaneously but depend on different cognitive processes. The preserved route direction accuracy under thermal stress suggests that recalling turn directions relies primarily on episodic memory for actions rather than on the detailed landmark encoding required for recognition. This interpretation is further supported by the eye-tracking results, which showed no significant association between landmark fixation and route direction accuracy, despite there being a strong link between landmark fixation and intersection recognition. Therefore, participants who paid more attention to landmarks remembered the intersections better; however, this additional attention did not improve their route recall in having a better memory for turning directions.

When looking at the route complexity, concerns about route simplicity might arise, which could affect the outcomes. However, as the route contained 12 binary-choice and 3 ternary-choice intersections with a weighted chance baseline (46.67%), the route composition underscores the idea that the preservation is not simply a consequence of task simplicity. Moreover, the mixed ANOVA on route accuracy (Section 4.3.2) revealed neither a main effect of Landmark Presence nor a Landmark × Condition (Heat vs. No-Heat) interaction, indicating that participants did not show automatic reliance on landmarks for direction recall. Instead, the findings suggest that even under thermal stress, a single pass of the route was sufficient to form a relatively stable memory for turn directions, whereas the more attention-dependent landmark recognition processes were substantially compromised.

5.1.3 Landmark Buffer Null Finding

Given the observed impairment in recognition memory, a critical question was whether strongly salient landmarks could offer a protective buffer for wayfinding decisions. However, the data provided no statistical support for this buffering hypothesis (*Hypothesis H1c*). For route direction accuracy (Section 4.3.2), the mixed ANOVA revealed no significant main effect of Landmark Presence ($F(1, 44) = 1.77$, $p = .19$), no main effect of Condition ($F(1, 44) = 0.25, p = .62$), and no Condition $\times$ Landmark interaction ($F(1, 44) = 1.06, p = .31$). Descriptively, the heat group showed slightly higher accuracy at landmark intersections (71%) compared to non-landmark intersections (63%), but this difference did not reach statistical significance.

There are several factors that might explain why this expected landmark buffer failed to materialize. First, the eye-tracking results showed that thermal stress reduced fixation duration on landmarks by an average of 35.7%, and Section 5.1.1 demonstrated that within this sample, higher landmark fixation was strongly associated with better intersection recognition (r = .62, p < .001). Previous studies have also reported that increased attention to landmarks is associated with improved spatial learning (Kapaj, Hilton, Lanini-Maggi, et al. 2024). When combined, these results suggest a *threshold effect:* under thermal stress, participants generally allocated too little attention to landmarks for them to achieve a consistent benefit. In other words, the attentional precondition for a landmark benefit may not have been met in the heat condition.

Second, the landmark positioning in this study was controlled at the level of intersection presence, but not systematically optimized with respect to the correct turn direction. Karimpur, Röser, and Hamburger (2016) emphasized the importance of landmark positioning relative to the line of travel in their effectiveness to function as spatial anchors. In the design of this study, the landmarks were always placed at an intersection, but not always on the side corresponding to the correct turn, as their placement was pseudo-randomized. This variability likely weakened the landmark's ability to serve as a direction cue. Therefore, if only the buffering function of landmarks were tested in future work, the landmark positioning should be manipulated explicitly to determine when and how landmarks can effectively buffer against heat-induced navigation impairments.

Importantly, this null result does not contradict the current broader landmark literature, but rather refines it for thermal stress. Prior studies demonstrated how landmarks typically function in neutral conditions and are often positioned or chosen to be towards the turning direction (ibid.). By contrast, this study demonstrates that under thermal stress with reduced visual attention, randomly positioned landmarks do not provide consistent benefits. This pattern suggests that landmark effectiveness depends on both attention availability and positional alignment with the navigation task. The mechanisms underlying these attention differences are examined in detail below (Section 5.2), where visual attention patterns during navigation are investigated as a potential driver of the observed memory dissociation.

5.2 Visual Attention

Having established the selective deficits in spatial memory (Section 5.1), the second research domain investigated the underlying attentional mechanisms. Two key questions were addressed: First, does thermal stress cause a strategic reallocation of attention (addressing *Hypotheses H2a and H2b*) or induce a general resource depletion? Second, what is the functional link between attention and memory performance (*Hypothesis H2c*)? Eye-tracking analysis revealed that thermal stress induced a generalized reduction in attention allocation, decreasing fixation duration uniformly across all Areas of Interest and thus supporting a resource depletion interpretation rather than strategic reallocation. Additionally, the data confirmed a strong coupling effect between attention and memory, with landmark fixation duration predicting intersection recognition sensitivity but not route direction accuracy. The following subsections interpret these findings in relation to the related work on visual attention during navigation and discuss their implications for understanding thermal stress.

5.2.1 Uniform Attention Reduction: Evidence for Resource Depletion

The cognitive mechanism underlying the memory deficits appears to be a global suppression of visual attention. Contrary to the hypothesized selective pattern of reallocation (*Hypotheses H2a and H2b*), thermal stress produced a uniform reduction in visual attention across all defined Areas of Interest. Normalized fixation duration (nFD) was significantly lower in the heat condition compared to the no-heat

condition for landmarks (-35.7% change, t(41.6) = -3.84, p < .001), intersections (-24.7% change, t(42.2) = -3.03, p = .004), arrows (-40.1% change, t(42.7) = -3.10, p = .003), and the environment (-11.3% change, t(40.6) = -2.38, p = .022). These represent large effects (average d $\approx$ -0.85 across all Areas of Interest), indicating substantial reductions in visual attention under heat rather than small or trivial differences. This pattern demonstrates a global attention reduction rather than a strategic reallocation toward navigation aids.

These findings contradict *Hypotheses H2a and H2b*, which anticipated a selective reduction in fixation duration on Landmarks and Intersection (H2a) and maintained or increased attention to Navigation Arrows (H2b). Instead, the observed uniform reduction of nFD across all AOIs suggests that thermal stress operates as a resource competition mechanism, where heat occupies limited attentional capacity, leaving fewer resources available for environmental processing. This interpretation fits within the broader cognitive load literature, which suggests that environmental stressors compete for limited working memory resources, shrinking the total available bandwidth for task-relevant processing (Hancock, Ross, and Szalma 2007). The uniform reduction in nFD, even for navigation arrows that might theoretically support the performance under stress, further indicates that thermal stress impairs general attention capacity rather than prompting an adaptive attention reallocation.

As established in Section 5.1, parallel frameworks propose that landmark and route knowledge develop through distinct cognitive processes. The observed generalized attention reduction suggests that thermal stress primarily disrupts the attention-intensive processes required for detailed landmark encoding, while leaving more automatic components of route memory relatively intact. The strong relationship between visual attention and spatial memory, as demonstrated by the significant correlation between landmark fixation duration and intersection recognition sensitivity (r = .62, p < .001), underlines that attention allocation to landmarks is a critical determinant of memory encoding quality. Therefore, under thermal stress, insufficient visual attention to landmarks appears to be the key mechanism for recognition memory deficits.

5.2.2 Attention-Memory Relationship

The data confirm that this reduction in visual attention was the primary driver of the observed memory deficits. Specifically, *Hypothesis H2c* is partially supported: a strong coupling exists between attention and memory, but exclusively for intersection recognition. The analysis of the correlation between normalized fixation duration and intersection recognition sensitivity (r = .62, p < .001) indicated that participants who spent more time fixating on landmarks during navigation also demonstrated better discrimination between seen and unseen intersections. This strong coupling validates the theoretical expectation that attention to environmental features during navigation allows for direct encoding of those features into memory. Interestingly, however, this attention-memory link was not universal, as nFD on Landmarks showed no significant correlation with route direction accuracy (r = .15, p = .33), indicating that memory for turn directions was independently formed from the amount of attention allocated to landmarks. This dissociation is particularly interesting given that thermal stress reduced fixation duration on landmarks by 35.7% and 24.7% on intersections.

The correlation between landmark fixation and recognition aligns with established theoretical frameworks of visual information processing. As already proposed by Just and Carpenter (1976), visual information is mainly processed during eye fixations and not during saccades, establishing the link between where people look and what they encode. More recent research in spatial cognition has demonstrated that strategic attention allocation during navigation is a key factor for spatial learning, with successful navigators focusing more on helpful map symbols and correctly identifying corresponding landmarks in the environment (Kiefer, Giannopoulos, and Raubal 2014). This is also confirmed by Liao et al. (2017) as they showcased that fixation patterns during navigation reflect the underlying cognitive processes of information encoding. The findings from this study extend this body of work by demonstrating that the fixation-recognition link remains robust even under thermal stress and overall attention depletion. The strong correlation (r = .62) suggests that despite the 35.7% reduction in landmark fixation under heat, participants who allocated more attention to landmarks still encoded them more effectively, as reflected in superior intersection recognition performance.

Furthermore, the absence of a correlation between landmark fixation and route direction accuracy further reveals the selective nature of the attention-memory relationship. As previously discussed in Section 4.3, route direction memory appears to rely mainly on episodic memory for actions, therefore recalling which direction to turn at each intersection, rather than on the detailed visual encoding of

landmarks. This interpretation of the data is also supported by the eye-tracking data, as participants were able to remember directions effectively regardless of whether they had fixated extensively on landmarks or not. This pattern aligns with the parallel acquisition framework (Section 5.1), which proposes distinct attentional requirements for different spatial memory processes. The present dissociation in correlations provides empirical evidence that landmark-based recognition is attention-intensive and strongly depends on fixation allocation, whereas episodic memory for turn directions can be formed with minimal attention to landmarks.

5.3 Physiological Arousal

The third research domain examined whether the observed cognitive and attentional deficits under thermal stress were accompanied by elevated physiological arousal. Specifically, were these deficits driven by sympathetic nervous system activation (similar to a classic stress response) or by cognitive resource depletion alone? To address this question, electrodermal activity (EDA) provided continuous measures of arousal. However, the interpretation of these EDA findings must remain cautious, because baseline measurements were collected after participants had already entered the thermally manipulated CAVE rather than before any heat exposure, and EDA was the only physiological index used (see Section 5.4.3 and Section 5.4.3). These design choices constrain how decisively null arousal effects can be interpreted as evidence against sympathetic involvement.

The recorded EDA data were decomposed into tonic skin conductance level (SCL) and phasic conductance responses (SCR), which index arousal and stress. These components respond differently to thermal load and cognitive demand: tonic SCL increases with ambient temperature, while phasic SCR reflects task-related cognitive engagement (Khan et al. 2019; Qasim, Bari, and Martinsen 2022). This distinction is critical for interpretation because if thermal stress impairs cognition through sympathetic activation, elevated EDA would be expected. Conversely, if thermal stress affects cognition mainly with resource depletion, arousal might remain unchanged. The following subsections examine arousal across temporal scales: 1) baseline (before navigation), 2) trial-level (entire task), 3) intersection-level (decision points), and 4) temporal dynamics (before/during/after decisions).

5.3.1 Baseline Arousal: The Counter-Intuitive Null

Before examining arousal during navigation, a manipulation check assessed whether heat exposure alone would elevate physiological arousal. If the sympathetic stress pathway proposed in *Hypothesis H3a* operates through direct thermal arousal, elevated baseline arousal in the Heat condition should be observed even before navigation begins.

Contrary to this prediction, no significant baseline differences emerged. Tonic arousal (SCL) was nonsignificantly lower in the Heat condition (M = 4.94 (μS) compared to No-Heat (M = 6.42 (μS), though not significantly (p = .078, d = 0.53). Phasic arousal (SCR rates) was also equivalent (Heat: M = 17.7 peaks/min; No-Heat: M = 15.1 peaks/min; p = .178, d = 0.41). Therefore, passive heat exposure did not produce measurable sympathetic arousal before the navigation task.

This null finding leads to three possible interpretations, which are not mutually exclusive. One explanation could be that thermoregulatory sweat may operate through different pathways than emotional stress, such that increased ambient temperature did not translate into higher sympathetic “stress” activation. Secondly, participants may have too high inter-individual variability, which can obscure group-level differences in samples of this size, even when effect sizes are moderate and therefore limit statistical power. Lastly, the thermal manipulation in this study resembled a moderate heat stress rather than extreme heat strain, which may be insufficient to trigger a reliable sympathetic stress response. Taken together, these considerations mean that the baseline null result is inherently ambiguous: it is consistent with the absence of a strong sympathetic response to the applied heat load, but the timing of the baseline recording within the heated environment also leaves open the possibility that transient arousal differences had already settled by the time EDA was measured.

5.3.2 Trial-Level Arousal: No Heat Effect During Navigation

Having established that thermal exposure did not elevate baseline arousal, the next step was to examine whether adding cognitive demand during the navigation task would lead to increased physiological arousal. If thermal stress was induced via a classical sympathetic "stress" pathway, one would expect tonic or phasic EDA arousal to rise during the main navigation task, especially during the heat condition.

The results, however, showed no such effect, as the baseline-corrected tonic arousal showed no significant difference between conditions ($t(42.9) = 0.26, p = .793, d = 0.08$). The same was also observed with phasic arousal (SCR rate) with no group differences observed ($t(41.2) = 1.59, p = .120, d = 0.47$), despite a numerically higher rate in the Heat group. This null effect at the trial level does not represent the outcomes one would expect when viewing it against existing work. Qasim, Bari, and Martinsen (2022) demonstrated that tonic SCL increases substantially with ambient temperature, while Khan et al. (2019) showed that phasic EDA reflects the cognitive load during demanding tasks. Together, these findings would support the expectation that combining elevated temperature with cognitive demand should produce heightened EDA. Yet, in this study, no such elevation occurred, despite clear evidence of impaired landmark-based memory and reduced visual attention under heat.

These findings lead to rejection of *Hypothesis H3a*, which predicted elevated tonic arousal during navigation under thermal stress. The trial-level null effects reinforce the baseline pattern: thermal stress did not manifest as generalized sympathetic activation. Instead, the pattern supports an interpretation wherein heat primarily impacts cognition through attentional resource depletion (reflected in memory and attention deficits) rather than through autonomic stress responses detectable via EDA.

5.3.3 Intersection-Level Arousal: No Decision-Point Stress Response

To understand whether arousal was specifically elevated at the intersection, EDA was analyzed within the combined window of the decision and execution phases at each intersection (approximately 12 seconds per intersection). If thermal stress triggered higher arousal during direction cues, one would expect elevated tonic or phasic EDA in the Heat condition at these decision points. As previously mentioned, phasic SCR is sensitive to moment-to-moment engagement with specific events (ibid.). The intersections during the navigation task represent the most cognitively demanding moments of the navigation task, as participants must process the navigation cue, recall or infer the correct turn direction, and execute the decision. Therefore, under thermal stress, it would be expected that the stress would be manifested as increased arousal at intersections.

However, the intersection-level analysis revealed no such effect. The ART mixed-effects model showed no significant main effect of Condition on tonic arousal ($F(1, 43.1) = 0.20, p = .66$) nor on phasic arousal ($F(1, 43.1) = 2.60, p = .11$). Furthermore, the landmark presence also did not result in any significant change of arousal at intersections (tonic: $p = .70$; phasic: $p = .91$). Moreover, the SCR rates at intersections were comparable to the overall trial averages, indicating that the "decision-making" moments did not result in a distinct arousal response relative to the general navigation context. Together with the trial-level null findings, these results indicate that, within the constraints of the current EDA measurement (including a baseline taken inside the thermal manipulation), thermal stress did not produce robust or systematic elevations in physiological arousal at any temporal scale, neither during the task overall nor at specific decision points.

These findings lead to rejection of *Hypothesis H3b*, which predicted elevated arousal at intersections and for landmark intersections under thermal stress, while simultaneously underscoring that more differentiated baseline protocols and additional physiological indices would be needed to fully rule out more subtle arousal effects. The null arousal pattern aligns with the null landmark buffer for memory performance (Section 5.1.3), suggesting that landmarks were not sufficiently engaging (cognitively or physiologically) to modulate EDA. This may reflect their pseudo-randomized positioning, which prevented systematic alignment with turn directions (Karimpur, Röser, and Hamburger 2016), or may indicate that reduced visual attention prevented landmarks from capturing sufficient cognitive processing to influence autonomic arousal. The intersection-level pattern reinforces the conclusion that thermal stress impairs navigation through cognitive mechanisms (attention and memory) rather than autonomic stress responses.

5.3.4 Temporal Dynamics: The Paradox of Decreasing Arousal

To understand if arousal fluctuated in response to specific navigation events, the EDA measures were examined at a more detailed temporal resolution by analyzing Cue Reactivity (change in SCL from baseline approach to decision phase) and action settlement (change in SCL from decision to execution phase). These metrics were used to capture different dynamics in arousal as participants encountered the navigation cue and subsequently executed their directional choice. With thermal stress, it was expected to have elevated arousal at these critical moments, consistent with models of task-related physiological engagement (Khan et al. 2019).

The analysis of the temporal dynamics, however, revealed an interesting paradox. Cue reactivity showed a significant negative effect across all 675 intersection events ($t(674) = -2.01, p = .045$), meaning that arousal decreased when seeing the navigation arrow, rather than increasing. The decreasing factor was equivalent across both conditions ($F(1, 45.6) = 1.26, p = .27$) and was not modulated by landmark presence ($F(1, 628) = 0.49, p = .48$). In contrast, action settlement showed no significant change ($t(674) = -0.13, p = .895$), indicating that execution imposed no additional physiological burden relative to decision-making.

This arousal decrease at cue presentation likely reflects a "relief" mechanism rather than a stress response. Anecdotal participant feedback indicated that under thermal stress, participants focused heavily on reaching the next directional cue, experiencing the appearance of the arrow as a moment of reassurance that resolved spatial uncertainty. This goal-focused orientation would naturally reduce arousal as uncertainty dissipated, as the navigation arrow is interpreted as a progress marker rather than a new demand. This interpretation aligns with the incidental learning design of the study, because participants were unaware of the requirement to encode the environment for later recall; they treated the navigation as a pure wayfinding task. Consequently, the appearance of the arrow signaled the successful completion of a navigation segment, triggering a physiological "settling" response rather than the heightened arousal associated with deliberate encoding effort.

These findings lead to rejection of *Hypothesis H3c*, which predicted altered temporal arousal dynamics (enhanced cue reactivity, reduced action settlement) under thermal stress. The Condition x Landmark interaction in action settlement approached but did not reach significance ($F(1, 628) = 3.51, p = .061$). When looking at the data descriptively, the Heat group showed a tendency toward greater relaxation (SCL decrease) at landmark intersections during execution, whereas the No-Heat group showed a slight increase. This finding, however, is very exploratory and is not backed by any statistical significance, given its p-value. It moreover supports the interpretation that the presence of a landmark alongside the arrow may have provided additional confirmation, further facilitating arousal reduction during the execution phase. Overall, the systematic decrease in arousal at decision points suggests that the navigation task was experienced as a sequence of problem-solving steps rather than a source of physiological stress, even under thermal load. This interpretation aligns with the incidental learning design: participants were unaware of the subsequent memory test and treated navigation as a wayfinding task rather than an encoding task.

Overall, the absence of systematic EDA differences between thermal conditions, when viewed alongside the clear cognitive and attentional impairments and the methodological constraints on baseline timing and physiological measurement, suggests that thermal stress in this paradigm most likely impaired navigation through cognitive resource competition rather than through a pronounced sympathetic arousal response, while leaving open the possibility that more sensitive or multimodal physiological assessments might detect subtler thermoregulatory contributions.

5.4 Study Outcomes: Mechanisms and Limitations

The overarching research question driving this study examined how thermal stress influences spatial memory and attention during VR navigation. Having addressed each empirical domain independently (spatial memory in Section 5.1, visual attention in Section 5.2, and physiological arousal in Section 5.3), the synthesis across all domains reveals a unifying mechanism: What explains the observed pattern of selective memory impairment, uniform attention reduction, and absent arousal elevation?

Three core findings emerge: First, thermal stress selectively impaired landmark-based intersection recognition ($d' = -0.63$ units; false alarms increased by 13.3%) while leaving route direction memory intact (*Hypothesis H1a supported; H1b rejected; H1c rejected*). Second, thermal stress produced a uniform reduction in visual attention across all environmental features, reducing landmark fixation by 35.7%

(*Hypotheses H2a supported; H2b contradicted*), yet landmark fixation predicted intersection recognition ($r = .62$) but not route accuracy (*Hypothesis H2c partially supported*). Third, electrodermal activity showed no elevation under heat across temporal scales, including baseline, trial-level, intersection-level, and temporal dynamics (*H3a, H3b, and H3c all rejected*).

These findings point to a single mechanism-cognitive resource competition, where thermal stress acts as a secondary cognitive load that competes for the same limited attentional resources required for landmark encoding. This mechanism is resource-competitive (heat occupies cognitive capacity), selective (only attention-dependent processes impaired), and cognitively direct (no physiological arousal elevation detected). The following subsections develop this model by synthesizing evidence across the three empirical domains and positioning findings within thermal stress and spatial cognition literature.

5.4.1 Primary Mechanism: The Cognitive Resource Competition Model

The theoretical foundation for understanding these effects is laid out by Hancock, Ross, and Szalma (2007), who synthesized 49 studies (528 effect sizes) and demonstrated that thermal stressors produce an overall performance decrement of approximately $d = -0.34$. Crucially, Hancock, Ross, and Szalma (ibid., p. 851) proposed that "stress forces the individual to allocate attentional resources to appraise and cope with the threat, which reduces the capacity to process task-relevant information". This resource competition predicts that thermal stress should impair performance by diverting limited cognitive resources away from primary task demands. However, Hancock, Ross, and Szalma (ibid.) analysis did not specify which cognitive processes within a complex task are the most vulnerable, nor did it clarify the precise pathway of how they are affected. The present findings address both gaps. By separating attention-dependent recognition memory (impaired) from automatic route memory (preserved), and by connecting this discrepancy to reduced visual attention (r = .62 between landmark fixation and recognition sensitivity), this study extends Hancock, Ross, and Szalma (ibid.) framework into a more specific model for spatial navigation: *in an active wayfinding context, thermal stress acts as a secondary cognitive load that competes for the same limited pool of attentional resources required for landmark encoding, while leaving more automatic route memory comparatively intact.*

This mechanism has three defining characteristics. First, it is *resource-competitive*: heat exposure occupies cognitive capacity that would otherwise be available for processing task-relevant environmental information. Second, it is *selective*: only processes that depend heavily on sustained attention (incidental encoding of visual landmarks) are impaired, whereas automatic or procedural processes (episodic memory for turn directions) remain intact. Third, it is *cognitively direct*: the impairment pathway appears to operate primarily through attention reduction. Although the electrodermal activity findings should be interpreted cautiously, given the methodological challenges discussed in Section 5.3.1, the absence of a clear arousal elevation across multiple temporal scales suggests that, at least in this study, the impact of thermal stress manifests as a cognitive burden rather than as an acute physiological stress response. The following subsections develop this resource competition model by synthesizing evidence across domains and positioning findings within thermal stress and spatial cognition literature.

5.4.2 Evidence Synthesis Across Three Domains

Memory Evidence: Selective Vulnerability

The resource competition mechanism is grounded in a fundamental empirical observation: the dissociation between impaired recognition memory and preserved route direction memory under thermal stress. This disassociation is neither trivial nor self-explanatory. At first glance, thermal stress might be expected to degrade all forms of spatial memory equally, as heat-induced cognitive impairment is often conceived as a global phenomenon affecting attentional capacity broadly (ibid.). Yet the findings of this study revealed an important different pattern. As documented in Section 5.1.1, intersection recognition sensitivity declined substantially under heat, with discriminability (d') reduced by 0.63 units and false alarm rates elevated by 13.3%. This impairment reflects an encoding deficit: heat-exposed participants showed reduced discrimination between previously encountered and novel intersections due to insufficient visual landmark encoding during navigation. In stark contrast, route direction memory remained robust and significantly above chance level for both groups. Thus, even under significant thermal stress, participants retained the ability to recall the direction of turns at intersections.

This selective pattern of impairment and preservation is very important in regard to theoretical literature pointing towards the existence of partially distinct cognitive systems underlying landmark recognition versus route memory formation. The parallel acquisition framework (Ishikawa 2006, Kim 2021) provides a theoretical lens for this dissociation. Unlike hierarchical models, this framework proposes that landmark and route knowledge develop simultaneously during navigation, each relying on distinct cognitive processes. While using this lens, the different impact of heat on the two memory systems makes intuitive sense: recognition memory depends critically on *sustained attentional encoding of visual details*; a process that requires allocating and maintaining focus on specific environmental features (landmarks, intersections) during the navigation sequence. Route memory, by contrast, is more closely tied to *episodic memory for actions*; the sequential recall of decisions made (turn left, then right, then straight). This clear distinction between visual encoding (attention-intensive) and action sequencing (more automatic) provided important implications for understanding how thermal stress affects spatial knowledge formation.

This distinction is further empirically supported by the eye-tracking results presented in Section 5.1.1, which demonstrated a strong coupling between landmark fixation duration and intersection recognition sensitivity ($r = .62$, $p < .001$). Notably, the same attentional metric showed *no significant relationship* with route direction accuracy ($r = .15$, $p = .33$). Simplified, participants who spent more time looking at landmarks during navigation were significantly more likely to successfully encode those landmarks into memory and therefore also perform well in the recognition task. However, the amount of attention allocated to landmarks did not explain the ability to recall turning directions. This divergence in attention-memory relationships directly supports the claim that recognition and route memory rely on partially distinct cognitive processes. The lower recognition under heat (together with route accuracy) is therefore best understood as a *selective targeting of attention-dependent encoding processes* with preservation of more automatic action memory, and not as a uniform degradation of all spatial knowledge.

Furthermore, this selective vulnerability aligns precisely with Hancock, Ross, and Szalma (2007) resource competition framework, and also extends it in an important way. Hancock, Ross, and Szalma (ibid.) meta-analysis showed that cognitive performance is the *least affected* by thermal stressors relative to perceptual and psychomotor tasks (cognitive: $d = -0.18$; perceptual: $d = -0.92$; psychomotor: $d = -0.46$). This finding might first suggest that spatial cognition should be relatively robust under heat. However, the results from this study reveal that *substantial heterogeneity* exists within the spatial cognition domain itself. Not all cognitive processes decline at the same rate; only those requiring *sustained attentional engagement* showed marked impairment. This refinement is critical because it shows that Hancock, Ross, and Szalma (ibid.) general cognitive resilience to thermal stress has an underlying selectivity: processes that can operate *automatically* survive, whereas processes demanding *active attentional allocation* are vulnerable. The preservation of route memory under heat further suggests that participants retained access to the episodic sequences they had formed during navigation, indicating that the thermoregulatory burden of heat did not hinder memory traces themselves. Rather, the impairment manifested as an *encoding failure*: fewer landmarks were sufficiently fixated and encoded during the navigation phase, resulting in weaker landmark representations available for later recognition testing. This encoding-failure interpretation is further supported by the specific error pattern observed, as documented in Section 5.1.1: false alarm rates increased by 13.3% while hit rates declined, which is a classic signature of deficient stimulus encoding rather than memory decay.

Attention Evidence: Uniform Capacity Reduction

Patterns of visual attention reduction across the navigation task clarify how thermal stress depletes attentional resources. As detailed in Section 4.4.7, thermal stress produced a significant reduction in fixation duration across all Areas of Interest, with effect sizes ranging from -11.3% (environment) to -40.1% (navigation arrows), which importantly was *not selective*. Contrary to Hypotheses H2a and H2b, which anticipated either a strategic reduction focused on landmarks and intersections (H2a) or a compensatory maintenance or increase in attention to navigation arrows (H2b), the observed pattern was a *uniform decline across all task-relevant features*. This uniformity is theoretically significant because it reveals the nature of the attentional constraint imposed by heat. If thermal stress triggered an adaptive or strategic reallocation of attentional resources (which would be the common hypothesis in stress and performance literature), one would expect to observe trade-offs in attention allocation: increased focus on the most important task elements for navigation (e.g., navigation arrows) at the expense of peripheral or supplementary features (e.g., landmarks). Such a pattern would indicate that participants

maintained overall awareness of task demands while managing their limited attention budget strategically. However, the findings show no evidence of such tactical adjustment; instead, attention to all visual features declines proportionally. This uniform reduction suggests that thermal stress operates as a *general constraint on attentional capacity*, not as a trigger for strategic optimization and reallocation. Thinking with this framework, the total pool of available attention shrinks, and because all environmental features are relevant for successful navigation, all experience approximately equal proportional losses. Notably, navigation arrows, despite their critical role in providing turning directions, receive no attentional protection under heat. This observation contradicts the implicit assumption of H2b that participants might compensate by allocating more attention to the most task-critical feature. Instead, the data suggest that participants *cannot compensate* because of the capacity constraint.

This uniform attention reduction aligns very well with the resource competition framework established by Hancock, Ross, and Szalma (ibid.), who argued that thermal stress depletes the capacity to process task-relevant information. The findings of this study extend this framework by specifying the processes *which get depleted and which sustain.* Visual attention (a foundational component of cognitive processing) shows substantial reduction under heat, yet this does not translate into the same overall impairment. The reason becomes apparent when examining which processes depend on sustained fixation and which do not. As landmark recognition depends critically on fixation duration ($r = .62$), reduced attention naturally produces corresponding memory failure. Conversely, as route memory does not depend on fixation duration ($r = .15$), it remains insulated from the capacity constraint. The uniform attention reduction, therefore, does not create uniform memory impairment, instead it creates *selective vulnerability* of processes that are attention dependent. This dissociation represents a key mechanistic insight: heat shrinks the total attentional capacity available, with differential consequences depending on how much each cognitive process relies on sustained visual attention.

Physiological Arousal Evidence: The Null Pattern and Its Implications

The electrodermal activity findings, discussed in detail in Section 5.3, provide critical evidence for distinguishing between competing mechanistic pathways. The absence of elevated physiological arousal across all temporal scales (baseline, trial, intersection, cue dynamics) distinguishes between two potential pathways through which thermal stress might impair navigation performance: arousal escalation versus cognitive resource depletion. The null finding in the EDA pattern, when interpreted cautiously given the methodological constraints, clearly favors the second interpretation. If thermal stress operated primarily by triggering sympathetic activation (a classic fight-or-flight stress response), a systematic increase in skin conductance during the cognitively demanding navigation task, particularly at the decision point, would be expected. Yet no such elevation occurred in this study. This suggests that the observed memory and attention deficits were not altered by heightened emotional or physiological stress, but rather by a more direct competition for attentional resources. The burden induced by thermal stress, therefore, appears to have worked as a secondary cognitive load, occupying processing capacity without triggering the autonomic signatures associated with threat appraisal. Combined with the attention-memory coupling ($r = .62$) and the uniform attention reduction, the EDA null reinforces the interpretation that thermal stress impairs navigation through cognitive resource competition rather than through arousal-mediated pathways.

Theoretical Integration

The combination of all findings across memory, attention, and physiological arousal domains enables a more precise articulation of how thermal stress affects spatial cognition, refining and extending four major theoretical frameworks. By demonstrating that thermal stress depletes visual attention uniformly while producing selective memory impairments, this study advances the understanding of the mechanism linking environmental stressors to cognitive performance.

The findings of this study demonstrate that thermal stress depletes visual attention uniformly across environmental features, creating selective vulnerability among cognitive processes based on their attentional demands. This refines the resource competition model discussed by Hancock, Ross, and Szalma (ibid.), who established that thermal stressors reduce "the capacity to process task-relevant information" but did not specify which cognitive resources are depleted or which processes are most vulnerable. The uniform reduction of 35.7% in the landmark fixation duration, combined with the strong correlation between fixation and recognition sensitivity ($r = .62$), provides direct empirical evidence that visual attention

is the limiting resource under thermal stress. Furthermore, the observation that this attention depletion does not uniformly degrade all cognitive processes (route memory with direction recall remained intact) challenges the assumption that thermal stress acts as a global cognitive suppressant. Instead, the mechanism works by being selective: processes that require sustained attentional encoding fail, while more automatic processes are not affected as much. The absence of consistent arousal elevation across baseline, trial, and intersection-level EDA measurements supports the interpretation that thermal stress operates primarily through cognitive resource competition rather than arousal pathways. This interpretation requires caution, however, given the methodological constraints discussed in Section 5.3.1. Hancock, Ross, and Szalma (2007)'s framework implicitly assumed arousal escalation as part of the stress response, yet this study's findings suggest that in this navigation context, the primary mechanism is attentional capacity reduction.

The found dissociation between impaired recognition and preserved route memory provides empirical evidence for differential vulnerability among parallel spatial knowledge systems under environmental stress. Prior work on parallel spatial knowledge acquisition (Ishikawa 2006, Kim 2021) examined these processes under neutral conditions but did not investigate their differential sensitivity to environmental stressors. The current findings of this study reveal that recognition memory (attention-intensive, requiring deliberate encoding of visual details) shows substantial impairment under heat, whereas route direction memory (relying on episodic memory for actions) remains robust. This difference in sensitivity demonstrates that parallel spatial systems have fundamentally different resource demands. Under the environmental stressor of thermal stress, the limited pool of available attention is insufficient to support high-demand encoding processes, but still enough to allow low-demand procedural processes to continue to operate effectively. This pattern validates the parallel acquisition framework while extending it to demonstrate that simultaneous development does not imply equivalent resilience under cognitive load.

The robust attention-memory coupling observed in this study extends foundational theories of visual information processes to the domain of thermally stressed navigation. Already established by Just and Carpenter (1976) is that visual information is processed during fixations, creating a direct link between where people look and what they encode. Recent work by Kapaj, Hilton, Lanini-Maggi, et al. (2024) found partial evidence that increased normalized fixation duration on landmarks leads to improved spatial knowledge, pointing towards visual attention allocation directly supporting spatial learning. The present findings extend this framework by demonstrating that the fixation-encoding relationship remains strong even under thermal stress ($r = .62$), despite a 35.7% reduction in overall landmark fixation duration. This persistence of the attention-memory link under stressors reveals that fixation duration is not only a correlation to encoding but a fundamental constraint: without sufficient visual attention allocated to environmental features, those features cannot be encoded into memory regardless of their salience or structural positioning. The null correlation between landmark fixation and route direction accuracy ($r = .15$, $p = .33$) further underlines the specificity of this relationship, demonstrating that the fixation-encoding link applies mainly to attention-dependent processes.

Signal Detection Theory further clarifies the mechanism: the elevated false alarm rate (Section 5.1.1: +13.3%) alongside stable response criterion (c) indicates encoding failure rather than retrieval deficit or response bias. This interpretation aligns well with the attention-based mechanism, which states that reduced fixation duration on landmarks during navigation leads to weaker or incomplete representations, which in turn produce the observed higher false alarm rates when novel intersections appear too similar to weakly encoded memories.

Summary: Mechanism and Methodological Context

Combined, these findings establish a coherent mechanistic account: thermal stress acts as a secondary cognitive load that depletes available visual attention, selectively impairing processes requiring sustained encoding (landmark recognition) while sparing more automatic processes (route direction memory). This study provides the first direct evidence, within an active navigation context, that thermal stress produces *selective* impairment of attention-dependent spatial memory processes while preserving automatic route knowledge, operating through uniform depletion of visual attention rather than physiological arousal escalation. The multimodal integration of behavioral, eye-tracking, and physiological measures revealed converging evidence: behavioral memory deficits corresponded to eye-tracking attention reductions, and the absence of physiological arousal markers supported a cognitive rather than stress-response mechanism, consistent with the resource competition account. By linking thermal stress research to spatial cognition theory through visual attention mechanisms, this study demonstrates that environmental heat

does not uniformly impair all navigation processes. Instead, it selectively degrades attention-dependent learning while leaving automatic wayfinding intact, a distinction with implications for understanding how climate change may differentially affect urban navigation in diverse populations.

5.4.3 Limitations and Validity Constraints

Having established the cognitive resource competition mechanism, it is essential to critically evaluate the methodological boundaries that qualify the interpretation and generalization of these findings. No single experimental study fully captures the complexity of real-world thermal stress during navigation; understanding these constraints contextualizes the contributions and identifies opportunities for future research. The following subsections organize limitations into three validity domains: internal validity (factors affecting causal inference), construct validity (measurement accuracy), and external validity (generalization beyond experimental conditions). These limitations highlight opportunities to refine, extend, and validate the cognitive resource competition framework across diverse populations, environments, and navigation contexts.

Sample Characteristics and Demographic Constraints

The sample of participants in this study consisted primarily of young, healthy university students with a mean age of around 24 years, which may limit the external validity of claims regarding thermal stress effects on spatial cognition. Younger adults generally exhibit higher thermal tolerance and cognitive reserves compared to older populations (Pandolf 1997). The magnitude of heat-induced cognitive impairments observed in this sample may therefore underrepresent effects in older populations, representing a conservative estimate of deficits in heat-vulnerable groups.

This limitation directly affects external validity claims regarding *Hypothesis H1a* (landmark recognition impairment) and *H2a* (visual attention reduction). The magnitude of these effects would plausibly be larger in older adults, who show accelerated cognitive decline under heat stress and reduced thermal tolerance (ibid.). The preserved route direction memory (*Hypothesis H1b rejection*) and null arousal findings (*Hypotheses H3a, H3b, H3c rejection*) are less vulnerable to age-based generalization, as they represent robust or absent effects rather than quantitative decrements, yet even these findings require validation in older adults before broader claims can be made.

Additionally, the university-based recruitment led to a cognitively advantaged sample with above-average education and likely above-average spatial ability (mean SBSOD score: 3.97 out of 7, indicating above-average baseline navigation self-efficacy). This advantage might buffer against heat-induced effects. Critically, heat-induced cognitive impairments are most consequential for heat-vulnerable populations (e.g., outdoor workers, transit-dependent residents, and older adults), yet this study excluded these groups entirely. The observed selective vulnerability of landmark encoding and preservation of route memory may therefore not generalize to individuals of different cognitive reserve or impaired thermoregulation.

Single-Exposure Design

This study used a single-exposure design in which participants navigated the route only once under either heat or neutral conditions. While this approach isolates the direct effects of thermal stress on incidental spatial learning, it does not capture three critical processes: 1) thermal acclimation with repeated exposure, 2) learning consolidation and long-term retention, and 3) strategic adaptation or coping responses.

Heat acclimation protocols involving repeated exposure produce adaptive changes that enhance thermal tolerance and reduce cognitive impairments (Parsons, Stacey, and Woods 2019). This would suggest that the magnitude of deficits observed in this study may overestimate the long-term impacts of thermal stress for individuals regularly experiencing thermal stress. Occupational contexts (outdoor workers, delivery personnel, construction laborers) involve repeated navigation under heat; the current findings do not clarify whether deficits persist, diminish through acclimation, or intensify with cumulative fatigue. This temporal dynamics question directly affects practical applications: if individuals rapidly acclimate, heat-adaptive navigation systems require less aggressive landmarks or decision-point reduction. If deficits persist or worsen, interventions must be substantially more aggressive.

The single-pass navigation design also prevents the depth of spatial learning, as participants only had one chance to encode the environment. Memory recognition testing was conducted immediately after navigation (within 2-3 minutes), capturing encoding and retrieval processes without measuring consolidation. Recent research on landmark-based knowledge shows robust retention over weeks post-learning (Kapaj, Hilton, and Fabrikant 2024; Wunderlich, Grieger, and Gramann 2023), yet the consolidation pathway under thermal stress remains unknown. Weaker representations formed under heat may be especially vulnerable to decay over time, or conversely, may consolidate well despite initial encoding deficits. Delayed testing (24 hours, 1 week, or 1 month post-navigation) would clarify whether the elevated false alarm rate reflects a transient encoding weakness or a persistent representational deficiency.

Potential Ceiling Effects in Route Memory

Route direction accuracy remained well above the weighted chance level (46.67%) for both conditions, with performance around 68% in each group. While this demonstrates that participants successfully encoded direction sequences, the moderate performance level raises a critical question: was the route sufficiently complex to fully stress procedural memory processes under heat, or did the task's relative simplicity mask potential heat-induced deficits? The absence of a significant thermal effect on route memory may reflect either genuine resilience of episodic action memory or insufficient task difficulty to reveal performance decrements. A true ceiling effect (performance near 100%) would indicate insensitivity to thermal manipulation. Performance at 68% does not constitute a ceiling, yet it leaves uncertainty: the observed equivalence between conditions (1.16% point difference) might reflect genuine thermal resistance of route memory (supporting *Hypothesis H1b rejection*) or might reflect insufficient task difficulty to reveal an effect. A more demanding route with increased intersections, longer duration, or greater visual complexity (pedestrians, vehicles, signage) might impose sufficient cognitive load to reveal heat effects on procedural memory that this design could not detect.

Furthermore, the single-pass navigation design inherently limits the depth and consolidation of spatial knowledge. Real-world navigation often involves multiple exposures, longer learning periods, and delayed retrieval testing, all of which might reveal thermal stress effects that remain hidden in immediate single-trial assessments. By only testing the immediate recall of turn directions from a single exposure, this study might have captured performance that is relatively robust to thermal exposure, leaving the question open whether more challenging navigation scenarios would demonstrate similar resilience. Future research should systematically manipulate route complexity and implement different test time intervals to establish the boundary conditions under which thermal stress begins to impair route memory.

EDA Baseline Timing

A main methodological limitation lies in the timing of the baseline electrodermal activity measurement. In this study, baseline EDA was recorded after participants entered the thermally manipulated CAVE but before navigation began, rather than before any heat exposure occurred. This design choice reflects a tradeoff: measuring baseline during the thermal condition captures how physiological arousal responds to heat exposure itself, allowing assessment of navigation-specific arousal changes relative to a heat-adapted baseline. However, it also means the "baseline" measurement may have already captured initial thermoregulatory responses or physiological settling after entering the heated environment, rather than representing a pure pre-exposure reference point.

Specifically, if thermoregulatory sweating begins within the first 5-10 minutes of heat exposure (which is physiologically plausible at 36°C), the baseline measurement might reflect a heat-adapted state rather than a neutral state. Consequently, the null finding at baseline could reflect either: 1) genuine equivalence in arousal (supporting the cognitive resource competition mechanism with no arousal involvement), or 2) measurement timing that obscures arousal differences that would appear with a true pre-exposure baseline. The moderate effect size ($d = 0.53$) points to a possible physiological difference, but the nonsignificant result cannot conclusively rule out arousal effects, particularly when the timing of baseline measurements is suboptimal.

This ambiguity is present in all EDA findings, as all are predicated on a baseline recorded within a thermal context. Ideally, three baselines would have been collected: 1) pre-exposure in a neutral environment (true baseline), 2) before navigation (heat-adapted baseline), and 3) during navigation (trial-level). With these multiple baselines, thermal acclimation dynamics could be dissociated from task-related arousal changes.

Landmark Positioning and Directional Alignment

Landmark positioning represents a further construct validity consideration that might have constrained the ability to observe buffering effects and therefore affected the interpretation of *Hypothesis H1c rejection*. Landmarks were consistently placed at intersections during the route; their placements at the intersections were pseudo-randomized rather than systematically aligned with the correct turn direction. Prior research has demonstrated that landmarks which are positioned along the line of travel towards the correct turning direction are encoded more effectively and produce stronger landmark-direction associations that support spatial learning and wayfinding (Karimpur, Röser, and Hamburger 2016). As this study did not want to optimize for spatial learning and instead represent a standard wayfinding task, the landmarks were present but not optimally positioned to serve as directional cues, which may explain the null finding for the landmark buffer hypothesis: both conditions showed similar route direction accuracy regardless of landmark presence.

This positioning choice reflects a deliberate design choice made to maintain experimental control, as pilot testing showed a systematic bias in landmark location and direction recall. This choice, however, came at the cost of ecological validity regarding how landmarks naturally support navigation in real environments. The pseudo-randomized approach ensured that participants could not just identify the landmark positioning in the direction recall questionnaire and consequently cipher that the turning direction would be the same as the landmark positioning. Had landmarks been systematically positioned to align with correct turns, they may have provided sufficient cognitive support to buffer against heat-induced attention depletion, revealing a landmark buffer that this design failed to detect. Future research should systematically manipulate landmark positioning (aligned vs. misaligned) to determine whether optimally positioned landmarks can successfully stabilize navigation performance under thermal stress.

Immediate Recognition Testing and Memory Consolidation

The recognition test was administered immediately after the navigation trial, assessing encoding and retrieval processes that occurred during navigation. While this design is commonly used in spatial memory tasks and allows for isolation of heat effects on the encoding phase, it does not capture any potential impacts on memory consolidation or longer-term retention. A key question remains: do thermal stress effects on recognition reflect encoding deficits, consolidation impairments, or both? This question would be especially interesting, as related work has shown that landmark-based knowledge showed robust retention over weeks when appropriately encoded (Kapaj, Hilton, and Fabrikant 2024; Wunderlich, Grieger, and Gramann 2023).

Immediate testing may therefore underestimate heat-induced deficits if thermal stress primarily impairs consolidation mechanisms, or overestimate deficits if weakly encoded memories decay rapidly. The higher false alarm rate is consistent with encoding failure, yet delayed testing might reveal larger deficits if weak representations fail to consolidate effectively. By examining only immediate recall from a single navigation task, this study captures a snapshot of memory performance rather than the full trajectory of spatial knowledge formation and retention.

Future research should incorporate delayed recognition tests at multiple timepoints (24 hours, one week, one month post-navigation) to determine whether thermal stress effects on landmark memory persist, amplify, or resolve over time and whether they reflect encoding, consolidation, or retrieval deficits.

Virtual Reality vs. Real-World Navigation

While Section 2.3.1 already established the physiological and perceptual validity of thermally augmented virtual environments, key differences between VR navigation and real-world wayfinding limit the generalization of these findings. Critically, participants navigated the environment using a foot pedal controller while remaining seated in the CAVE, providing visual and proprioceptive feedback without actual physical locomotion. Although research has validated that the foot pedal controller is comparable to walking (Cheng, E. Lin, et al. 2023), the absence of physical locomotion and the demands of actual walking present a significant difference from real-world navigation. Real-world urban navigation inherently involves sustained physical exertion, continuous proprioceptive feedback from actual movement, and the integration of multiple sensory systems in dynamic interaction with the environment.

This difference is of high importance in regard to thermal stress research. Physical locomotion itself already generates metabolic heat and increases the thermoregulatory burden, amplifying the effects of ambient thermal stress. Participants navigating under heat in real-world conditions face multiple burdens,

as the external thermal load is combined with the metabolic heat of walking, whereas participants in VR only experience the external heat. The magnitude of heat-induced effects might therefore underestimate the impairments that would occur when walking in warm urban environments, where thermoregulatory demands accumulate cumulatively with physical exertion.

Additionally, the VR environment eliminated potential distractions (traffic, crowds, uneven terrain) that normally compete for attention in real-world navigation. This created a controlled but less ecological representation of spatial learning. Future research could use mobile eye-tracking and physiological monitoring during outdoor navigation under thermal stress to validate whether the cognitive resource competition mechanism generalizes to physically active wayfinding contexts.

Physiological Measurement Selection and Cognitive Load Assessment

Electrodermal activity was chosen to be the primary physiological indicator of thermal stress and cognitive load during navigation, yet this choice represents a significant measurement limitation. While EDA is a well-established index of sympathetic nervous system activation and emotional arousal, it might not optimally capture the cognitive demands of spatial learning or the specific mechanisms through which heat impairs attention and working memory. Other physiological measures like skin temperature, electroencephalography (EEG) (Cheng, E. Lin, et al. 2023), and pupil diameter (Kiefer, Giannopoulos, Duchowski, et al. 2016) would have maybe offered a more direct assessment of heat stress physiology.

The reliance on EDA alone limits the mechanistic insight, as it also failed to identify any arousal differences between conditions across all measured timepoints (baseline, trial-level, intersection-level, and temporal dynamics at decision points). The complete absence of any detectable arousal differences raises the question if EDA is sufficiently sensitive to the specific form of thermal stress applied in this study, or whether the cognitive resource depletion mechanism operates without triggering measurable sympathetic activation and is therefore not captured by EDA. By also employing a multimodal approach in physiological measurement with the use of skin temperature to directly track thermoregulatory state, EEG to assess brain patterns during spatial encoding, and pupil diameter to index real-time cognitive workload, clearer evidence could be found to check if heat impairs navigation through attentional resource depletion, elevated thermoregulatory burden, or other pathways that EDA alone cannot detect.

Laboratory Heat vs. Real-World Urban Heat

The thermal heat in this study was radiant heat exposure delivered via infrared lamps in a CAVE environment, focusing on the head and neck area, which is substantially different from the multifaceted thermal conditions experienced during outdoor urban navigation. Real-world heat stress does not only involve elevated ambient temperatures but also humidity, solar radiation, wind patterns, and surface radiant heat from pavement and buildings, which are all factors synthesized in the Wet Bulb Globe Temperature (WBGT) metric (Yaglou and Minard 1957). WBGT, which combines all the mentioned factors into a single physiological strain index, provided a more ecologically valid representation of heat exposure than ambient temperature alone. The administered heat exposure during the study, while providing experimental control by isolating heat exposure, did not capture the cumulative thermoregulatory demands of actual outdoor heat stress.

Additionally, the duration of heat exposure during the study (10-15 minutes) is substantially shorter than typical urban commutes (30-60 minutes) and occupational thermal strain (4-8 hour shifts). The observed deficits may therefore represent only initial thermal stress effects; longer exposure would likely reveal larger impairments. Real-world heat stress further includes variable wind exposure, evaporative cooling effects, and shade-seeking opportunities that provide intermittent physiological relief unavailable in the controlled laboratory setting. While the laboratory environment enabled precise observation of thermal effects on spatial cognition, the observed landmark recognition deficits and attention reductions may not fully generalize to pedestrians navigating real cities under sustained heat stress. Future studies incorporating WBGT-matched outdoor navigation or extended laboratory exposure would clarify generalization to realistic urban thermal conditions and test whether cognitive resource depletion accumulates nonlinearly with prolonged heat stress.

AOI Classification Methodology and Gaze Segmentation

The eye-tracking analysis relied on manually defined Areas of Interest (AOIs) to classify fixations into functionally meaningful categories, enabling structured quantification of visual attention allocation but

introducing methodological limitations. First, AOI boundaries were defined subjectively based on visual salience, and manual labeling of gaze data for each participant introduces potential systematic errors or inconsistencies, particularly at edge cases where fixations fall near AOI borders.

Second, by definition, all fixations fell within an AOI, as only fixations within the CAVE projection system are recorded. The Environment AOI functioned as a residual category capturing all fixations not classified as Landmarks, Intersections, or Arrows, obscuring variations within the broader visual scene and potentially masking important attentional patterns. This limitation restricts the mechanistic interpretation of the observed uniform fixation reduction across AOIs under heat.

Future research should therefore use automated gaze classification algorithms to eliminate manual labeling bias and provide more nuanced insight into how thermal stress reallocates attention within the navigation scene.

Summary and Implications of Limitations

It is important to note that these limitations do not invalidate the core findings of this study, but rather contextualize their scope and establish boundary conditions for interpretation. Each limitation represents a distinct research opportunity: 1) to examine age-diverse and heat-vulnerable populations for whom thermal stress poses greater physiological burden, 2) to validate findings in real-world outdoor navigation contexts with WBGT-matched thermal conditions, 3) to systematically manipulate route complexity, landmark positioning, and exposure duration, 4) to incorporate multimodal physiological measurement beyond EDA, and 5) to employ long-term studies that capture acclimation and memory consolidation processes over time. By acknowledging these boundaries, this study establishes a transparent foundation for future research that can further create models of how environmental thermal stress affects human spatial cognition across diverse populations, age groups, and urban contexts. The following section explores the broader implications of these findings for understanding the mechanisms of thermal stress effects on cognition and their relevance to designing resilient navigation systems and urban environments in an era of increasing global heat exposure.

5.5 Implications for Society, Geography, and GIScience

Having established that thermal stress impairs landmark-based spatial memory through attentional resource competition rather than through physiological arousal escalation (Section 5.4.1), and having critically examined the methodological boundaries of these findings (Section 5.4.3), this section showcases the practical and theoretical implications for urban geography, navigation system design, public health, and spatial cognition theory. With climate projections indicating increasingly frequent extreme heat events in urban environments (Calvin et al. 2023; United Nations 2018), understanding how thermal stress affects pedestrian wayfinding is not only an academic question but a matter of public safety and environmental justice (as described in the UN Sustainable Development Goal 11: Sustainable Cities and Communities (United Nations 2015)). Current heat-aware navigation research has focused mainly on route optimization to minimize thermal exposure (Feng et al. 2024; Neset et al. 2022) and not on the cognitive performance deficits. The following subsections translate the empirical findings into actionable recommendations across four domains: 1) heat-informed urban design principles, 2) enhancements to navigation systems that adapt to thermal conditions, 3) public health interventions for heat-vulnerable populations, and 4) theoretical contributions to spatial cognition frameworks demonstrating how environmental stressors selectively impair parallel knowledge systems.

5.5.1 Urban Geography and Climate Adaptation

Current urban heat mitigation strategies prioritize reducing thermal exposure through green infrastructure and reflective surfaces (Kumar et al. 2024) but exclude any cognitive dimensions revealed by this study. While research on the Urban Heat Island (UHI) effect documents how elevated temperatures alter pedestrian mobility and route choice (Deilami, Kamruzzaman, and Liu 2018; Deilami, Rudner, et al. 2020), these studies have not examined whether affected pedestrians can still navigate effectively despite thermal discomfort. This section outlines how cities can strategically enhance pedestrian support infrastructure (e.g., shading, wayfinding signage, and thermal refugia) to compensate for heat-induced cognitive deficits and fulfill the dual mandate of thermal comfort and spatial safety.

Strategic Shade Provision: Protecting Cognition through Pedestrian Infrastructure

As this study established, attention depletion under cognitive load is the primary mechanism. through which thermal stress impairs spatial memory, an intervention could be strategic shade provision at decision-critical locations. Recent research demonstrates that shade from trees reduces human-perceived heat exposure and decreases physiological equivalent temperature (PET) by 0.018°C per 1% increase in pedestrian shading coverage (Gu and Zhang 2025). As such, street trees are one of the most effecitve measures, they can reduce heat stress up to four times more effectively than any other urban intervention (Jiang et al. 2025).

Operationally, cities can prioritize shade provision at *navigation-critical zones*: major intersections where pedestrians must make directional decisions, transit hubs where wayfinding complexity is highest, and areas in which more vulnerable populations traverse more often. A coordinated strategy for shadow-oriented urban greening can create "Shadeways", which are sidewalks or pathways through the city that have a relatively high amount of natural and built (artificial) shading that provide thermal comfort for active travelers (Deilami, Rudner, et al. 2020). Such infrastructure provides multiple benefits: it reduces urban heat island effects, improves air quality through vegetation filtration, increases active transportation by making walking thermally feasible, and supports mental health through green space exposure (Khalili, Kumar, and Jones 2024). Critically, shaded spaces also provide *cognitive recovery zones* where pedestrians can pause, re-orient, and re-encode their spatial location before proceeding. This addresses the uniform attention depletion observed in this study without requiring navigation aids to be redesigned.

Wayfinding Signage as Cognitive Support

Existing heat-aware navigation systems optimize routes to minimize thermal exposure (Feng et al. 2024; Neset et al. 2022) but overlook the spatial memory challenges revealed here: under heat, pedestrians encode landmarks less effectively, misidentify unfamiliar intersections as familiar ones, and require additional cognitive support at decision points.

Signage used for wayfinding (e.g., directional signs, maps, and informational displays) can serve as external cognitive support, extending the backbone of spatial processing from internal memory to visual search. Research on pedestrian wayfinding preferences identifies several design principles that enhance sign effectiveness under degraded attentional conditions: clear typographic hierarchies, high color contrast between sign elements and background, placement at decision-critical intersections rather than midway along paths, and integration with multimodal information (text, symbols, landmark identifiers, distance/time estimates) to accommodate diverse user strategies and cognitive styles (Zhou and Ujang 2024). The idea, therefore, is simple: if attention on landmarks is depleted, the importance of signage becomes higher as it might compensate for internal memory deficits.

Alignment with Sustainability Goals

These interventions align with the UN Sustainable Development Goal 11 (universal access to safe, inclusive green spaces by 2030 [11.7]; United Nations (2015)). The inclusion of urban greenery applies to SDG 13 (Climate Action) by reducing urban heat island effects, and also SDG 3 / SDG 11b, making pedestrian travel safer.

These interventions are especially important for vulnerable populations such as older adults and lower-income residents who rely on walking for mobility, and they face heightened thermal and cognitive burden (Deilami, Rudner, et al. 2020). Strategic shade and evidence-based wayfinding thus constitute climate justice interventions by ensuring pedestrian safety and spatial autonomy as urban temperatures rise. Future urban planning must recognize that pedestrian cognitive performance is as essential to public safety and equity as physical thermal comfort.

5.5.2 GIScience and Navigation Systems

Current advancements in heat-aware navigation systems represent the progress and need towards climate-adaptive urban mobility (Feng et al. 2024; Neset et al. 2022), yet they operate under a critical limitation as they optimize for thermal exposure while ignoring cognitive performance during spatial encoding. This section demonstrates how geographic information systems and navigation tools can be enhanced to account for the heat-cognition coupling revealed in this study. Three main suggestions

emerge from the findings of the study: 1) dynamic landmark salience adjustment based on thermal conditions, 2) complexity-weighted routing that minimizes decision-point density under heat, and 3) demographic personalization reflecting differential cognitive vulnerability.

Cognitive Performance as a Navigation Design Parameter

Based on the findings of this study, four enhancements to heat-aware navigation are proposed.

First, thermal-adaptive landmark augmentation: Rather than displaying landmarks statically on maps, navigation apps should dynamically increase landmark prominence when ambient temperature or predicted thermal stress exceeds certain thresholds. The strong landmark-recognition correlation ($r = .62$) established that increased landmark fixation directly supports memory encoding. This is especially important under thermal stress, when landmark attention drops. This suggestion enhances landmark salience through larger icons, verbal labels, or audio cues (e.g., turn left at the red church), which directly compensate for attentional depletion.

Second, decision-point minimization weighted by thermal conditions: Beyond optimizing for distance or thermal exposure, routing algorithms should also consider decision-point density when thermal stress is anticipated. The preserved route memory finding suggests that pedestrians retain directional memory well even under heat stress, implying that routes with fewer intersections may be preferable when thermal load is high. This becomes particularly relevant for turn-by-turn navigation systems where each decision point requires active attention; users of such systems would benefit from routes with simplified junction sequences that reduce cognitive load at critical moments, even if the total distance is slightly longer.

Third, demographic personalization: Heat-aware systems should incorporate user profiles including age, heat sensitivity, spatial ability, area familiarity, and prior app usage patterns. Systems could learn from user behavior to identify which interventions (landmark augmentation, simplified routes, shade-seeking prompts) are most effective for each individual, enabling increasingly personalized guidance over time.

Fourth, temporal recommendations as cognitive risk management: Navigation systems could adapt to thermal conditions by: 1) recommending cooler times of day when trip scheduling is flexible, or 2) deferring exploration of unfamiliar routes to periods of lower thermal stress. The preserved route memory finding suggests that pedestrians can reliably execute familiar routes under heat, so systems should avoid introducing new routes (which require landmark encoding) during high thermal load.

Spatial Data Infrastructure: Formalizing Cognitive Salience

Implementing these enhancements requires substantial data gaps to be addressed. Current geographic databases (such as OSM or city models) encode characteristics such as building type, height, and function, but not the saliency of a building by determining its visibility index or uniqueness relative to surrounding features, which would make a building more recognizable under heat stress. The strong fixation-recognition link found in this study suggests that formalizing salience through crowd-sourced annotation or computer-vision-derived metrics would enable evidence-based landmark design. With this data, a new cognitive-thermal performance index could be computed, which combines ambient and land surface temperature with landmark density, intersection complexity, route familiarity, and user demographics into a unified index. Such an index could be able to predict navigation success probability and transform route optimization to a personal level.

These implications show how GIScience and navigation technology can partially adapt to compensate for heat-related cognitive constraints, but they cannot eliminate human vulnerability. This directly leads to the broader public health and equity question beyond design and technology, which tries to answer who is most affected, and what interventions are needed to maintain safe, autonomous mobility as heat becomes more frequent and intense.

5.5.3 Public Health and Occupational Safety

Heat is typically framed as a threat to physical health (e.g., dehydration, exhaustion, cardiovascular strain). The findings of this study expand this framing by adding *cognitive safety risk* as an additional dimension during navigation. Already during moderate thermal stress, wayfinding is impaired through attentional depletion after a short exposure, suggesting that reliability may deteriorate precisely when safe mobility is most important. This section outlines implications for 1) pedestrian safety and 2) occupational training and protection.

Pedestrian Safety Scenarios and Vulnerable Populations

Three scenarios illustrate the practical consequences of heat-impaired navigation.

First, tourist wayfinding failures: Tourists are a high-risk group, as they navigate unfamiliar environments, often under time pressure and with limited local knowledge to compensate for errors. The results showed that under heat, landmark recognition performance declined and participants increasingly misidentified unfamiliar intersections as familiar ones. This can lead to a vicious cycle as getting lost increases time outdoors, which increases heat exposure, which can further impair encoding and attention. Beyond discomfort, this can translate into safety-relevant outcomes, such as unintentionally entering unsafe areas, missing time-critical connections, or failing to locate cooling options. Practical implications should therefore not only warn users about thermal stress, but also provide *navigation support* when thermal stress is high.

Second, older adults and heat-sensitive populations: The sample of this study only examined young healthy adults, while still finding attention reductions. Long-term research demonstrated that cumulative extreme heat exposure accelerates cognitive decline in older adults, particularly among minority residents and those in disadvantaged neighborhoods (E. Y. Choi, Lee, and Chang 2023). Furthermore, older adults have also been shown to have reduced cognitive performance under heat stress, with effects moderated by humidity and physical activity levels (Pandolf 1997; Schlader et al. 2011). Therefore, if younger healthy adults already show impairments, it is likely that older adults experience substantially worse deficits. In practice, this can have different consequences, such as not being able to get to medical appointments, disorientation during essential navigation (grocery shopping, pharmacy visits), or increased anxiety and avoidance of outdoor mobility during heat waves. Interventions should therefore include support services during high thermal stress periods (e.g., assisted mobility for essential trips), simplified routing, and clearly signposted "cool routes" and cooling stops around transit hubs.

Third, repeated exposure and cumulative fatigue: This study only examined a single, roughly 12-minute navigation exposure. However, many people (e.g., outdoor workers, delivery personnel, construction laborers, and emergency response personnel) experience repeated or prolonged heat exposure while navigating. Occupations that require reliable movement under heat (e.g., firefighters (Thompson et al. 2024)) could use training protocols to train their spatial memory: 1) baseline navigation under neutral conditions, 2) repeated practice under heat on familiar routes, and 3) transfer tests on new routes under heat. This protocol is based on the findings that direction memory remained comparatively preserved in the study, suggesting that repeated route training may remain effective even when landmark recognition fails under thermal stress (Parsons, Stacey, and Woods 2019).

5.5.4 Theoretical Contributions to Spatial Cognition

Beyond these practical implications for pedestrian safety and occupational contexts, the findings refine how spatial cognition is theorized under environmental stress. They challenge pure hierarchical spatial knowledge theories, strengthen attention-memory frameworks, and arousal-centric explanations of stress-related impairment. Furthermore, this study also advances spatial cognition theory methodologically by showcasing the power of multimodal psychophysiological methods to enable mechanistic investigation.

Parallel Spatial Knowledge Systems: Differential Vulnerability to Environmental Stressors

Classic hierarchical models (Siegel and White 1975) propose that spatial learning progresses through a hierarchical sequence: landmark recognition $\rightarrow$ route knowledge $\rightarrow$ survey knowledge. Under a strictly hierarchical interpretation, impairments in landmark processing should result in route-level deficits, because route representations are built upon landmark recognition at decision points. In contrast, more recent work argues that multiple forms of spatial knowledge can be acquired in parallel, with partially independent representations and strategies (Ishikawa and D. Montello 2006; Kim and Bock 2021). This study extends the parallel framework by providing empirical evidence that these parallel systems inherit *differential vulnerability to environmental stressors*.

The dissociation found in the results (landmark recognition impairment with preservation of route memory) cannot be explained by simple hierarchical models. Instead, the pattern aligns much better with parallel acquisition frameworks: recognition memory depends critically on sustained attentional encoding of visual details, whereas route memory relies on episodic memory for action sequences independent of landmark fixation. Thermal stress selectively impaired the attention-intensive system while sparing the more automatic procedural system.

This refinement matters theoretically because it pushes spatial cognition models to account not only for how representations develop, but also for how they fail under constraints. Practically, this suggests matching interventions to system vulnerability: in hot conditions, navigation aids should reduce reliance on recognition judgments (e.g., by minimizing decision-point density) and instead strengthen action-oriented guidance, while also supporting landmark encoding through salience enhancement as discussed in Section 5.5.2.

Attention-Memory Coupling: Robustness Under Thermal Perturbation

A second contribution concerns the robustness of the attention-memory relationship under environmental stressors. A well-established idea in visual cognition is that fixations reflect information selection and that fixation patterns predict what is encoded into memory (Kiefer, Giannopoulos, Raubal, and Duchowski 2017). In spatial cognition, recent evidence similarly shows that attention to task-relevant AOI improves later navigation performance and spatial knowledge (Kapaj, Hilton, Lanini-Maggi, et al. 2024). The findings of this study extend this relationship by adding a heat-stress context: body state (thermal load) $\rightarrow$ perceptual state (reduced attention) $\rightarrow$ cognitive outcome (impaired memory) (Wolbers and Hegarty 2010). This is especially important as it shows that this relationship endures thermal stress and can therefore be used as a metric for spatial cognition research under environmental stressors.

Methodological Innovation: Multimodal Psychophysiology in Thermal VR

This study also contributed methodologically, as it demonstrated the feasibility and the value of combining behavioral memory measures, eye-tracking, physiological sensing, and controlled thermal manipulation within an immersive navigation task. This multimodal approach enabled detailed dissociation analyses revealing that subjective discomfort, attentional allocation, and physiological arousal respond independently to thermal stress, which would not have been visible with a single method.

This multimodal approach opens three fields for future mechanism testing. First, it supports mediation questions (e.g., does reduced landmark attention statistically mediate heat-related memory impairment?). Second, it allows boundary-condition mapping: identifying when heat begins to impair which subsystem (landmark recognition vs. route memory) and whether effects scale with exposure duration. Third, it offers a replicable template for studying other environmental stressors (noise, crowding, air quality) using the same structure: controlled stressor induction, eye-tracking as an attention proxy, physiology as a state proxy, and signal-detection approaches as precise memory metrics.

5.6 Future Research Directions

While this study establishes a foundation for understanding thermal stress and its coupling to navigation, significant opportunities remain for extending, validating, and implementing these findings. Future work can be categorized into two categories: immediate extensions that are feasible with modest additions to the current study design, and a longer-term category that positions heat-cognition interactions as a core component of climate-resilient mobility research.

5.6.1 Immediate Extensions

Replication with heat-vulnerable populations

This study only examined healthy adults; the next step would therefore be to test if the observed findings generalize or even intensify in groups that are likely to experience stronger heat strain or reduced cognitive reserve, such as older adults or children. Conceptually, this would allow us to directly test the interaction effects of age x heat and clarify whether the observed impairment represents a floor or a lower bound for vulnerable groups. From an applied perspective, these groups are also the most relevant for public-health and accessibility implications.

Systematic manipulation of landmark positioning

This study found no landmark buffer, which directly contradicts Karimpur, Röser, and Hamburger (2016)'s study, which showed that correct-turn-side landmarks help spatial learning. A targeted follow-up could systematically vary landmark location (correct side vs. opposite side), distance to the intersection, and visual salience while keeping route geometry constant. The outcome would strengthen both theory (what aspects of landmark encoding are robust under stress) and design (how to place or highlight landmarks for maximal resilience).

Dynamic thermal exposure

This study employed heat as a static stressor, having a constant ambient temperature with no variation during the navigation task. Real-world scenarios, by contrast, involve escalating heat, intermittent cooling (seeking shade), and cumulative fatigue over time. A next step would model heat as a dynamic stressor to test whether attention and memory decline nonlinearly and establish recovery thresholds critical for occupational and public health applications.

Real-world validation

Mobile eye-tracking in actual urban heat would bridge the VR-field gap and validate ecological claims. Participants navigating in real urban environments during real thermal stress while wearing eye-tracking and physiological measuring systems would reveal whether VR-derived effects are replicated in real-world urban environments. These environments crucially also come with full sensory richness, such as, for example, air movement, thermal radiation, and crowd dynamics.

5.6.2 Long-Term Research Agenda

Individual difference modeling

A longer-term study could build predictive models of who is most likely to experience navigation impairment under thermal stress. This could be achieved by developing heat-condition risk profiles incorporating physiological vulnerability (age, fitness, heat tolerance), cognitive factors (spatial ability, cognitive style), and contextual factors (area familiarity, task pressure). Predictive models could classify individuals as heat-vulnerable, heat-resilient, or intermediate, enabling personalized navigation assistance and occupational fitness recommendations.

Adaptive real-time systems

To implement the findings, a long-term project could integrate the findings into a navigation system that adjusts assistance dynamically when thermal strain is high. This system would dynamically augment landmarks, simplify routes, or alert users to cooling centers when cognitive load exceeds thresholds. Such a system would represent a significant advancement in navigation system development.

Cross-cultural validation

Finally, the heat-cognition relationship should be tested across different urban morphologies and cultural contexts. Grid-based street networks, medieval European street patterns, and dense Asian megacities differ in intersection complexity, landmark structure, and navigational strategies. Cross-site studies would clarify how much of this effect is universally applicable and what parts are context-dependent, enabling locally adapted design recommendations and globally transferable models.

Chapter 6

Conclusion

Urban heat is typically framed as a physical health hazard (dehydration, exhaustion, heat stroke), but safe and independent mobility requires cognitive functions such as attention, spatial encoding, and memory-guided decision-making that may also be vulnerable to thermal stress. This thesis reports a study that examined the cognitive dimension of thermal adaptation by testing whether heat stress affects how people learn and remember routes and landmarks during pedestrian navigation.

6.1 Study Goal, Research Questions, and Experimental Approach

The overarching goal of this study was to determine how thermal stress, relative to neutral conditions, affects spatial learning during navigation in an urban virtual environment, and how such effects are reflected in patterns of visual attention and physiological arousal (Section 1.3). This research was motivated by the absence of empirical work examining spatial cognition under heat stress, which has direct implications for urban design, navigation system development, and climate adaptation strategies.

A controlled Heat (38°C) vs. No-Heat (24°C) study was conducted in an immersive VR CAVE where 46 healthy young adults navigated an urban route. Eye-tracking measured attention to landmarks and navigation cues; electrodermal activity indexed physiological arousal; post-navigation spatial memory was assessed via signal-detection analysis of intersection recognition and route-direction recall.

6.2 Principal Findings: Selective Memory Impairment and Uniform Attention Reduction

6.2.1 Research Question 1: Spatial Memory Under Thermal Stress

The key finding is that heat produced selective impairment of spatial memory rather than global cognitive decline. Thermal stress significantly impaired landmark-based intersection recognition sensitivity, with discriminability d' reduced by 0.63 units. This impairment was driven primarily by a 13.33% increase in false alarm rates (13.04% in No-Heat vs. 26.38% in Heat), indicating that heat-exposed participants more frequently misidentified unseen intersections as previously encountered. Hit rates also showed a modest decline (69.86% vs. 64.93%), consistent with incomplete landmark encoding rather than catastrophic memory loss.

In contrast, route-direction memory remained comparatively stable (only a 1.16% difference between Heat M = 67.54% and No-Heat M = 68.70%), with similar accuracy across conditions and performance above chance. This distinction is theoretically informative, as it is better suited to describe parallel spatial knowledge acquisition frameworks (Ishikawa and D. Montello 2006; Kim and Bock 2021), rather than strongly hierarchical frameworks in which landmark degradation should cascade into route knowledge (Siegel and White 1975). The results therefore support the conclusion that thermal stress can selectively impair landmark-based recognition while sparing a procedural route representation, meaning that navigators may still “know where to turn” even when place recognition becomes noisier.

6.2.2 Research Question 2: Visual Attention Allocation Under Thermal Stress

The use of eye-tracking data enabled the establishment of a mechanistic-level link that helps explain the dissociation in spatial memory. Heat reduced the visual attention on navigation-relevant features, with decreased fixation time and duration across the defined Areas of Interest, rather than a targeted reallocation to compensatory cues. However, the coupling between attention and memory remained even under heat, as landmark fixation predicted recognition performance. This aligns with broader evidence that gaze reflects encoding success (Kiefer, Giannopoulos, Raubal, and Duchowski 2017) and with navigation research highlighting the role of landmark attention for learning (Kapaj, Hilton, Lanini-Maggi, et al. 2024). This dissociation directly links attention reduction to recognition impairment while explaining preservation of route memory-processes by stating that this process is less dependent on visual landmark encoding

Additionally, participants spent 56.7% of trial time on AOIs under heat versus 75.7% in neutral conditions, indicating not only reduced fixation duration but also greater gaze fragmentation under thermal stress. The overall uniform pattern, therefore, suggests thermal stress depletes general attentional capacity rather than triggering strategic reallocation toward task-critical features.

6.2.3 Research Question 3: Physiological Arousal Under Thermal Stress

The third research question coupled physiological arousal to thermal stress; however only resulted in null findings. The thermal manipulation successfully induced subjective discomfort (the thermal comfort questionnaire resulted in a very large effect of $d = 2.16$); however, electrodermal activity did not show the expected heat-related of elevated physiological arousal at any temporal scale (baseline p = .078; trial-level p = .793; intersection-level p = .66). This null arousal pattern, despite clear subjective discomfort and behavioral deficits, suggests thermal stress operates primarily through cognitive resource competition rather than sympathetic nervous system activation.

6.3 Contributions and Outlook

This work advances three domains. *Theoretically*, it refines parallel-systems frameworks of spatial cognition by demonstrating differential vulnerability of attention-dependent landmark recognition versus procedurally anchored route memory under thermal stress. *Methodologically*, it demonstrates the feasibility and added value of combining thermal VR with synchronized eye-tracking and electrodermal activity (EDA) in a spatial navigation paradigm. *Practically*, it motivates a "cognitive layer" in heat adaptation, informing navigation system design and urban planning that account for heat's selective disruption of landmark-based learning. These contributions are especially critical as urban heat waves increase in frequency and intensity, making cognitive resilience a public health priority.

Future work should establish boundary conditions across age groups and heat-vulnerable populations, conduct field studies in real urban environments, and test whether strategically positioned landmarks buffer against thermal attention deficits. Longitudinal testing at multiple retention intervals will clarify whether heat primarily impairs encoding, consolidation, or retrieval.

6.4 Take-Home Message

Heat is not only an exposure problem, but it is also a cognition problem. As global temperatures continue to rise, navigation design must recognize that thermal mitigation is not merely a comfort issue but a cognitive necessity for safe urban mobility.

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Appendix A

Appendix - Information Sheet and Consent Form

Information Sheet and Consent Form

Study for Master Thesis: Pedestrian Navigation under different temperature conditions in VR

July 2025

Participant ID:_____

Dear Participant,

Thank you for your interest in participation! Please read all of the following information very carefully to decide whether to participate in this study.
You are invited to participate in a study conducted by Alessandro Joshua Pierro (alessandrojoshua.pierro@uzh.ch) as part of his master's thesis research related to urban pedestrian navigation, carried out at the Department of Geography of the University of Zurich (UZH). The project is supervised by Prof. Dr. Sara Irina Fabrikant (sara.fabrikant@geo.uzh.ch) and Dr. Armand Kapaj (armand.kapaj@geo.uzh.ch).

Purpose of the study
With this study, we wish to gain insights into how people navigate in urban VR environments given different temperature conditions.

General Information
The study will take place at the Department of Geography of the University of Zürich, at the Irchel Campus, in the GIVA CAVE (room Y25-J87), and it will require about **60 minutes of your time.**

Procedure of the study
See the separate procedure sheet.

Voluntary Participation
Your participation in the study is entirely voluntary. You may withdraw your consent to participate in the study at any time without providing notice or reasoning. You can pose questions about the experiment at any time.

Inclusion and exclusion criteria
Any healthy young adult **between 18 and 40 years old, with normal or corrected to normal vision, and with a good understanding of English**, may participate in this experiment. The exclusion criteria listed below ensure that our statements are derived from a normal healthy population who can comfortably complete the experiment.

- History of neurological disorders such as epilepsy or migraines.
- History of cardiovascular disease.
- History of strong motion sickness.

Obligations of the participant

- You are expected to carefully follow the given instructions and fully and faithfully complete all questionnaires and experiment tasks.
- You must immediately express any uncomfortable experience during the experiments.
- You must inform the experimenters of any changes in health status that may affect your inclusion in the study.

Risk to the participants

This study will be carried out in a research laboratory with a changing room temperature depending on the experimental condition simulated in the VR environment. There are no physical or other effects on participants' health, besides the room temperature during the experiment.

Benefits to the participant

This study offers no direct benefits to the study participants. Participants will be given a small token of appreciation as a thank-you gift for their participation.

Data confidentiality

This study involves recording your personal information. All data are coded by replacing the names with an ID code and are made anonymous. Furthermore, your name will never be used in any of our reports and publications. All collected data will be kept encrypted and stored on secure media protected by a password only known to researchers listed above. The personal information provided here is stored for a period of 10 years due to a legal obligation. A local ethics committee may examine the information during this period. All the information is stored in a locked laboratory space and on a highly secure server at the Department of Geography of the University of Zurich.

Changes to the information provided

Any changes in the study that may affect the safety of your participation or your privacy, we shall inform you in writing.

Costs

The entire study will not bear any costs to the participants.

Termination of participation

Participation will be cancelled if you decide to withdraw from the study. Likewise, if you are unable to understand/follow instructions from the study conductor. All obtained data will be permanently deleted.

Study Results

If you would like to be informed about the results of this study, let the study conductor know. A copy of the study results can then be sent to you later.

Contact persons

If you have any questions or worries about the study, please contact the persons listed below (you will receive a copy of this document).

- Alessandro Joshua Pierro (alessandrojoshua.pierro@uzh.ch)
- Prof. Dr. Sara Irina Fabrikant (sara.fabrikant@geo.uzh.ch)
- Dr. Armand Kapaj (armand.kapaj@geo.uzh.ch)

This study has been registered with the Ethics Committee of the Faculty of Philosophy, University of Zurich. In case of questions or complaints about ethical issues regarding this study, please contact the Chair of the Ethics Committee of the Faculty of Philosophy using this email address: chair.ethics.committee@phil.uzh.ch.

INFORMED CONSENT

By participating in this study, I agree and affirm that:

1) I was given enough time to read this information sheet.
2) I understand the requirements of the experiment, and I agree to participate in this study.
3) My participation is entirely voluntary, and I have not been forced to participate in this study in any way.
4) I acknowledge that I may withdraw my consent to participate in this study at any time without any further notice or reasoning.
5) I agree that my data may be used in an anonymized form for research purposes only and may be published in academic research publications.
6) I understand that a local ethics committee may examine my personal details to check the activities of this research study.
7) I understand that my personal information will be kept confidential under all circumstances.
8) I understand that the study investigators, in the interest of the study, may terminate my participation at any time.
9) I understand that I must follow the instructions of the experimenter and comply with the requirements of this and other instruction sheets.

With your signature, you confirm that you have read and understood the above information and agree to participate in the experiment under the conditions described therein.

Signature of participant	Signature of study experimenter
_____	_____
First and last name in block letters	First and last name in block letters
_____	_____

Date and place: _____

Revocation of Consent Form

Study for Master Thesis: Study for Master Thesis: Pedestrian Navigation under different temperature conditions in VR

July 2025

Participant Number: _____

Revocation of consent

I hereby withdraw my consent to participate in the study described above.

Signature of participant

_____

First and last name in block letters

_____

Date and place: _____

By withdrawing your consent, you do not in any way affect your relationship with the University of Zurich.
The revocation can be requested at any time and without giving reasons.

Please send the revocation of consent to Prof. Dr. Sara I. Fabrikant, Geographical Information Visualization and Analysis, Department of Geography, University of Zurich, Winterthurerstrasse 190, 8057 Zurich.

Appendix B

Appendix - Questionnaires

B.1 Demographic Survey

Demographic Survey

Dear participant,

Thank you for taking the time to join my Master's thesis study. The goal of this study is to investigate the impact of thermal comfort on human navigation behavior.

Below, you will be asked to complete a questionnaire and provide information regarding yourself.

Note: All data will be kept strictly confidential. No information will be published in this study that allows any conclusions to be drawn about you as a person.

Participant ID

Please enter your Participant ID code here, which was provided with the same email as the link for this form.

_____

Gender

☐ Female ☐ Male ☐ Other

Age

_____

What is your highest level of completed education?

- ☐ High School (Sekundarstufe/Gymnasium)
- ☐ Apprenticeship Qualification (Lehrabschluss)
- ☐ Bachelor
- ☐ Master
- ☐ PhD
- ☐ Other

If you are currently enrolled at a university level, what is your current Major?

Major: _____

If you are currently enrolled at a university level, what is your current Minor?

Minor: _____

What is your current occupation?

_____

B.2 Santa Barbara Sense of Direction Questionnaire

Sense of Direction Questionnaire

Dear participant,

Thank you for taking the time to join my Master's thesis study. The goal of this study is to investigate the impact of thermal comfort on human navigation behavior.

Below, you will be asked to complete a questionnaire and provide information regarding your sense of direction and orientation skills in the environment.

Note: All data will be kept strictly confidential. No information will be published in this study that allows any conclusions to be drawn about you as a person.

Participant ID

Please enter your Participant ID code here, which was provided with the same email as the link for this form.

1. I am very good at giving directions.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

2. I have a poor memory for where I left things.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

3. I am very good at judging distances.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

4. My "sense of direction" is very good.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

5. I tend to think of my environment in terms of cardinal directions (N, S, E, W).

Strongly agree 1 2 3 4 5 6 7 strongly disagree

6. I very easily get lost in a new city.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

7. I enjoy reading maps.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

8. I have trouble understanding directions.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

9. I am very good at reading maps.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

10. I don't remember routes very well while riding as a passenger in a car.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

11. I don't enjoy giving directions.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

12. It's not important to me to know where I am.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

13. I usually let someone else do the navigational planning for long trips.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

14. I can usually remember a new route after I have traveled it only once.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

15. I don't have a very good "mental map" of my environment.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

B.3 Thermal Sensitivity Questionnaire

Thermal Sensitivity Questionnaire

Dear participant,

Thank you for taking the time to join my Master's thesis study. The goal of this study is to investigate the impact of thermal comfort on human navigation behavior.

Below, you will be asked to complete a questionnaire and provide information about your sensitivity to heat, such as, for example, during hot weather conditions.

Note: All data will be kept strictly confidential. No information will be published in this study that allows any conclusions to be drawn about you as a person.

Participant ID

Please enter your Participant ID code here, which was provided with the same email as the link for this form.

_____

1. I often feel uncomfortable or stressed during hot weather.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

2. I easily adapt to warm temperatures.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

3. I often seek shade or cooler areas when walking outdoors during hot days.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

4. I can tolerate heat better than most people I know.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

5. Exposure to direct sunlight significantly reduces my ability to concentrate.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

6. I rarely experience heat-related discomfort even in very hot conditions.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

7. I usually avoid outdoor activities when temperatures exceed 34°C.

Strongly agree	1	2	3	4	5	6	7	strongly disagree

8. Hot environments negatively impact my cognitive performance (e.g., memory, attention, etc.).

Strongly agree	1	2	3	4	5	6	7	strongly disagree

B.4 Thermal Comfort Questionnaire

Thermal Comfort Questionnaire

Dear participant,

This questionnaire will assess your perception of the felt air temperature during the navigation task you just completed.

Note: All data will be kept strictly confidential. No information will be published in this study that allows any conclusions to be drawn about you as a person.

Participant ID

To be filled by the experimenter.

_____

1. I felt uncomfortable during the experiment.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

2. My performance in the experiment was impacted by the felt air temperature.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

3. The felt air temperature made it difficult for me to concentrate during the experiment.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

4. I found it easy to ignore the felt air temperature and focus on the experiment.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

5. I experienced significant physical discomfort (e.g., sweating) during the experiment.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

6. The felt air temperature was unpleasant throughout the experiment.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

7. The felt air temperature made the experimental task seem more difficult.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

8. I frequently wished during the experiment that the felt air temperature was:

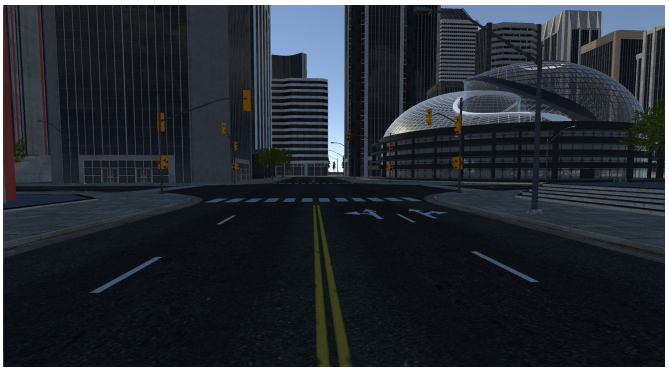
Much hotter 1 2 3 4 5 6 7 Much colder

B.5 Intersection and Route Questionnaire

The following images were used for the Intersection and Route Recognition Questionnaire.

B.5.1 Intersections Morning

Direction Nr. 10 (Landmark Nr. 6)



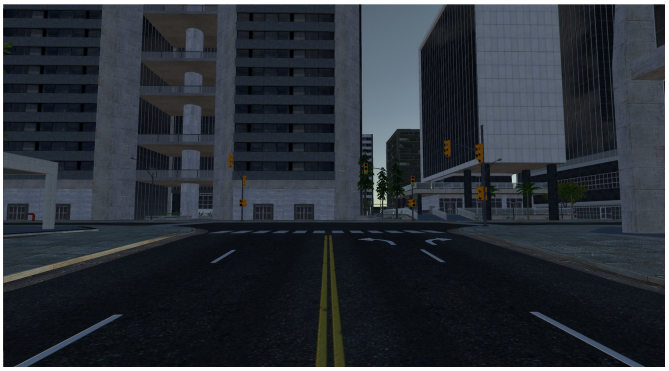
Direction Nr. 11 (No Landmark)

Direction Nr. 12 (Landmark Nr. 7)

Direction Nr. 13 (Landmark Nr. 8)

Direction Nr. 14 (No Landmark)

Direction Nr. 15 (No Landmark)



Direction Nr. 16 (Landmark Nr. 9)

Direction Nr. 17 (No Landmark)

Direction Nr. 2 (Landmark Nr. 1)

Direction Nr. 3 (Landmark Nr. 2)

Direction Nr. 4 (No Landmark)

Direction Nr. 5 (Landmark Nr. 3)

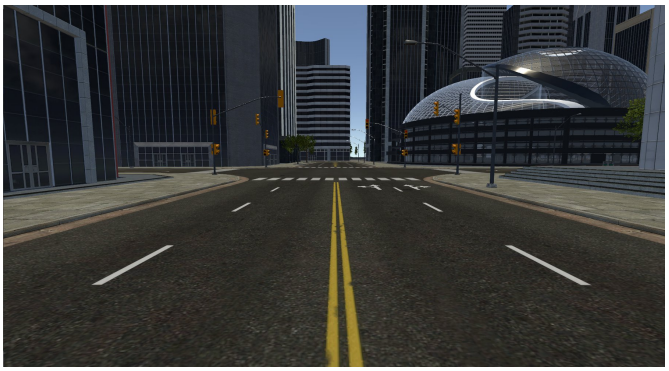
Direction Nr. 6 (Landmark Nr. 4)

Direction Nr. 7 (Landmark Nr. 5)

Direction Nr. 8 (No Landmark)

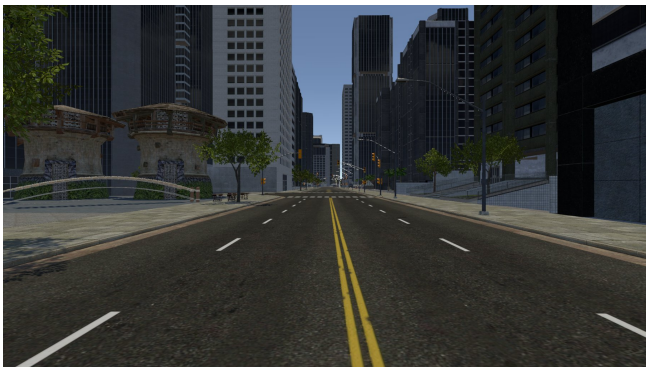
B.5.2 Intersections Noon

Direction Nr. 10 (Landmark Nr. 6)

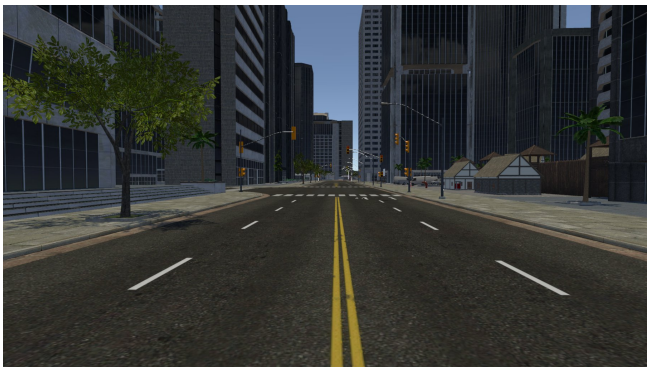


Direction Nr. 11 (No Landmark)

Direction Nr. 12 (Landmark Nr. 7)



Direction Nr. 13 (Landmark Nr. 8)



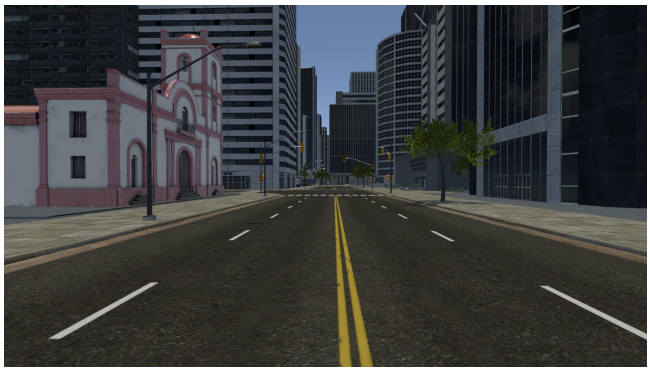
Direction Nr. 14 (No Landmark)

Direction Nr. 15 (No Landmark)

Direction Nr. 16 (Landmark Nr. 9)

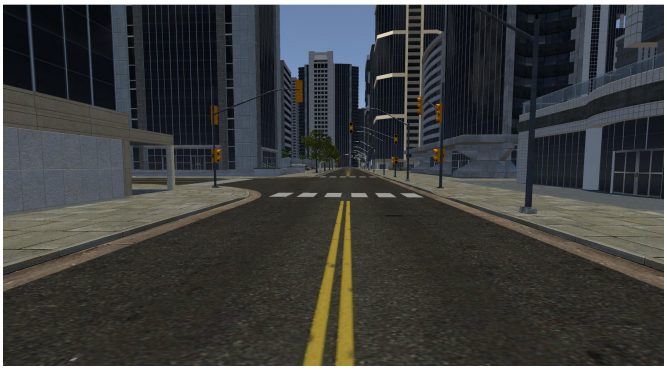
Direction Nr. 17 (No Landmark)

Direction Nr. 2 (Landmark Nr. 1)



Direction Nr. 3 (Landmark Nr. 2)

Direction Nr. 4 (No Landmark)



Direction Nr. 5 (Landmark Nr. 3)

Direction Nr. 6 (Landmark Nr. 4)

Direction Nr. 7 (Landmark Nr. 5)

Direction Nr. 8 (No Landmark)

B.5.3 Decoy Intersections Morning

Unseen Intersection Nr. 1

Unseen Intersection Nr. 2

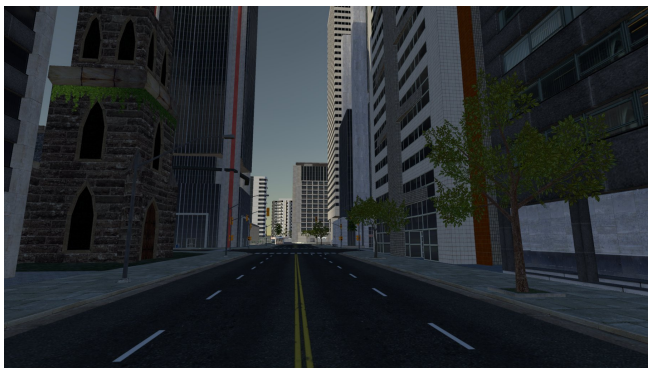
Unseen Intersection Nr. 4

Unseen Intersection Nr. 5

Unseen Intersection Nr. 6

Unseen Intersection Nr. 7

Unseen Landmark Nr. 1



Unseen Landmark Nr. 2

Unseen Landmark Nr. 3

Unseen Landmark Nr. 4

Unseen Landmark Nr. 5

Unseen Landmark Nr. 6

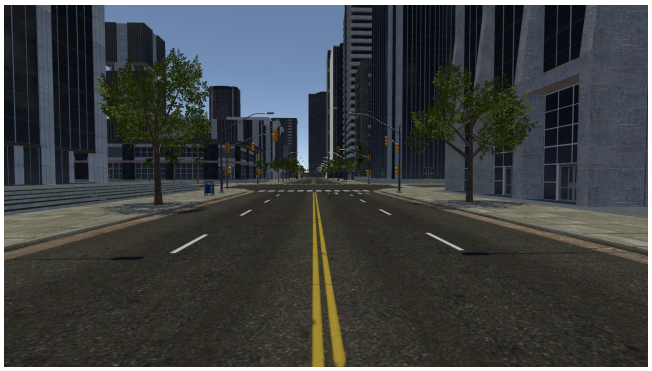
Unseen Landmark Nr. 7

Unseen Landmark Nr. 8

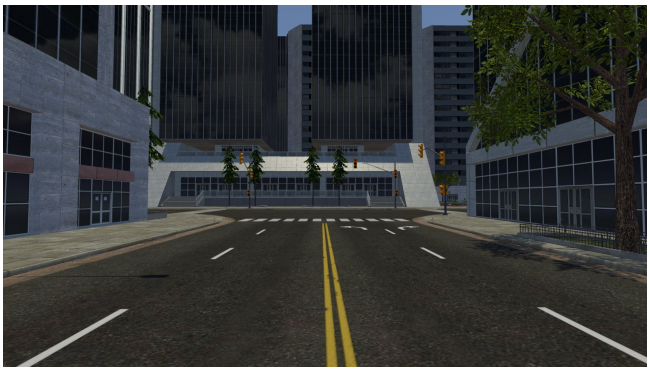
Unseen Landmark Nr. 9

B.5.4 Decoy Intersections Noon

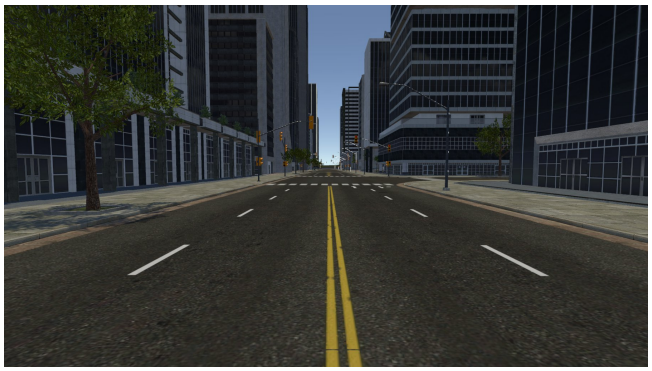
Unseen Intersection Nr. 1



Unseen Intersection Nr. 2

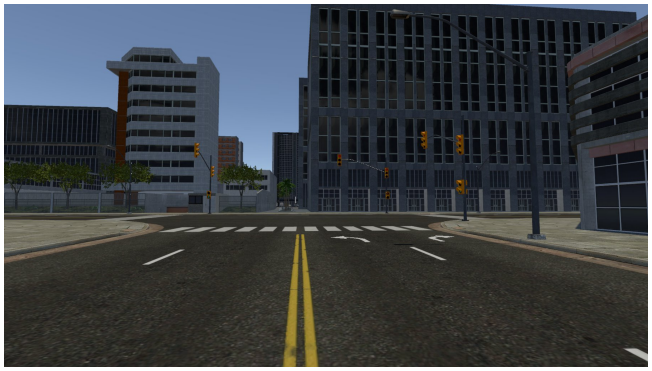


Unseen Intersection Nr. 4

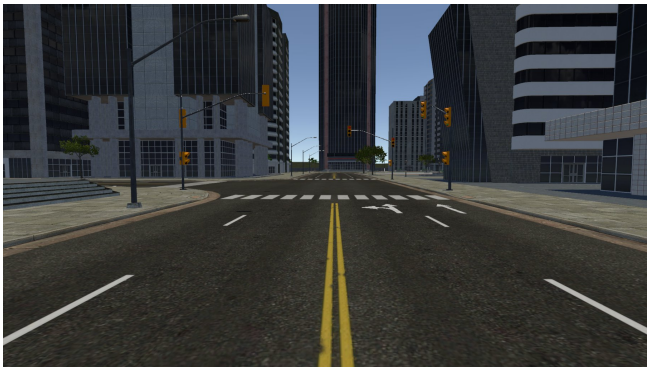


Unseen Intersection Nr. 5

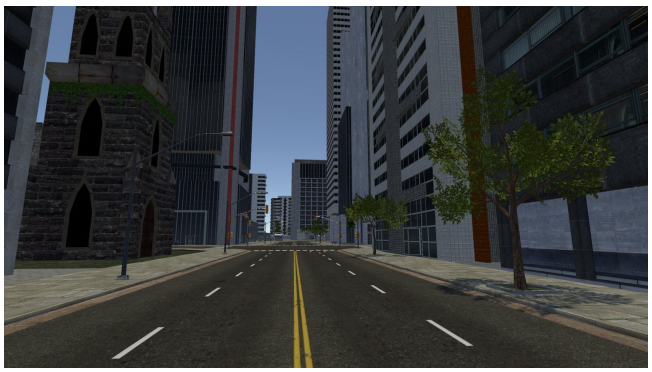
Unseen Intersection Nr. 6



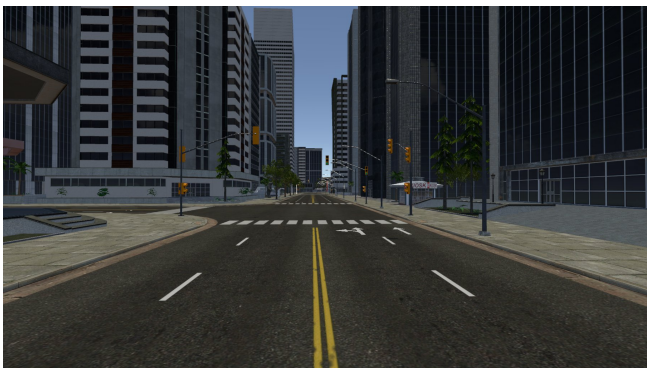
Unseen Intersection Nr. 7



Unseen Landmark Nr. 1

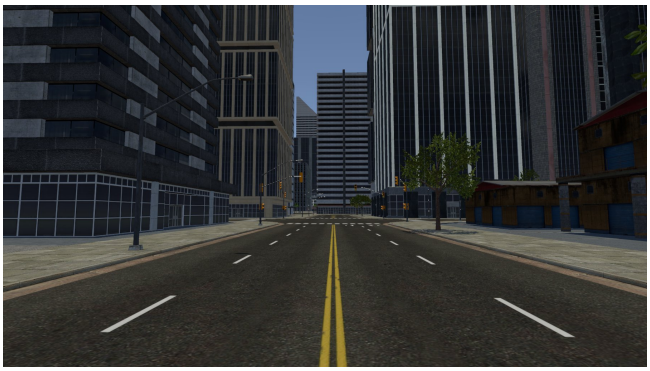


Unseen Landmark Nr. 2

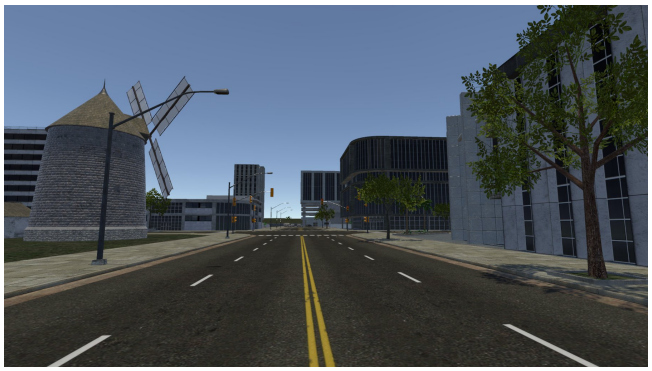


Unseen Landmark Nr. 3

Unseen Landmark Nr. 4

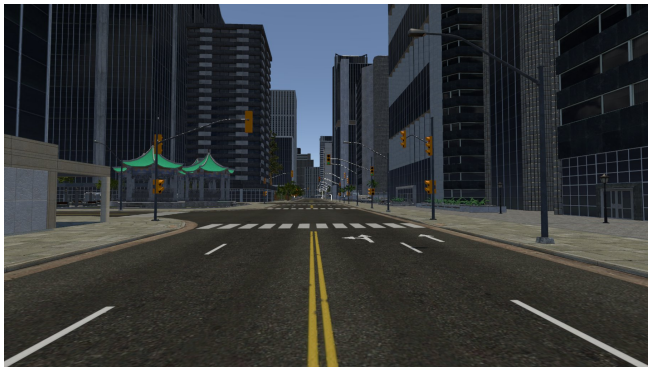


Unseen Landmark Nr. 5



Unseen Landmark Nr. 6

Unseen Landmark Nr. 7



Unseen Landmark Nr. 8

Unseen Landmark Nr. 9

Appendix C

Appendix - Application Ethics Committee

Application form for Approval of a Research Project

March 2022

Based on the "Antragsformular der Philosophisch-humanwissenschaftliche Fakultät der Universität Bern" and the „Checkliste für ethische Beurteilung von psychologischen Forschungsvorhaben" of the Swiss Psychological Society (SPS)

☒ Individual application ☐ Group application

☐ Amendment Approval Nr. (for amendments)

1. General Information

a. Name and contact information of applicant	**Alessandro Joshua Pierro** **Department of Geography** **University of Zurich – Irchel** **CH-8057 Zurich, Switzerland** **alessandrojoshua.pierro@uzh.ch**
b. Name(s) of person(s) carrying out the research, including contact information	**Alessandro Joshua Pierro** **Department of Geography** **University of Zurich – Irchel** **CH-8057 Zurich, Switzerland** **alessandrojoshua.pierro@uzh.ch** **Prof. Dr. Sara Irina Fabrikant** **Geographic Information Visualization & Analysis** **Department of Geography / Digital Society Initiative** **University of Zurich – Irchel** **CH-8057 Zurich, Switzerland** **Room: Y25-L86** **sara.fabrikant@geo.uzh.ch** **+41 44 635 5150**

	Dr. Armand Kapaj **Geographic Information Visualization & Analysis** **Department of Geography / Digital Society Initiative** **University of Zurich – Irchel** **CH-8057 Zurich, Switzerland** **Room Y25-L-88** **armand.kapaj@geo.uzh.ch** **+41 44 635 51 52**
c. Who provides funding for the research project?	**None**
d. Responsible department	**Department of Geography**
e. Sub-discipline	**GIScience**
f. Subject/Title of project	**Evaluating the impact of heat exposure on spatial learning during a virtual reality navigation study in an urban environment.**

g. Summary of project (max. 1'000 characters)

The aim of this empirical study is to investigate how heat exposure (two levels: heat, no heat [control]) influences pedestrians' navigation behavior and spatial learning in a virtual reality (VR) urban environment. Heat manipulation will be achieved through visual effects in the urban VR (shadows, warm tones, etc.) and a thermal heat source (e.g., a heat lamp or radiators). On the one hand, the results will provide further understanding of how hat exposure influences human navigation behavior and spatial learning of an urban environment. On the other hand, the findings provide the opportunity to support urban planners in building future pedestrian-friendly cities to mitigate increasing urban heat island effects and facilitate human mobility.

h. Time period for which approval is requested	**June 2025 – June 2026**
i. Does the research funding body require an assessment from an ethics committee?	☐ Yes ☒No
j. Does the research funding body or the law require a project registration?	☐ Yes. Relevant legislation: ☒ No

2. Research Procedure

a. Participants (targeted number, sex, age, education, population)

Based on power analyses in G*Power for a linear regression with one tested predictor and a minimum power of 0.80 and a medium effect size (f2 = 0.20), we plan to recruit 42 participants. The participants will be evenly distributed across the heat exposure conditions

(heat vs. no heat) based on gender and self-reported spatial abilities (see Appendix 3: Demographic Data and Santa Barbara Sense of Direction [SBSOD] Scale), and self-reported heat sensitivity (see Appendix 4: Thermal Sensitivity Questionnaire). The participant inclusion criteria consist of healthy adults aged between 18 and 40 years old, able to understand English, with no history of neurological disorders such as epilepsy or migraines, no history of cardiovascular disease, and no history of strong motion sickness (see inclusion and exclusion criteria in Appendix 1: Information Sheet and Consent Form).

b. What personal data are acquired (study variables)?

We will collect demographic data (i.e., age, gender) and self-reported spatial abilities using a standardized instrument (see Appendix 3), spatial learning performance measures (i.e., task completion time, recognition of landmarks seen during navigation, and recall of route directions at landmarks; see Appendix 6 and Appendix 7, respectively), perceived thermal comfort (see Appendix 8), eye movement recordings with an eye-tracking device, and electrodermal activity (EDA) recordings including skin conductance and skin temperature.

c. How are participants recruited?

We will be using various internal and external mailing lists.

d. How are participants being informed prior to the assessment? *Please attach all the information materials to the application.*

Before the experiment starts, the participants are provided with an information sheet and consent form (see Appendix 1).

e. How is the study carried out from the point of view of the participants? *Please describe in a separate document and attach to the application.*

While the participants sign up for the study during the recruiting phase, they will be provided with the information sheet and consent form (see Appendix 1), the study procedure (see Appendix 2), the demographic and Santa Barbara Sense of Direction (SBSOD) Scale (see Appendix 3), and the thermal sensitivity questionnaire (see Appendix 4), alongside with a participant ID number. During this phase, they will be asked to sign the consent form and fill out the questionnaires online. The reason for this is to be able to evenly distribute the participants on the two experimental conditions (heat vs. no heat) before the study, while controlling for gender, spatial abilities, and thermal sensitivity. The experimenters will be available to answer any questions related to their participation during this stage. On the experiment day, participants will be welcomed into a laboratory room with a controlled temperature set to approximately 22 degrees Celsius. This baseline period of around 10 minutes will allow participants to stabilize their body temperature before the start of the navigation task. Next, participants will receive a training session to become familiar with the virtual reality (VR) setup and will receive detailed information on how to navigate the VR environment using a foot paddle controller. Next, we will equip the participants with the eye-tracking (ET) and electrodermal activity (EDA) sensors and provide the necessary instructions about the navigation task. After the navigation task, we will remove the ET and EDA devices, and participants' spatial learning of the environment will be tested (see Appendices 6 and 7). Following these tests, we will ask participants to report their level of thermal comfort during the navigation task (see Appendix 8). Finally, participants will be debriefed on the study aim and thanked for their participation (see Appendix 9).

f. What are the exact instructions during the study? Which questionnaires are being used? Please state the verbatim instructions, the tasks or questionnaires and attach to the application.

For the exact instructions given to participants at the beginning and during the study, and the questionnaire being used, please see the following appendix files in order of appearance:
Appendix 2: Procedure,
Appendix 3: Demographic and Santa Barbara Sense of Direction (SBSOD) Scale,
Appendix 4: Thermal Sensitivity Questionnaire,
Appendix 5: Navigation Task Instructions,
Appendix 6: Landmark Recognition Test,
Appendix 7: Recall of Route Directions Test,
Appendix 8: Thermal Comfort Questionnaire,
Appendix 9: Debriefing.

g. How are participants being informed after the data acquisition? What is reported back? *Please include in the separate document.*
After the data acquisition, the experimenter will debrief the participants regarding the study's objectives in both verbal and written forms. For the written objectives, see Appendix 9.

3. Specific Ethical Aspects of the Project

a. Did you check "yes" to one or more items on the self-assessment checklist? *If yes, please briefly describe any risks associated with the study.*
No.

b. Is participation remunerated or are participants otherwise compensated? If yes, in what form and how much?
Participants will not be compensated. A small token of appreciation will be provided as a thank you in the form of an ice-cream.

c. If participation is undertaken for academic course credit (e.g. mandatory test subject - hours) is it possible to obtain the course credit in alternative ways?
Participants will not be given any course credit for this study.

d. Is the voluntary nature of participation through informed consent ensured? *Please submit consent form.*
Yes, participants will be asked to sign a consent form before participating (see Appendix 1).

e. Are there any disadvantages for possible participants if they don't partake in the study? *If yes, specify.*
No, there are no disadvantages for potential participants if they do not participate.

f. Is it possible for participants to withdraw their participation at any given time without any explanations without having to bear any negative consequences?
Yes, participants can withdraw at any given time without any explanation and without having to bear any negative consequences (as stated on the consent form; see Appendix 1).

g. For participants under the age of 16 years: Is written consent obtained from their legal guardian? *Please submit consent form.*
Not applicable.

h. Is participation of persons with limited capacity/ incapability of judgment or the participation of minors possible or intended? *If yes, please clarify:*
No.

i. Are participants exposing themselves to a risk that requires insurance coverage? If yes, what is the risk and what insurance coverage has been taken out? Please attach any potential insurance documents.
No, participants are not exposing themselves to any substantial risk.

4. Strains During the Assessment

a. Will the *physical integrity* of participants be affected (e.g. by taking drugs, having blood samples taken)? Is there a possibility for adverse effects (e.g. headache)? If yes, please clarify.
While one group of participants will navigate under the heat condition for 10-15 minutes during the experiment (i.e., between 36–38 degrees Celsius), we do not expect any substantially adverse physical effects from participating in this study beyond what participants might experience during a hot summer day in Zurich. They will be provided with refreshments after the study and will be able to stay in an air-conditioned room to cool down.

b. Will the *psychological integrity* of participants be affected (e.g. ability to concentrate, induction of negative emotions)? Is there a possibility of adverse psychological effects? If yes, please clarify.
No, we do not expect any adverse psychological effects from participating in this study.

c. Will participation affect the *social integrity* (e.g. participation contributes to a bad reputation)? Is there a possibility for adverse social effects? If yes, please clarify.
No, we do not expect any adverse social effects from participating in this study.

d. If any one question 4a-c has been answered with yes, do the strains or consequences go beyond what can be considered an everyday occurrence ("minimal risk")?
No, as explained in point 4a, the exposure of some participants to the heat condition does not go beyond minimal risk.

e. If question 4d has been answered with yes, please explain your course of action and specify the protective measures for the participants: **Not applicable.**

f. Will participants be asked to disclose personal experiences (e.g. stressful experiences), sensitive information (e.g. sexual behavior, drug use) or attitudes (e.g. political preferences)? *If yes, please clarify:* **No, none of the questionnaires in this study are personal in nature beyond basic demographics data (i.e., gender and age).**

g. Will participants be deliberately misinformed or falsely informed (with the intent to deceive) about the goals and the execution of the project (e.g. by manipulated feedback about their performance)? *If yes, please clarify* (especially the debriefing): **No, we do not involve deception in the study.**

h. Will it be necessary for people to partake in the study without knowing so and without previously having given informed consent (e.g. covert observation of people in non-public spaces)?
No, participants will be asked for informed consent before participating (see Appendix 1).

5. Specifications Regarding Data Protection

a. Are picture, film or audio recordings or any other type of behavior recordings intended?
Behavior recordings include participants' eye movements, electrodermal activity, participants' movement through the virtual environment, and their performance on spatial learning tests.

b. How are the acquired data anonymized?
Participants will be assigned anonymized ID numbers, which are written on all documents and recorded data. The consent forms linking the participants' identity to the participant number are kept in a locked safe and will be accessible only to the research team listed on this application. All the recorded behavioral data (i.e., movements on the VR environment, eye movement recordings, EDA recordings, and all the questionnaires and tasks) will include only the anonymized ID number and no personal identifying information of the participants. The ID number present on the consent form is done in case participants wish for their data to be deleted after the experiment. Thus, allowing the research team to retrieve all their recorded behavior data.

c. How is the confidentiality of the data ensured?
The consent forms are kept as a hard copy in a locked safe where only the above-listed investigators have access. After anonymization (ID numbers only), the collected data will be transferred to a UZH-hosted server to which, again, only the above-named investigators have access. This data will be stored securely for 10 years after the experiment.

d. Is it possible for participants to ask for their data to be deleted anytime?
Yes, participants can contact any of the listed investigators to request that their data be deleted, without providing any reasons.

e. Will acquired data be partially or completely deleted after the expiration of a specific time period?
Yes, all the data will be deleted after 10 years, unless published in a public data repository.

f. Do you plan to publish the data on a public data repository such as the Open Science Framework?
The fully anonymized data will only be published on a public data repository if the master's thesis is turned into a conference or journal publication.

6. Submission of Application

Please upload the completed and signed application form together with the other application documents as one single pdf-file on OLAT.

Prof. Dr. Christopher Hopwood
University of Zurich
Institute of Psychology, P.O. Box 34
Binzmühlestrasse 14
CH-8050 Zürich
chair.ethics.committee@phil.uzh.ch

7. Place, Date and Signature of Applicant

Zurich, May 21, 2025

_____

Appendix 1: Information Sheet and Consent Form

Information Sheet and Consent Form

Study for Master Thesis: Pedestrian Navigation under different temperature conditions in VR

June 2025

Participant ID:_____

Dear Participant,

Thank you for your interest in participation! Please read all of the following information very carefully to decide whether to participate in this study.
You are invited to participate in a study conducted by Alessandro Joshua Pierro (alessandrojoshua.pierro@uzh.ch) as part of his master's thesis research related to urban pedestrian navigation, carried out at the Department of Geography of the University of Zurich (UZH). The project is supervised by Prof. Dr. Sara Irina Fabrikant (sara.fabrikant@geo.uzh.ch) and Dr. Armand Kapaj (armand.kapaj@geo.uzh.ch).

Purpose of the study
With this study, we wish to gain insights into how people navigate in urban VR environments given different temperature conditions.

General Information
The study will take place at the Department of Geography of the University of Zürich, at the Irchel Campus, in the GIVA CAVE (room Y25-J87), and it will require about **60 minutes of your time.**

Procedure of the study
See the separate procedure sheet.

Voluntary Participation
Your participation in the study is entirely voluntary. You may withdraw your consent to participate in the study at any time without providing notice or reasoning. You can pose questions about the experiment at any time.

Inclusion and exclusion criteria
Any healthy young adult **between 18 and 40 years old, with normal or corrected to normal vision, and with a good understanding of English**, may participate in this experiment. The exclusion criteria listed below ensure that our statements are derived from a normal healthy population who can comfortably complete the experiment.

- History of neurological disorders such as epilepsy or migraines.
- History of cardiovascular disease.
- History of strong motion sickness.

Obligations of the participant

- You are expected to carefully follow the given instructions and fully and faithfully complete all questionnaires and experiment tasks.
- You must immediately express any uncomfortable experience during the experiments.
- You must inform the experimenters of any changes in health status that may affect your inclusion in the study.

Risk to the participants

This study will be carried out in a research laboratory with a changing room temperature depending on the experimental condition simulated in the VR environment. There are no physical or other effects on participants' health, besides the room temperature during the experiment.

Benefits to the participant

This study offers no direct benefits to the study participants. Participants will be given a small token of appreciation as a thank-you gift for their participation in the form of an ice-cream.

Data confidentiality

This study involves recording your personal information. All data are coded by replacing the names with an ID code and are made anonymous. Furthermore, your name will never be used in any of our reports and publications. All collected data will be kept encrypted and stored on secure media protected by a password only known to researchers listed above. The personal information provided here is stored for a period of 10 years due to a legal obligation. A local ethics committee may examine the information during this period. All the information is stored in a locked laboratory space and on a highly secure server at the Department of Geography of the University of Zurich.

Changes to the information provided

Any changes in the study that may affect the safety of your participation or your privacy, we shall inform you in writing.

Costs

The entire study will not bear any costs to the participants.

Termination of participation

Participation will be cancelled if you decide to withdraw from the study. Likewise, if you are unable to understand/follow instructions from the study conductor. All obtained data will be permanently deleted.

Study Results

If you would like to be informed about the results of this study, let the study conductor know. A copy of the study results can then be sent to you later.

Contact persons
If you have any questions or worries about the study, please contact the persons listed below (you will receive a copy of this document).

- Alessandro Joshua Pierro (alessandrojoshua.pierro@uzh.ch)
- Prof. Dr. Sara Irina Fabrikant (sara.fabrikant@geo.uzh.ch)
- Dr. Armand Kapaj (armand.kapaj@geo.uzh.ch)

This study has been registered with the Ethics Committee of the Faculty of Philosophy, University of Zurich. In case of questions or complaints about ethical issues regarding this study, please contact the Chair of the Ethics Committee of the Faculty of Philosophy using this email address: chair.ethics.committee@phil.uzh.ch.

INFORMED CONSENT

By participating in this study, I agree and affirm that:

1) I was given enough time to read this information sheet.
2) I understand the requirements of the experiment, and I agree to participate in this study.
3) My participation is entirely voluntary, and I have not been forced to participate in this study in any way.
4) I acknowledge that I may withdraw my consent to participate in this study at any time without any further notice or reasoning.
5) I agree that my data may be used in an anonymized form for research purposes only and may be published in academic research publications.
6) I understand that a local ethics committee may examine my personal details to check the activities of this research study.
7) I understand that my personal information will be kept confidential under all circumstances.
8) I understand that the study investigators, in the interest of the study, may terminate my participation at any time.
9) I understand that I must follow the instructions of the experimenter and comply with the requirements of this and other instruction sheets.

With your signature, you confirm that you have read and understood the above information and agree to participate in the experiment under the conditions described therein.

Signature of participant	Signature of study experimenter
_____	_____
First and last name in block letters	First and last name in block letters
_____	_____

Date and place: _____

Revocation of Consent Form

Study for Master Thesis: Pedestrian Navigation under different temperature conditions in VR

June 2025

Participant Number: _____

Revocation of consent

I hereby withdraw my consent to participate in the study described above.

Signature of participant

_____

First and last name in block letters

_____

Date and place: _____

By withdrawing your consent, you do not in any way affect your relationship with the University of Zurich.
The revocation can be requested at any time and without giving reasons.

Please send the revocation of consent to Prof. Dr. Sara I. Fabrikant, Geographical Information Visualization and Analysis, Department of Geography, University of Zurich, Winterthurerstrasse 190, 8057 Zurich.

Appendix 2: Experiment from the point of view of participants

Dear Participant,

Thank you for your decision to participate in our study. This document contains information regarding the course of the study. Please read the following instructions carefully.

Questionnaires

First, you will be asked to provide demographic information about yourself, including information about age, gender, educational background, and work experience. You will then complete a questionnaire about your spatial skills and orientation in space. Please choose the answer that best suits you for each question. However, try not to think too hard about your answer. The first answer that comes to your mind may be the right one for you. Next, you will complete a questionnaire to collect data on your self-reported thermal sensitivity.

VR training session

Next, you will receive a training session to become familiar with the virtual reality (VR) setup, where you will receive detailed information on how to navigate the VR environment using a foot paddle controller.

Eye-tracking (ET) and electrodermal activity (EDA) sensors

After the training session, we will prepare the eye-tracking (ET) and the electrodermal activity (EDA) devices, which you will wear throughout the navigation part of this experiment. An ET is a recording device of your eye movements and fixation. This device is similar to normal glasses and will record only what you see in the virtual environment and not your face. An EDA device captures the changes in skin activity, such as sweat, through two single-use measuring electrodes that will be placed on the index and middle finger of your non-dominant hand.

Navigation task

After being equipped with the ET and EDA devices, you will solve a navigation task in an urban virtual reality environment. During the navigation task, you will be asked to navigate the predefined route following the instructions displayed on the VR environment and reach the destination point. Try to reach the destination walking as you would normally walk when exploring a new environment.

Post navigation task

At the end of the navigation task, the ET and EDA devices will be removed, and you will be asked to answer questions in the form of questionnaires. Specifically, you will be asked about your navigation experience and perceived air temperature during the navigation task.

Debriefing

Upon experiment completion, participants will be fully debriefed on the study goals and thanked for their participation.

This procedure sheet is designed to give you an overview of today's experiment. You do not need to remember every detail of the procedure. The detailed instructions for each task will be given before the task.

Appendix 3: Demographic and Santa Barbara Sense of Direction (SBSOD) Scale

Demographic Data Collection

Please fill out the following form regarding your demographic data.

Gender

☐ Male ☐ Female ☐ Other

Age

_____

Educational Background

Highest level of completed education: _____

If you are currently enrolled at a university level, what is your current Major and Minor?

Major: _____ Minor: _____

Occupation

_____

Sense of Direction Questionnaire

Participant ID: _____

The following statements are of the SBSOD questionnaire (Hegarty et al., 2002) and ask you about your spatial and navigational abilities, preferences, and experiences. After each statement, you should circle a number to indicate your level of agreement with the statement. Circle "1" if you strongly agree that the statement applies to you, "7" if you strongly disagree, or some number in between if your agreement is intermediate. Circle "4" if you neither agree nor disagree.

1. I am very good at giving directions.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

2. I have a poor memory for where I left things. I am very good at judging distances.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

3. I have a poor memory for where I left things.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

4. I am very good at judging distances.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

5. I tend to think of my environment in terms of cardinal directions (N, S, E, W).

Strongly agree 1 2 3 4 5 6 7 strongly disagree

6. I very easily get lost in a new city.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

7. I enjoy reading maps.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

8. I have trouble understanding directions.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

9. I am very good at reading maps.

Strongly agree	1	2	3	4	5	6	7	strongly disagree

10. I don't remember routes very well while riding as a passenger in a car.

Strongly agree	1	2	3	4	5	6	7	strongly disagree

11. I don't enjoy giving directions.

Strongly agree	1	2	3	4	5	6	7	strongly disagree

12. It's not important to me to know where I am.

Strongly agree	1	2	3	4	5	6	7	strongly disagree

13. I usually let someone else do the navigational planning for long trips.

Strongly agree	1	2	3	4	5	6	7	strongly disagree

14. I can usually remember a new route after I have traveled it only once.

Strongly agree	1	2	3	4	5	6	7	strongly disagree

15. I don't have a very good "mental map" of my environment.

Strongly agree	1	2	3	4	5	6	7	strongly disagree

Hegarty, M., Richardson, A. E., Montello, D. R., Lovelace, K., & Subbiah, I. (2002). Development of a self-report measure of environmental spatial ability. In *Intelligence* (Vol. 30).

Appendix 4: Thermal Sensitivity Questionnaire

Thermal Sensitivity Questionnaire

Participant ID: _____

Please indicate your level of agreement with each of the 8 statements listed below. The bi-polar rating scale goes "1" strongly agree to "7" strongly disagree with "4" that indicates neither agreement nor disagreement.

1. I often feel uncomfortable or stressed during hot weather.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

2. I easily adapt to warm temperatures.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

3. I often seek shade or cooler areas when walking outdoors during hot days.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

4. I can tolerate heat better than most people I know.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

5. Exposure to direct sunlight significantly reduces my ability to concentrate.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

6. I rarely experience heat-related discomfort even in very hot conditions.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

7. I usually avoid outdoor activities when temperatures exceed 34°C.

Strongly agree 1 2 3 4 5 6 7 strongly disagree

8. Hot environments negatively impact my cognitive performance (e.g., memory, attention, etc.).

Strongly agree 1 2 3 4 5 6 7 strongly disagree

ASHRAE Standard 55. (2017). *Thermal environmental conditions for human occupancy*.

Lai, D., Guo, D., Hou, Y., Lin, C., & Chen, Q. (2014). Studies of outdoor thermal comfort in northern China. *Building and Environment*, *77*, 110–118. https://doi.org/10.1016/j.buildenv.2014.03.02

Appendix 5: Navigation Task Instructions

Navigation Task Instructions

You will be navigating an urban residential area in a virtual reality (VR) environment. Your task is to navigate the predefined route following the instructions displayed on the VR environment and reach the destination point. Try to reach the destination walking as you would normally walk when exploring a new environment. At the end of the navigation task, you will answer some questions about the navigation experience presented in a series of questionnaires.

Appendix 6: Landmark Recognition Test

Landmark Recognition Test

Participant ID: _____

Dear participant,

This questionnaire will test your landmark knowledge of the navigation tasks you completed before in the virtual environment. You will be shown images of landmark features and asked whether you recognize them from before.

Note: All data will be kept strictly confidential. No information will be published in this study that allows any conclusions to be drawn about you as a person.

Question 1:

Did you see this building during the navigation?

○ **Yes** ○ **No**

Appendix 7: Recall of Route Directions Test

Recall of Route Directions Test

Participant ID: _____

Dear participant,

This questionnaire will test your route knowledge of the navigation tasks you completed before in the virtual environment. In this questionnaire, only the actual landmark buildings that you encountered along the navigation route are shown in a random order. Your task is to indicate the turning direction you took after seeing each landmark building.

Note: All data will be kept strictly confidential. No information will be published in this study that allows any conclusions to be drawn about you as a person.

Question 1:

Which direction did you go after seeing this landmark building?

◯ **Straight**	◯ **Turned Left**	◯ **Turned Right**

Appendix 6: Thermal Comfort Questionnaire

Thermal Comfort Questionnaire

Participant ID: _____

Please respond to each statement with how it applies to the felt air temperature during the experiment. The bi-polar rating scale goes "1" strongly agree to "7" strongly disagree with "4" that indicates neither agreement nor disagreement.

1. **I felt uncomfortable during the experiment.**

Strongly agree 1 2 3 4 5 6 7 strongly disagree

2. **My performance in the experiment was impacted by the felt temperature.**

Strongly agree 1 2 3 4 5 6 7 strongly disagree

3. **I frequently wished the environment was cooler/warmer during the experiment.**

Strongly agree 1 2 3 4 5 6 7 strongly disagree

4. **The heat made it difficult for me to concentrate during the experiment.**

Strongly agree 1 2 3 4 5 6 7 strongly disagree

5. **I found it easy to ignore the temperature and focus on the experiment.**

Strongly agree 1 2 3 4 5 6 7 strongly disagree

6. **I experienced significant physical discomfort (e.g., sweating) during the experiment.**

Strongly agree 1 2 3 4 5 6 7 strongly disagree

7. **The temperature conditions felt unpleasant throughout the experiment.**

Strongly agree 1 2 3 4 5 6 7 strongly disagree

8. **The temperature conditions made the experimental task seem more difficult.**

Strongly agree 1 2 3 4 5 6 7 strongly disagree

ASHRAE Standard 55. (2017). *Thermal environmental conditions for human occupancy*.

Lai, D., Guo, D., Hou, Y., Lin, C., & Chen, Q. (2014). Studies of outdoor thermal comfort in northern China. *Building and Environment*, *77*, 110–118. https://doi.org/10.1016/j.buildenv.2014.03.026

Appendix 9: Debriefing

Debriefing

Dear participant

Thank you once again for your time and effort participating in my study! Now that you have completed the experiment, we would like to provide further information about my study objectives.

Urban heat stress and pedestrian navigation behavior

Numerous prior studies have highlighted that rising temperatures and the phenomenon known as Urban Heat Islands pose a significant challenge for growing urban populations worldwide. High urban temperatures not only affect people's physical comfort and health but can also influence pedestrians' daily mobility behaviors, and cognitive functions, such as attention, spatial memory, and space-time decision making, and overall well-being. This, in turn, can affect how effectively and efficiently people are able to navigate their surroundings and recall spatial information. The understanding of how exactly and to what extent these processes are affected by heat exposure is crucial for designing better and more heat-resilient future urban environments and navigation aids, adapted to climate change.

Study goals

The main goal of this study is to understand how urban heat exposure influences pedestrian navigation behavior and spatial learning. Depending on your assigned group, you either experienced the environment on a cloudy day with visual shade and no heat, or the same environment but on a hot summer day with visual and physical heat conditions. We hypothesize that perceived heat will negatively affect navigation efficiency and spatial learning. Specifically, we expect that participants experiencing hot summer conditions will have greater difficulty learning the environment, resulting in poorer landmark recognition and less precise recall of turning sequences. We hope to gain further insights into how urban heat influences pedestrian navigation behavior and how future cities might be designed to better support comfort and safety in increasingly hot urban living conditions.

We truly appreciate the time and effort you invested in helping us explore these study goals. Your participation will help us develop better strategies for making cities more walkable and resilient in the face of rising temperatures.

If you have any questions about the study or would like to receive a summary of the results once the project is completed, you are welcome to contact us at:

Alessandro Joshua Pierro: alessandrojoshua.pierro@uzh.ch

Prof. Dr. Sara Irina Fabrikant: sara.fabrikant@geo.uzh.ch

Dr. Armand Kapaj: armand.kapaj@geo.uzh.ch

AI Declaration

I acknowledge the use and application of the artificial intelligence tools (AI) listed below throughout the writing and reviewing of this thesis.

General statement

No raw data files, confidential datasets, or access credentials were shared with any AI system. Where available, privacy / "private mode" settings were enabled. AI outputs were treated as supportive suggestions only.

Coding assistance

- **ChatGPT (GPT-4.1, GPT-5)** and **Claude Sonnet (4.5)**: Support for coding tasks (e.g., drafting functions, troubleshooting errors, improving readability, and commenting).

All code developed with AI support was created iteratively and reviewed line-by-line by me. No AI-generated code was adopted without my verification through testing, inspection, and reproducible execution. I take full responsibility for all coding implementations and their correctness.

Figure and visualization assistance

- **ChatGPT (GPT-4.1)** and **Claude Sonnet (4.5)**: Assistance in producing figures and data visualizations in `Python` and `R` (e.g., plotting code structure, formatting, and export settings).

AI support was limited to code suggestions for visual outputs based on my own analytical results. All final figures were generated by me, and no figure-related code was executed without my verification. All conceptual choices (what to show, how to parameterize, and how to interpret) were made by me.

Literature support and theoretical clarification

- **ChatGPT (GPT-4.1, GPT-5)** and **Perplexity Deep Research**: Assistance in explaining and clarifying theoretical and methodological concepts, and for targeted double-checking of whether key aspects of the experimental design had been considered.

AI tools were not used to discover, select, or summarize academic sources for citation. All literature research was conducted independently by me, and all cited sources were retrieved, read, interpreted, and integrated by m

Conceptual development and research design

No AI tools were used to generate the core research question, develop the theoretical framework, or propose the main conceptual argumentation of this thesis. AI support was limited to critical review prompts to help identify potential missing points in the experimental design; all final design decisions were made by me.

Editorial assistance

- **ChatGPT (GPT-5)** and **Perplexity Deep Research**: Linguistic revision of texts, focusing on grammar, sentence structure, tense consistency, terminology, and stylistic coherence.
- **Gemini 3 Flash/Pro**: Translation between German and English, and synonym refinement.

In all instances where AI was used for editorial purposes, I reviewed and approved the output for factual and linguistic accuracy. AI was not used to generate original content or to paraphrase external sources, and no summaries of texts were produced. I take full responsibility for the final wording and content of the thesis.

Personal Declaration

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

Zurich, 25 January 2026