Mental Breadcrumbs: Developing biometric methods to understand how emotions and sensory cues affect wayfinding

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Abstract. How do one's emotions, mental state, and the spatial environment interact? Interdisciplinary research methods in architecture and neuroscience can be used to examine the interrelated factors of mental load, sensory cues, emotions, and memory in wayfinding. The objective is to propose a biometric methodology for quantifying the emotional and cognitive experience of wayfinding, and to present a pilot experiment on the impact of mental load on wayfinding. The methodology collected biometric (electrodermal activity, electroencephalogram, heart rate, accelerometer), visuospatial (GPS, camera), and interview data. The pilot study revealed a new category of sensory cues used by individuals to wayfind. Identified as "breadcrumbs" and associated with subjective emotions, researchers propose an addition to Kevin Lynch's elements of the built environment that contribute to cognitive mapping. The aim is to invite a rethinking of the typically precedent-based nature of spatial design, bolstering the discussion with individual experience data to encourage evidence-based design.

Keywords: Interdisciplinary Design, Biometric, Wayfinding, Sensory Cues, Mental Load

1 Introduction

How do one's emotions, mental state, and the spatial environment interact? Why are some built environments easier to navigate than others? What spatial cues do people use in wayfinding, and how are they impacted by one's cognitive load?

Emerging interdisciplinary research methods drawn from collaborations between architecture and neuroscience have allowed spatial design researchers to expand beyond a predominant reliance on observational studies (ESUM, 2017; Werner et al., 2019). Biometric wearable technologies can augment our understanding of the human spatial experience by giving researchers quantitative insights into the real-time physiological changes experienced by people in the field. Specific physiological metrics have been shown to be correlated with emotion, stress, memory, and attention, providing a wealth of information for experience analysis (Antonenko et al., 2010; Kyriakou et al., 2019). The presented work is part of this new frontier in architectural research that quantifies the human experience with biometric sensor technologies (Karakas & Yildiz, 2020).

The objective of this paper is a) to propose a biometric methodology for quantifying spatial experience, which examines the interrelated factors that contribute to the wayfinding experience - mental load, sensory cues, emotions, and memory - and b) to present a pilot experiment using this methodology to explore the impact of mental load on pedestrian wayfinding. The researchers organized volunteers to take two urban walks, the first of which was designed to impose a low mental load and the second, a high mental load. The pilot study revealed a new category of sensory cues used by individuals to wayfind. Identified as "breadcrumbs" and associated with subjective emotions, researchers propose an addition to Kevin Lynch's elements of the built environment that contribute to cognitive mapping.

This paper is the second in a series that aims to better understand the human experience of built environments. It builds upon prior work by the researchers that examined air travel passenger experience in airports (Song et al., 2022). Observations from the prior work indicated a possible relationship between an individual's mental load and spatial stress. Drawing from those findings, this paper presents a refined biometric methodology that can be deployed in a wider range of built environment contexts. The methodology collects biometric data (Electrodermal Activity (EDA), Electroencephalogram (EEG), Heart Rate, Accelerometer), visuospatial data (GPS, Body camera), and qualitative data (interviews, drawings). It is then analyzed through a dashboard designed by the research team. The dashboard facilitates visual cross-referencing to glean possible relationships among the different data streams.

The methodology is designed to be replicable with substitute technologies as available to other researchers around the world. Ultimately, the researchers hope to encourage a rethinking and redesigning of the typically precedent-based nature of spatial design, by bolstering the discussion with individual experience data to encourage evidence-based design.

1.1 Literature Review

Measuring the human experience of the built environment has posed an enduring challenge to architects, urban planners, and designers. The foundational research investigating this include Kevin Lynch's work on people's urban cognitive maps, which identified five elements of the built environment that contribute to mental mapping (Lynch, 1960) and William Whyte's work on human behavior at public spaces (Whyte, 1980). Researchers today have built upon these by incorporating novel technologies from eye-trackers (Sayegh et al., 2015), biometric sensors (Poh et al., 2010, Sagl et al., 2019), camera analysis (Schlickman & Domlesky, 2019), to AI/machine learning (ESUM, 2017). Using these tools, experience research has been conducted in a variety of physical settings, from within passenger automobiles (Healey & Picard, 2005) to city centers (Andreani & Sayegh, 2017).

The commercialization of wearable health products has made these tools more readily accessible than before. Additionally, technological advances have eased the transition from conducting research indoors to outdoors in the field (Poh et al., 2010). The field has also benefited from the rise in "hacking culture" within digital Do-it-yourself (DIY) subcultures (Bechthold & Sayegh, 2015), which promotes the creation of new combinations of tools that subvert the existing conventions of the original technology and generate unexpected outcomes.

The topic of interest in this research work is "wayfinding", defined as the purposive and motivated process of finding a path from an origin to a destination, that involves deciding on a sequence of turns and continuation of travel path (Golledge, 1999). Of the variety of research experiment setups for investigating wayfinding, this research uses Golledge's description of *Explore and Retrace,* where people explore an unfamiliar environment and then attempt to retrace their path back to starting point. The goal is to understand how people acquire new primary information about their environment in their "explore" phase, and how that information gets used in the "retrace" phase. The act of retracing one's steps relies heavily on one's memory and attention (Nori et al., 2009; Pazzaglia et al., 2018). This research is interested in investigating the ways that emotion and attention interact with memory and affect one's ability to retrace one's steps.

2 Methodology

This research proposes a biometric methodology for quantifying the experience of wayfinding, examining the interrelated factors that contribute to it such as mental load, sensory cues, emotions, and memory. To demonstrate this methodology setup, the researchers present a pilot experiment of urban walks that investigate the impact of mental load on wayfinding.

2.1 Data Type & Wearables Technology Selection

The researchers used an equipment setup that combines biometric wearables, body cameras, and interviews. The specific data types collected are enumerated in Table 1, followed by a description of their relevance to quantifying experience of the built environment. The methodology was intentionally designed to be applicable in a variety of settings and replicable by researchers with varying available technology. The researchers chose technologies which balance reliability and availability. The following table lists the researchers' choices of biometric products and associated validation studies, so that others may make informed decisions for possible substitutions.

Table 1. Quantitative data types collected by the methodology and their relevance.

Data Type	Wearable Product Used	Relevance to research topics
Electrodermal Activity (EDA)	Empatica E4	Used as a strong indicator of heightened physiological activity correlated with heightened emotional states (Kyriakou et al., 2019; Poh et al., 2010).
Electroencephalogram (EEG)	OpenBCI Electrode Cap	Used as a strong indicator of cognitive load, focus and attention, and confidence level in decision making (Antonenko et al., 2010).
Heart Rate (HR)	Garmin	Used as a weak indicator of stress and heightened emotional states, and a weak indicator of amount of bodily movement. (Kyriakou et al., 2019)
Accelerometer	Empatica E4	Shows the amount and speed of bodily movement
Global Positioning System (GPS)	Garmin	Shows exact geographical location which can be overlaid on maps and plans.
Body camera		Shows first-person perspective view of what was visible to the individual

2.2 "Explore & Retrace" Urban Walks Experiments

To develop the methodology, a pilot experiment was conducted with volunteers. Eight participants were outfitted with the equipment setup, and took two urban walks, one designed for low mental load, and another for high mental load.

Walk 1 (Low mental load): Participants explore an unfamiliar neighborhood.

- Step 1: Participants are instructed to wander in a predetermined unfamiliar neighborhood for 20 minutes, with the intent of getting lost. Participants were advised to not consult a map, to avoid walking continuously straight, and to take multiple turns. They are equipped with the aforementioned wearables and given a rule stating:
  - Do not listen to audio, or wear headphones
- Step 2: After 20 minutes, participants are instructed to call researchers who now instruct them to retrace their steps and return to their starting point using the same exact path.

Walk 2 (High mental load): The same set of participants explores a different unfamiliar neighborhood, replicating the conditions of Walk 1, but given a different rule stating:

- Listen to music during the walk
- Mentally count the number of people and animals encountered

2.3 Qualitative Data Collection: Interviews & Drawings

The researchers supplemented the quantitative data with qualitative data collection to better understand the individual experience (Mauss & Robinson, 2009). First, upon their return from each walk, the participants were given a blank piece of paper and asked to draw from memory the route that they took (Figure 1). Secondly, the researchers conducted a conversational interview guided by a questionnaire. The answers were recorded verbatim and then categorized through a qualitative data coding process. The questionnaire was worded to help elucidate 1) what environmental elements people used for retracing, 2) the moments people felt uncertain, and 3) the moments people felt changes in emotion, and 4) the moments people experienced changes in mental load. Thirdly, the researchers presented the participants with the satellite map of the GPS tracked route to record their reaction. Lastly, the participants were asked to annotate the map with self-reported moments of elevated emotions, marking discrete moments as dots, continuous moments as lines, labeling their annotations with one word and noting whether it was a positive (+) or negative (-) emotion.

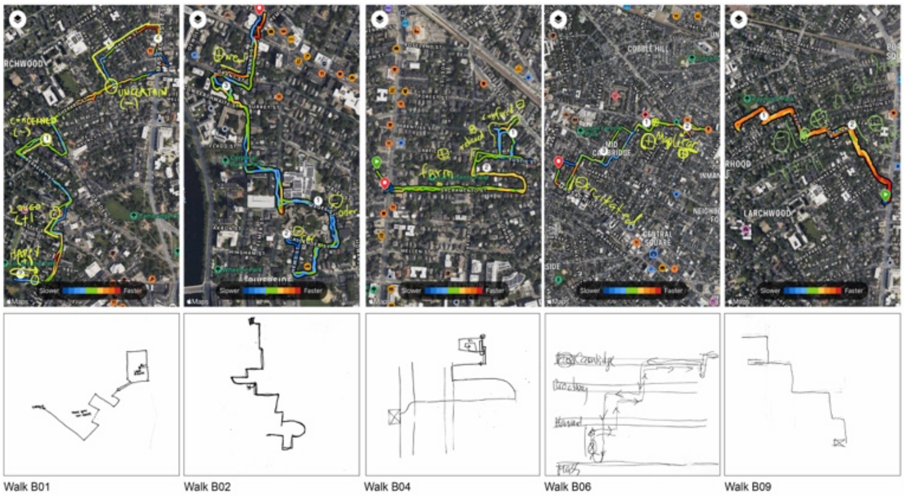

Figure 1. GPS maps of the participants' urban walks (explore + retrace), annotated by the participants with self-reported moments of elevated emotions. Bottom drawings show cognitive maps drawn by the participants.

2.4 Dashboard

To facilitate analysis of the collected data, the researchers designed a dashboard which allows concurrent visualization of the various data streams. The dashboard contains three main types of information, 1) Route data: the path taken by the participant, 2) Subjective data: self-reported sensory environmental elements and emotions, and 3) Biometric Data: EDA, EEG, HR, and ACC. The dashboard unrolls the walking path into segments from *Explore + Retrace*. The simultaneous visualizations assist researchers in understanding the relationships among different data streams, changes in emotion, and wayfinding decisions.

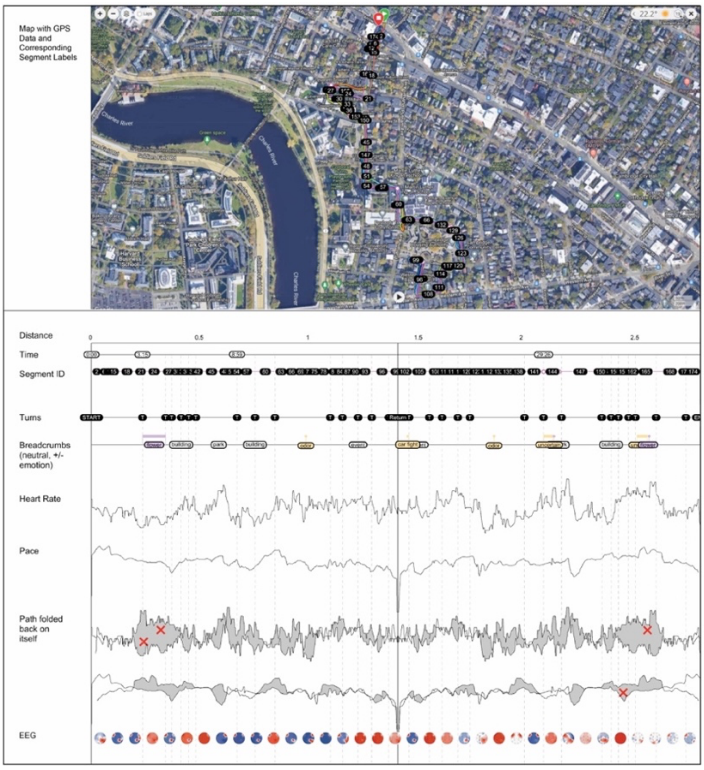

Figure 2. Dashboard for concurrent analysis of 1) route data, 2) self-reported data, and 3) biometric data, which are mapped onto an unrolled walking path identified as discrete segments.

3 Findings & Discussions

As part of developing this methodology, a pilot study was conducted to better understand the types of findings and analysis that are possible with this type of research. Using the proposed methodology, the pilot experiment resulted in three main types of findings. First is a catalog of sensory cues acquired by participants from the environment that aid in wayfinding. Second is a relationship between high mental load and one's decreased ability to wayfind and remember their spatial experience. Third is an observation that emotion plays an outsized role in spatial memory, and that a higher mental load increases perceptual distortions during wayfinding. Altogether, these findings function as proof-of-concept for the proposed methodology's particular combination of biometric, visuospatial, and qualitative data collection.

3.1 The Breadcrumbs Catalog

In the seminal work, *The Image of the City*, Kevin Lynch introduces five elements of the built environment that give shape to one's "cognitive map" of the city (Lynch, 1960). These elements are identified as nodes, paths, edges, districts, and landmarks. The researchers propose an additional element, identified as "breadcrumbs", referencing the story of Hansel and Gretel. In the story, breadcrumbs were hints left on a trail to help the children find their way back home. In this paper, the researchers use the term "breadcrumbs" to refer to sensory cues from the environment that aid in the process of wayfinding.

Breadcrumbs are distinct from Lynch's landmarks in that landmarks are identified through spatial prominence, size, and "figure background contrast" (Lynch, 1960). In contrast, breadcrumbs are smaller and individually determined pieces of sensory information gathered from the immediate environment. The researchers established this new category after noticing participants repeatedly mentioning a type of environmental sensory cue that did not fit in Lynch's identified elements (Table 2).

Self-reported breadcrumbs can be cataloged as subjective or objective information (Table 3). For example, an interview participant who recalled an objective breadcrumb reported, "the house was blue," whereas another participant's subjective breadcrumb was, "the color of the house was very ugly." Researchers found that participants logged more subjective breadcrumbs than objective ones. The memories of breadcrumbs were often associated with personal perception of the environment and indicated individual preference such as, the place "seemed like a nice place to live," or "it smelled very fishy."

Table 2. The number of times a type of breadcrumb was mentioned following Walk #1.

Environmental Breadcrumb Types	Participants ID								Total
	A01	A02	A03	A04	A05	A06	A07	A08	
Architectural elements	2	5	6	2	2	2	2	2	23
Programmatic elements (e.g school, bakery, construction zone)	2	5	4	1	1	3	1	2	19
Urban Built environment (with text, e.g. street signs)	0	2	1	2	0	2	2	2	11
Urban Built environment (without text)	3	1	1	2	2	1	1	1	12
Urban Furniture, Cars, etc. (objects occupying the sidewalk and street)	1	2	1	4	0	2	3	2	15
Nature and Animals	2	5	2	3	0	2	2	2	18
Human	4	1	1	0	3	3	0	2	14
Topography (Elevation changes)	0	0	0	0	0	0	1	0	1

Table 3. Catalog of Reported Breadcrumb

Subjective Breadcrumbs	**Objective Breadcrumbs**
Feeling tired from incline Feeling happy from someones smile Inspired by abundance of greenery and beautiful yards Frightened by dog barks Feeling uninspired by monotonous residential styles, Hungry from smell of indian food. Overwhelmed by construction noise Feeling safer with stop signs	Topography and elevation changes Human, Nature and Animals Urban Built Environment Programmatic Elements (eg School, Bakery) Urban Built Environment (w/text, eg. street names, dead end, building signs,slow down) Architectural Elements Urban Furniture, Cars, Objects, (objects encountered along the way)
Examples from Participants: • *"Excited by old green car and I took a picture"* • *"Noticed surprisingly spacious garden"* • *"saw construction workers who were doing exciting things"* • *"surprised by how beautiful the neighborhood was"* • *"seemed like a nice place to live"* • *"the color of the house was either very bright or very ugly"* • *"street that was so idyllic"* • *"attic window - and wondered how I could live there"* • *"giant consturction machine looked like giant spider robot"* • *"felt it was an out of ordinary sculpture"* • *"house that was painted blue/green/purple - it was odd"* • *"the corners were very annoying"* • *"Beach smell, very fishy"*	Examples from Participants: • *"There were two chairs on the road"* • *"Noticed a guy and a girl gardening"* • *"Then I saw the pole with Loki the missing cat"* • *"3 painter vans along the same street"* • *"weathered wood shingle"* • *"None of the houses here have awning"* • *"Noticed street signs"* • *"All the streets were very narrow."* • *"parking lot $240/mo"* • *"side walk was very bumpy"* • *"saw a hanging bed sheet"* • *"wooden pathway"* • *"there was a church bell"*

In addition, the researchers frequently observed a strong relationship between the presence of a breadcrumb (as reported during interviews) and a corresponding change in physiological data and self-reported emotions. Often, the breadcrumb was identified as the reason for the change in emotion. Figure 3 shows one such example of a participant's growing uncertainty and anxiety about correctly retracing the path (as reported during interview and corresponding increase in heart rate). The subsequent recognition of a visual breadcrumb confirmed the accuracy of the path taken, resulting in the subsequent drastic lowering and stabilization of heart rate. The same sequence of events is repeated later in Figure 3. The events diagrammed in Figure 3 were not an isolated case; participants reported heightened navigational certainty after encountering breadcrumbs.

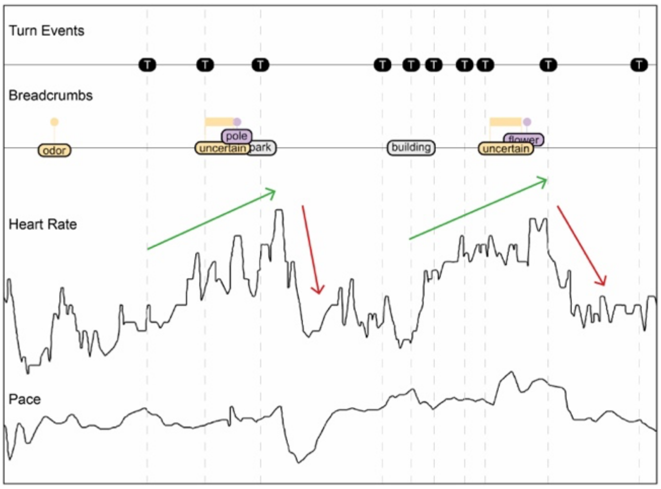

Figure 3. A zoomed in portion of the dashboard shows an example where the recognition of a breadcrumb triggers a significant change in physiological response.

3.2 The Impact of Mental Load on Wayfinding

Wayfinding requires the cognitive learning of an environment. Cognitive learning is the acquisition of this knowledge of one's environment is a dynamic process of continuous updates affected by a person's emotion, memory, and attention (Golledge, 1999). To better understand this process, the researchers analyzed the effects of increased mental load on wayfinding abilities, as it relates to sensory cues, emotion, and memory.

The experiment revealed that changes in mental load impacted the participants' experience and accuracy of wayfinding. A greater number of volunteers correctly retraced their route during the lower mental load walk than the higher mental load walk. Higher mental load seemed to negatively affect the acquisition of new environmental information and "breadcrumbs." Participants mentioned fewer specific breadcrumbs during interviews following the second walk. This decrease in information acquisition also seemed to lower a person's ability to recognize and use previously encountered sensory inputs as wayfinding cues.

Not only does high cognitive load affect one's ability to acquire new environmental information, but it also affects one's ability to encode experience into memory (Yegiyan & Yonelinas, 2011). The experiment showed that the mental logging of breadcrumbs was highly correlated to self-reported emotion. Higher cognitive load lowered the number of self-reported discrete positive emotional moments during their walk.

3.3 Perception vs. Reality

This research is particularly interested in the effect of emotion and mental load on distorting one's perception of wayfinding. The researchers used the techniques of mental map drawings and EEG Signal-to-Image to externally visualize the participants' internal perceptions. The mental maps illustrate how the participants remembered their route, allowing researchers to better understand how their spatial memory and perception is affected by emotions and mental load. The EEG Signal-to-Image produces a visualization of how the participant's brain is processing what the participant sees, through distorting one's visual experience with the recorded EEG signals.

Comparing the mental maps drawn by the participants to the GPS data allows researchers to identify patterns among the distortions between one's perception and reality (Figure 1). Most participants overestimated the number of turns taken during their walks and expressed surprise when shown the GPS map afterwards. Event perception plays a fundamental role in the memory of human experience (Zacks et al., 2007), and self-produced events, such as deciding to take a turn, are perceived more significantly in one's memory. Every "event" looms disproportionally large in one's memory, and active decisions are given priority in memory.

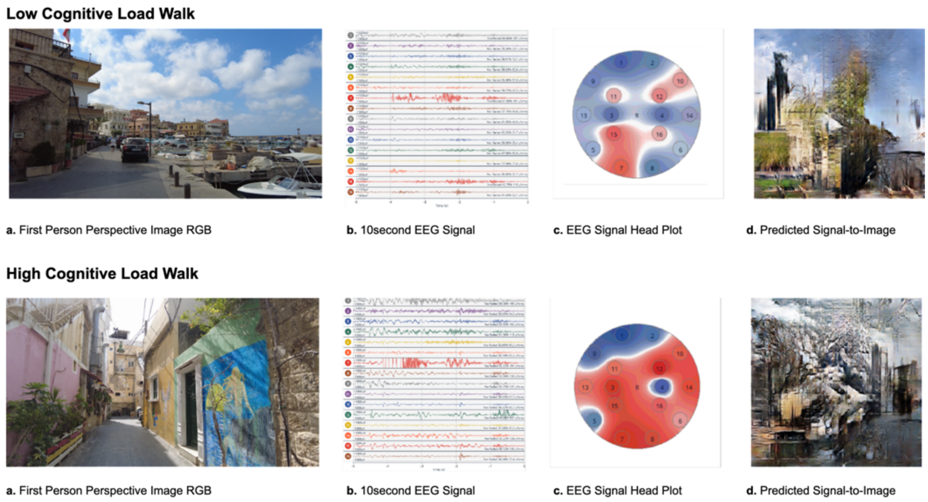

Figure 4. Shows the relationship between video footage, EEG brain signals, and predicted Signal-to-Image, and the comparison between Signal to Image prediction during low cognitive load and high cognitive load.

To further explore the effects of mental load on one's perception of reality, the researchers used the EEG Signal-to-Image technique as part of the methodology (Figure 4). The EEG Signal-to-Image technique provides insight into the hidden effect of cognitive load on the processing of sensory cues. During walks of low cognitive load, the brain more accurately processed the visual information that the eyes saw from the immediate physical environment. Thus, the resulting Signal-to-Image output had a visual similarity the environment as documented by the body camera worn by the participant. During walks with high cognitive load, the cognitive processing of immediate visual information is clouded by other mental processes, and the resulting Signal-to-Image output shows an image that is more greatly distorted by cognitive interference.

4 Conclusion

The above findings serve as proof-of-concept for the proposed methodology of combining biometric, visuospatial, and qualitative data collection. It also demonstrates the potential of the dashboard as a versatile analysis tool for researching the topics of sensory cues, cognitive mapping, memory, emotion, and wayfinding. The main strength of the methodology is that it provides an alternative to the typically precedent-based nature of architecture and urban design and facilitates evidence-based experiential design through the addition of quantitative individual experience data.

The most obvious application of this research method and dashboard would be in post-occupancy evaluations of architecture and public spaces. The initial findings from the pilot study begin to suggest recommendations for the urban design of neighborhoods. Since breadcrumbs associated with spikes in emotion are more readily encoded into memory, urban designers should consider increasing sensory variety when designing neighborhoods to improve an individual's cognitive map and lower one's spatial anxiety.

We hope that the presented research methodology allows researchers around the world to conduct experiments in a variety of built environment settings, and that this type of research will facilitate speculations on alternative scenarios for designing public spaces, architecture, and urban neighborhoods. This collection of interdisciplinary knowledge on individual experiences can empower and enable better design within the built environment.

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