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“Just Follow the Lights”: A Ubiquitous Framework for Low-Cost, Mixed Fidelity Navigation in Indoor Built Environments

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ABSTRACT

Indoor navigation is an important daily task in a variety of contexts (*e.g.,* offices, hospitals, airports). However, navigational ease is not always considered when buildings are designed, making wayfinding a difficult and frustrating experience. Moreover, existing solutions are expensive, highly specialized, or both. In this work, we examine how a system of connected low-cost displays designed as an open API can be leveraged to guide users to their destinations quickly, easily, and with minimal cognitive load. Following a formative survey (*N*=58), we designed: (i) a system of linked, low-fidelity indicators, (ii) a novel map ingestion mechanism for quick and easy deployment, and (iii) a framework for controlling and interacting with an ecosystem of mixed-fidelity devices. We then evaluated our system through a controlled user experiment (*N*=18) that explores the impact of indicator density and route complexity on performance. Our work shows low-cost embedded indicators can improve indoor navigational experiences by delivering many of the same benefits as more costly solutions, we argue that such indicators would complement existing navigational solutions in a mixed-fidelity ecosystem, and we discuss use-cases as well as design recommendations for deploying similar systems.

1. Introduction

Indoor navigation is an important daily task for many people in a variety of contexts (*e.g.,* offices, hospitals, airports). Despite its importance, navigational ease is often compromised when a new building is designed due to practical considerations such as construction costs, aesthetics, or utility (*i.e.,* structural concerns, routing of electrical, HVAC, etc.), which may inform the layout more than usability does Seidel and Rappaport (1994). This often makes wayfinding (*i.e.,* the act of orienting one’s self in a space, planning a route, and traveling to a destination) a difficult and frustrating experience Arthur and Passini (1992). The downstream impact of these decisions in building layout can result in inefficient workflows, wasted time, and users becoming dissatisfied with their experience in these spaces Zimring (1990). However, the advent of interactive digital signage and the proliferation of the Internet-of-Things (IoT) presents new opportunities for creating smoother, more streamlined navigational experiences Ashton et al. (2009). We envision a rich ecosystem of varying fidelity devices, communicating via open APIs and coordinating their actions to support a wide range of functionality and interactivity. This system, aware of user presence, needs, and preferences, could, among other things, guide them through a complex space by displaying directions along their route.

Previous work on indoor navigational support has focused on the cognitive factors of wayfinding Golledge (1999), solutions to technical challenges like localization Fallah et al. (2013) or navigating without GPS Brush et al. (2010), and evaluating systems geared toward supporting different user populations from everyday pedestrians Müller et al. (2008); Rukzio et al. (2009) to populations with accessibility concerns A. Karimi et al. (2014); Ahmetovic et al. (2016); Chang and Wang (2010); Fixova et al. (2014); Liu et al. (2008); Zhang et al. (2008). These works lay a strong foundation for the exploration of wayfinding challenges, but the literature also tend to focus on: (i) navigation solutions that utilize large and costly public displays Coenen et al. (2016); Kray et al. (2006, 2008), special purpose mobile applications Arthur and Passini (1992); Brush et al. (2010); Roy et al. (2017), or large quantities of Bluetooth beacons Huang et al. (2009), (ii) contexts such as transportation hubs Coenen et al. (2016); Kataoka et al. (2016) or outdoor spaces Rukzio et al. (2009), and (iii) displaying other informational content like advertisements or inter-office messages Coenen et al. (2016); Kray et al. (2006). Evaluations of such systems have also been

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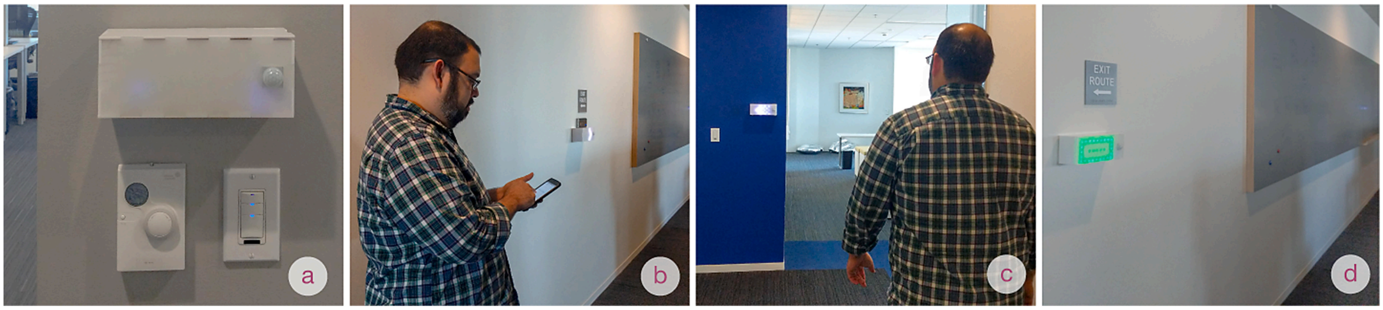


Fig. 1. A four picture banner, left-to-right: (a) wall light switches and a rectangular box with LED lights embedded in it, (b) a man using a mobile phone to select from a list of rooms to nagivate to, (c) the same man walking down a hallway without the phone looking toward a display in the distance, and (d) a display unit on a blank wall displaying the arrival signal.

mixed, with many providing support for the user's sense of navigational ease but not resulting in significant performance improvements over existing baselines in controlled studies. This is problematic as such systems are costly for everyday use-cases.

Toward addressing these limitations, we explore how a connected set of low-cost displays can be leveraged to guide users to their destinations quickly, easily, and with minimal cognitive load (see Figure 1 and Supplemental Video). We theorize that such a solution could be used independently or to augment existing systems, with the overarching goal of creating a scalable, connected, and coordinated ecosystem of devices working together intelligently to guide users. As a proof of concept, we designed a system of linked, low-fidelity indicators, a novel map ingestion mechanism to quickly and easily deploy such a system, and a framework for controlling and interacting with an ecosystem of mixed-fidelity devices. In this work, our research questions include: *How can we design a low-cost system that improves indoor navigational performance while keeping users engaged in their environment? What impact does display density and route complexity have on performance? And, what does this mean for the scalability of such systems?*

To answer these questions, we conducted a multi-stage study with 58 participants recruited from a software company that focused on navigation in a large and active office environment. We started by conducting a survey to determine the types of navigational challenges experienced by our population and to inform our system design. We then designed a prototype navigation system built with inexpensive off-the-shelf parts and evaluated it using a mixed-methods approach, including a controlled user experiment and semi-structured interview (N=18). Our results show that a low-cost system of networked LED indicators can improve the wayfinding experience without the need for larger, more expensive, high-fidelity hardware, boosting confidence and leading to faster, more reliable, and more consistent user performance. The direct contributions of this work include: (i) a low-cost system for indoor navigation with a lightweight and open deployment paradigm as well as a novel map ingestion mechanism, (ii) a formative study that explores current perceptions of existing navigation solutions while also reaffirming the need for additional navigational support in everyday buildings, (iii) a controlled study that evaluates performance and the interaction of display density and route complexity against an existing baseline, and (iv) design recommendations for deploying similar systems.

2. Background and Related Work

We describe the growth in IoT, its influence on Human-Building Interaction, and how this frames our work on low-cost and open solutions for building navigation. We also provide a brief overview of research on indoor navigation.

2.1. IoT and Human-Building Interaction

The use of internet-connected devices has grown incredibly in the last several years. By 2010, there were more devices connected to the internet than people on the planet Evans (2011). As a result, there is much ongoing work into best practices, frameworks, and protocols for using these devices together Atzori et al. (2010); Gubbi et al. (2013); Sezer et al. (2018); Zanella et al. (2014) and it is clear that, beyond the benefit of information access, these ubiquitous devices offer myriad opportunities for creative solutions to everyday problems.

Increasingly, IoT devices are being integrated with built environments to provide new interactions with, and services to, occupants. For example, researchers have designed IoT-based sensing solutions to assist in the care of assisted living patients Ray (2014), allow homeowners to monitor structural health Mauriello et al. (2019), and create playful interactions, such as during Taylor Swift's *1989 World Tour* (held in 2015), where thousands of concert-goers took part in a stadium-wide collaborative light show using wireless bracelets that lit up in time to the music Clément et al. (2016). These examples highlight a growing interest in the area of Human-Building Interaction (HBI) that focuses on designing new ways to interact with buildings and bridges numerous research communities including computer science, architecture, and urban design Alavi et al. (2019, 2016). In this work, we develop a low-cost IoT solution for deploying linked displays embedded in the built environment at decision points that can improve indoor navigational experiences and performance.

By being relatively inexpensive, easy to deploy, and intuitive, our platform could be included as part of building construction or retrofits, aiding any existing indoor navigational systems and expanding our capacity to design new interactions in the built environment. Such a system could help users find colleagues in a complex office layout as easily as it might support a visitor or a first-responder. By building systems like this using a common open API, these interactions would not be limited in scope to singular locations, but could instead create experiences that transition seamlessly across multiple locales. A user visiting Paris for the first time, for example, could use their hotel room entertainment system to request directions to the Mona Lisa. After leaving their room, light-up indicators in the hallway could guide them out of the hotel and, once outside, their mobile device could immediately bring up a map and display GPS guided directions. Upon reaching the Louvre, a digital sign could greet the user and suggest a detour to the Information Desk to pick up an informative brochure on Leonardo da Vinci, while also indicating the direction to the Denon Wing, where the Mona Lisa resides. Working in concert, these systems create an experience that transitions seamlessly from location to location and, more importantly, from device to device, thanks to an open API that would allow for a system that encourages collaboration between devices by being flexible, extensible, and scalable.

2.2. Indoor Navigation

Research in the area of indoor navigation has generally focused on three areas: (i) exploring cognitive factors and navigational challenges, (ii) developing solutions to technical challenges, and (iii) evaluating navigational systems with different user populations. Here we focus on exploring gaps in this literature that can be addressed by low-cost indoor navigation systems that improve user experience and performance.

2.2.1. Cognitive Factors

Navigation is a cognitively difficult task. Golledge (1999) found that users depend on cognitive maps, but that these maps are not true representations, rather, they are abstractions of a space. Moreover, Ishikawa and Montello (2006) point out that spatial capabilities vary widely between people and that this greatly influences one's ability to form reliable cognitive maps. The greater the disconnect between physical spaces and mental maps, the more difficult it becomes to effectively navigate. Arthur and Passini (1992) determined that, even for those familiar with a space, wayfinding can lead to significant amounts of uncertainty and stress. Roger M. Downs (1977) breaks down navigational tasks into four main subtasks: self-localization, route planning, traversing the path, and discovering the destination. The first two tasks require a global understanding of the physical space, but once these tasks are completed this global understanding can be discarded. The second two tasks require only a local understanding of the predetermined path, but this understanding must be maintained throughout the wayfinding experience. We aim, similar to prior work in this area, to create a system which reduces the cognitive load of a user by (i) performing orientation and route planning, (ii) reducing their need for accurate cognitive maps, and (iii) guiding them to the destination so traversing the path does not require maintaining spatial information.

2.2.2. Wayfinding Technology

Much of the research on indoor navigational aid focuses on using mobile devices to locate users and convey navigational information. Huang and Gartner (2009) provide an in-depth survey of mobile indoor navigation systems, including a break down of features into four main categories: user localization, route communication, context-aware adaptation, and "other features" (*e.g.,* the network design of such systems). However, precise indoor localization is a difficult task Al-Ammar et al. (2014); Kolodziej et al. (2017). Indoor spaces tend to block radio waves Dedes and Dempster (2005), existing WiFi and Bluetooth devices can often interfere Lau et al. (2009), dead-reckoning is quite error-prone Randell et al. (2003), and even if the user's location is known, communicating route information can be difficult. While there are many different ideas for how one may communicate a route (*e.g.,* typically using directional arrows), there is little work focusing on the evaluation of their efficacy and, as per Huang and Gartner (2009), further testing, in general, is necessary to determine how best to display such information though prior work informs design choices such as the use of arrows over text O'Neill (1991). For localization issues, information can be provided at decision points using barcodes paired to digital maps Mulloni et al. (2011); Serra et al. (2010) or using photos paired with turn-by-turn instructions Möller et al. (2014); Roy et al. (2017). Existing commercial solutions have followed these trends. For example, platforms like Eyedog specialize in providing mobile support for hospitals using pictures of indoor landmarks and decision points paired with navigational information. However, one limitation of this approach is that users must stop along their way to gather information with their phones. Interestingly, a recent study comparing Eyedog to a text-based application (SoleWay) suggests that even with indoor mobile support users continue to rely on posted signage to assist with navigation, matching mobile instructions to indoor conditions De Cock et al. (2019). Our work addresses this limitation by creating a set of linked displays to complement existing navigational solutions while keeping users engaged in their environment and reducing the need to stop for directions. By combining ego-centric navigation and environment-embedded cues, we eliminate the need for precise localization and orientation of users which is a difficult problem to overcome with indoor navigation solutions.

Research into linked displays has commonly focused on large, public digital displays or kiosks Butz et al. (2001); Clinch (2013); Taher et al. (2009) that deliver navigation instructions in heavily congested transportation hubs Coenen et al. (2016); Kataoka et al. (2016) or hospitals (*e.g.,* Taher and Cheverst (2011))—environments that most users visit infrequently. While these solutions tend to provide support to users by lowering the cognitive load, they rarely provide significant performance improvements (*i.e.,* quicker completion times) compared to non-technical solutions like maps or posted signage. Closer to our work is the work of Kray *et al.* who focused on developing a navigational system by repurposing smaller displays already deployed in an office environment Kray et al. (2006, 2008, 2005). This work explored user preferences around temporarily displaying navigational information on displays originally assigned to other tasks (*e.g.,* leaving notes for office communication, displaying names and schedules) and qualitative assessments of how such a system might support wayfinding without specifically evaluating performance. Moreover, the authors note that cost is a limiting factor in terms of scaling deployment Kray et al. (2005). We show that even with simple indicators, costing an order of magnitude less than traditional displays, navigational performance can be improved, increasing the scalability and likelihood of adoption of such systems.

Our work builds on this literature by exploring how a connected set of low-cost displays can be leveraged to provide many of the same benefits as more costly systems, including guiding users to their destinations quickly, easily, and with minimal cognitive load. Our focus on indoor office environments, we believe, demonstrates how such systems might be scalably deployed to address navigational challenges in everyday situations. Our system, as described in Section 4, also contributes a simple map ingestion and markup method that, unlike prior work, lowers the complexity of deploying, reconfiguring, and maintaining the system while its open API-based architecture allows for future integration with other IoT devices toward creating a mixed-fidelity ecosystem of mobile, kiosk, and other IoT devices. Moreover, we extend prior work by exploring how both the density of indicators embedded in the space and the complexity of routes impacts user performance through a controlled study that compares to an existing baseline (*i.e.,* posted maps) and we discuss what these factors mean for scalability.

3. Study 1: Formative Survey & Design Activity

To understand and reaffirm challenges and expectations when navigating large and complex spaces, including spaces that users visit frequently, we conducted a formative survey with a design activity to inform our system. While prior work in this area provides an understanding of wayfinding in indoor spaces and potential solutions, we sought to reaffirm these findings specifically with recurrent visitors to large spaces (*i.e., office workers in large office environments*). The design activity focused on how users might prefer information be displayed on an LED display, which we explored as a low-cost complement to existing navigational aids. Materials and procedures were assessed by internal reviewers for ethics and privacy risks.

3.1. Method

We recruited participants at a software company through internal email lists and word-of-mouth (see Supplementary Materials). Our recruitment ad specified we were looking for both full-time employees and interns with varying experience navigating the campus. Commercial snacks were made available as an incentive.

3.1.1. Formative Survey

The formative survey included twenty-one 7-point Likert and several open-ended, short response questions, including questions about experiences with navigating unfamiliar indoor spaces in general and the large office campus they frequent for work. This particular campus contained forty-eight floors spread over three buildings (connected by covered skybridges) plus four additional floors in nearby buildings. To understand the perceived benefits and trade-offs of various navigation modalities, participants were asked about their perspectives on six conventional and hypothetical navigation technologies based on recent research literature on AR/VR maps Brock et al. (2018); Giannopoulos et al. (2015); Huey et al. (2011), ambient lighting Matviienko et al. (2015); Olivier et al. (2007), and conversational interfaces Dethlefs et al. (2010). The survey was conducted on paper (see Supplementary Materials for full list of questions) and took approximately 15 minutes to complete.

3.1.2. Design Activity

A subset of survey participants (*i.e.,* those who participated in the survey before our prototype was constructed) also completed a short (< 20-minute) design activity. Using prepared paper journals (see Supplementary Materials), participants were asked to sketch several lo-fidelity mock-ups of potential signage that could convey specific information (*e.g.,* turn left, directions intended for multiple users on different routes) and be displayed on a 5×10 LED matrix. They were provided crayons and instructed to write text or use multiple frames to provide additional details (*e.g.,* animation).

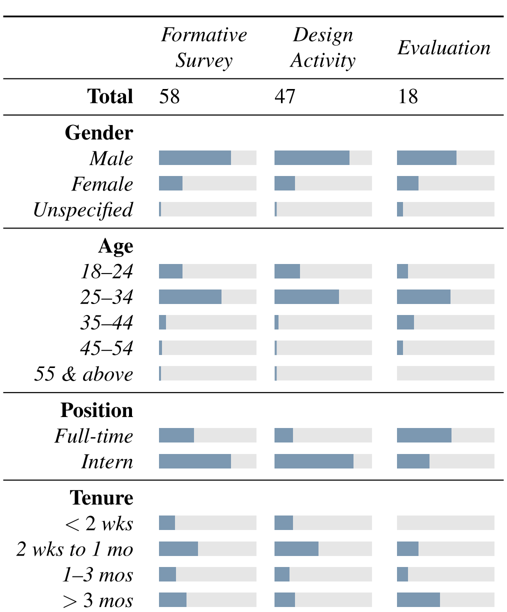
3.1.3. Data Analysis

Survey data was digitized and descriptive statistics were generated. Two members of the research team performed a thematic analysis Braun and Clarke (2006) of the open-ended responses, iteratively double-coding each response. Similarly, the design activity data was digitized and clustered around common themes. Finally, participants in our evaluation study (Section 5) also completed the formative survey before evaluating the system (though they did not complete the design activity); we include this data here.

3.1.4. Participants

In all, 58 participants (43 male, 14 female, 1 preferred not to specify) completed the survey (see Table 1). The majority of the participants were between the ages of 25–35 (64%) with the remaining being either 18–24 (24%) or 36 or older (12%). All participants were employees at a single campus of a software company (26% full-time, 74% interns). Over half (55%) were new campus, with tenures less than one month.

Table 1
Participant Demographics.



3.2. Survey Results

We report on perceived challenges with indoor navigation generally and in large office buildings similar to our deployment as well as the perceived usefulness of several hypothetical technologies that might provide navigation support in the future.

3.2.1. Indoor Navigation

We asked participants nine 7-point Likert questions related to navigating in unfamiliar environments, including how often they feel lost and what methods they employ to find their way. About a third (35%) found navigating unfamiliar indoor spaces difficult and less than half (47%) felt confident when navigating. Most (82%) commonly rely on posted signage or maps when lost and are less likely to ask others for directions. As for challenges participants encounter, about a quarter (21%) noted a problem with the mental overhead of orienting or localizing on posted maps. Several (17%) mentioned non-visible, insufficient, or confusing signage. Interestingly, some (12%) noted indoor spaces often lack landmarks either because everything looks the same (*i.e.,* layout/decor) or because the space prevents seeing outside landmarks. Finally, a few (7%) noted use of non-intuitive and inconsistent naming/numbering conventions.

As we planned to deploy an experimental prototype in an office setting, we asked participants about their experiences navigating their office campus. Compared to general navigation tasks, participants found navigating the office campus similarly difficult. Most participants (70%) used maps posted on walls to find people and conference rooms. Just over a third (36%) opted to use online maps or ask others for directions (28%). When asked if they found anything challenging about the campus, many noted difficulty with navigating between multiple connected buildings because connections and bridges were often unmarked on signage and maps. Related to this, participants mentioned that the office layouts were generally confusing and, similar to prior results, noted a lack of general signage as well as confusing and non-intuitive naming/numbering conventions.

To understand whether familiarity with the campus affected perceived challenges in navigation, we conducted a post-hoc analysis between participants who had been on the campus for less than one month (55% of participants) versus those who were there one month or longer (up to 23 years on campus). In both general navigational situations and situations specific to the office campus, no significant differences were found. Especially in the case of office navigation, this suggests that familiarity with the space did not increase perceptions of confidence or ease of navigation. For example, *P41*, who had worked on the campus for 23 years, indicated that one challenge was the open-floor plans which were harder to navigate than closed-office floors because of the lack of directional indicators. He noted, *"I can never figure out which end of the map is the front of the building."*

3.2.2. Futuring

We asked participants their perspectives on six emerging technologies based on literature (Table 2). For each technology, participants rated (i) how useful it would be, and (ii) how likely they would be to use it on 7-point Likert scales (Summarized results in Table 2, full results and questions in Supplementary Materials). Participants were also asked to explain each rating with an open-ended response.

Participants were most positive about mobile applications, large digital displays, and embedded lights. Participants preferred mobile applications because they were always with you, efficient, easy to use, and accurate. However, corroborating prior work Coenen et al. (2016); Rukzio et al. (2009), participants were concerned with installing

Table 2
For six hypothetical navigation technologies, users were asked (1) how useful they would find the technology and (2) how likely they would be to use, on 7-point Likert scales (higher is better).

Technology	*Description*	*Usefulness*	*Would Use*
Mobile application	Apps which display your location on a map, path to destination, and turn-by-turn directions.	$m = 5.93$ $sd = 1.18$	$m = 5.69$ $sd = 1.39$
Robot guide	A robot guide that leads you to your destination.	$m = 3.38$ $sd = 1.86$	$m = 3.36$ $sd = 1.96$
Large digital display	Large digital signage that displays personalized navigation information when approached.	$m = 5.03$ $sd = 1.65$	$m = 4.90$ $sd = 1.88$
AR headset	An augmented reality (AR) headset that displays a path for you to follow in your field of vision.	$m = 3.90$ $sd = 2.10$	$m = 3.22$ $sd = 1.94$
Embedded lights	A set of lights along paths, hallways, etc. that glow or flash to indicate the path to follow.	$m = 4.78$ $sd = 1.68$	$m = 4.36$ $sd = 2.01$
Audio guide	An audio-only system that provides turn-by-turn directions to the user via an earpiece.	$m = 4.09$ $sd = 1.61$	$m = 3.57$ $sd = 1.83$

additional applications to navigate different buildings, motivating the need for a ubiquitous framework. Conversely, some considered phones a hassle (and distracting) to take out and use for indoor navigational purposes. Many would use them in unfamiliar spaces if building layouts were complex, as a backup or only once lost.

Large displays were viewed as helpful and easy to use. However, there was concern that displays were less private, less practical, and a potentially complex solution to indoor navigational issues. These factors made embedded lighting appealing as they were, for example, relatively simple. However, participants were concerned that such systems might not be able to handle multiple users well.

Participants were critical about robot guides and, despite feeling that AR headsets, wearables, and audio guides could be useful, participants said they would not use them. With robot assistants, participants said they may use these systems as a novelty, but were concerned that robots would be too slow and would cause congestion. Some of the more interesting responses mentioned concern that they would be wasting the robot's time. There was also concern that using a robot guide for navigational assistance would be a "weird" experience that did not fit into current social norms.

With AR and wearables, participants were primarily concerned by the form factor and needing to carry additional devices which made this solution feel burdensome and overly complex. These solutions were viewed as a novelty and it was noted that they could only be used if these devices were lighter than current headsets emerging in consumer markets. While audio-only systems were positively perceived as being private, participants viewed these solutions as being hard to follow and preferred visual interfaces. Finally, when asked for final feedback on the survey, participants noted that error correction was particularly difficult in current navigation solutions. That is, if they found themselves lost, finding the correct route requires them to either go back to the nearest sign or map and re-orient themselves or, if completely lost, wander aimlessly until stumbling upon another navigational aid.

3.3. Design Activity Results

Of the 58 participants who completed the formative survey, 47 participants also completed the design activity (Table 1). Participants could submit as many designs as they wished. While we summarize our results here, numerous examples have been supplied in our Supplemental Materials.

3.3.1. Traveling to Destinations

Of 63 designs to indicate a turn, most (95%) consisted of arrows or chevrons (Figure 2a) in the direction of the turn, with varying degrees of animation (*e.g.,* scrolling, flashing). The remaining designs were line-based (*e.g.,* a scrolling line in the indicated direction). There were 55 designs indicating "continue straight" on a path. Similarly to turn

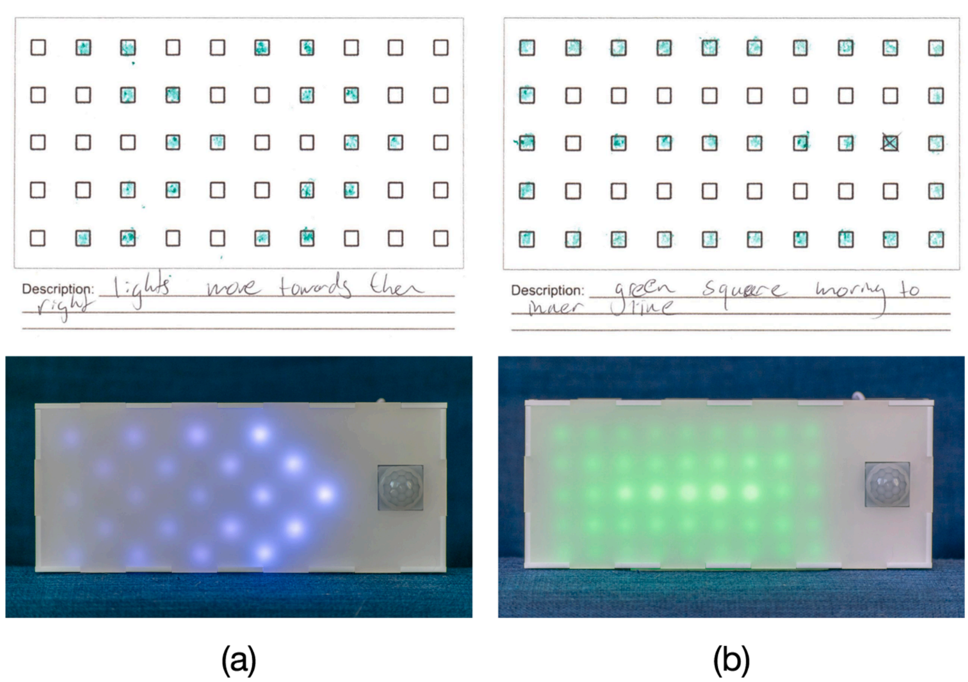


Fig. 2. Two completed paper worksheets showing arrows and a flashing grid in green with the implemented digital versions displayed below.

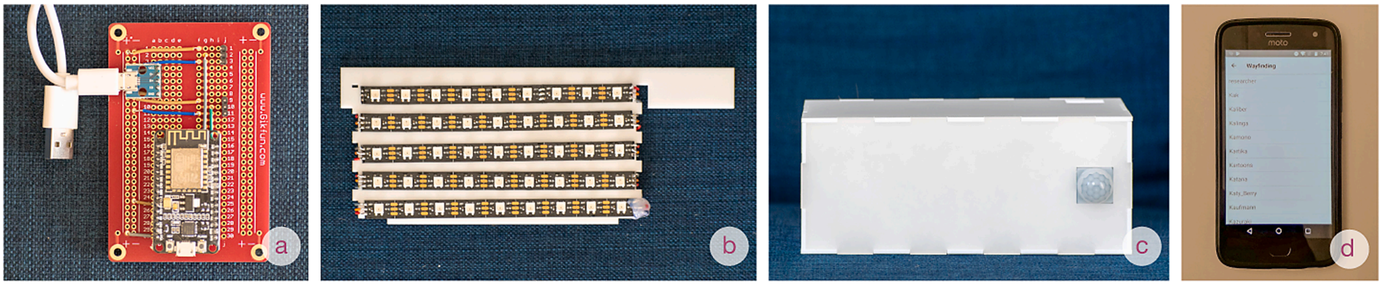


Fig. 3. A four picture banner featuring a small printed circuit board, LED matrix affixed to a plastic insert, a rectangluar enclosure, and a mobile phone.

indicators, most participants (73%) used chevrons, arrows, or lines. These shapes mostly pointed upwards, with a minority (< 1%) pointing to the right. Other shapes (*e.g.,* circles, rectangles) were also used. In addition to shapes, participant often also included flashing animations in their designs. Indicating arrival at a destination had the most variation in designs ($n = 56$), with no clear consensus (Figure 2b). Many (38%) contained checkmarks. An equal amount (38%) used other shapes (*e.g.,* rectangles, diamonds, circles) or text (*e.g.,* `ARR`, `END`, `!!`). Remaining designs (24%) were abstract (e.g., flashing entire indicator) or objects (*e.g.,* flags).

3.3.2. Error Correction and Multiple Users

There were 58 designs submitted for indicating a user was traveling in the wrong direction. Almost all (95%) used red in the design, with the majority displaying a large "X" (60%). Some also featured common signs such as stop signs. Some (10%) used a "down arrow" signaling the user to turn around. Finally, 50 designs indicated directions to multiple users. Participants were prompted to show one user going left and another going right. Designs largely used the same types of designs (arrows, chevrons) as in the single indicators, and most commonly differentiated between users by color (72%). Most showed these directions on a single screen side-by-side (54%), while others showed them stacked (14%) or flashing between users (12%).

4. Prototype System Overview

When designing our system, we used an iterative approach. We began with an early prototype used to evaluate the clarity of the directional cues, soundness of the technical design, and ease of configuration/deployment. In the next stage, we constructed an enclosure that could protect sensitive components, blend in with local aesthetics, and diffuse the LED lights without reducing the clarity (Figure 3). Finally, we created a system for ingesting map data, a cloud-based back-end allowing integration of further devices, and a mobile application for user interaction.

4.1. Design Goals

Based on the formative study, literature review, and internal discussion, we developed a set of four design goals to address practical concerns about deployment and meet user expectations about usage.

4.1.1. Lightweight Deployment

The system should be easy to deploy, with minimal need for existing infrastructure. Thus, the hardware should have its own networking capabilities, there should be a simple means of capturing map data, and the system should scale easily and affordably.

4.1.2. Modular Ecosystem

In our formative study, three navigational aids stood out as preferred by participants: mobile phones, digital signage, and LED indicators. Our system should be designed with an eye toward modularity to accommodate these varying preferences, as opposed to previous multi-device systems Kray et al. (2008); Müller et al. (2008); Rukzio et al. (2009); Taher et al. (2009) which were built with a fixed set of devices. Modularity allows building operators to add new hardware or functionality (*e.g.,* accessibility options).

4.1.3. Minimal Cognitive Load

The intent of the prototype navigation system is to reduce the cognitive load required for wayfinding in unfamiliar or complex spaces. Therefore, directional cues should be conveyed via arrows or simple shapes, as per participant expectations in the formative study, and should be animated when possible, as this is highly effective at drawing attention Gutwin et al. (2017). Additionally, our system should communicate route information frequently to users, reassuring them they are on the correct path and bolstering their confidence in the system.

4.1.4. Low Buy-in

To help encourage user adoption, the system should have a low barrier to entry. In particular, it should be intuitive, easy to understand, and should minimize the need for custom hardware or software on the part of the users. For example, while the system may be augmented by a mobile app, it should not require one. The solution must also cost-effectively scale. Any necessary hardware should be low-cost and readily available.

4.2. System Design

The system consists of three major components (see Figure 4): map ingestion and representation, an inter-device communication/control layer, and a cloud-based layer.

4.2.1. Floorplan Ingestion and Representation

Our system reduces the amount of manual effort necessary to map an environment, requiring only that the system installer annotate a roughly to-scale floorplan of the space using any vector graphics program. We chose to use a custom representation rather than an existing one such as IndoorGML Lee et al. (2018) to reduce the amount of unneeded information, and thus lower the cost and complexity. This floorplan does not need to be a highly precise engineering drawing; any reasonable floorplan image can be used (Figure 5), even a photograph of a physical map of the kind typically posted in a building. The process can easily be modified to use even simpler tools for map markup, such as Microsoft PowerPoint, if desired. Additionally, icon packages can be added to tools like Adobe Illustrator, allowing for easier drag-and-drop-style markup. Users begin by marking the position of each navigable location, and each installed indicator with unique markers, as in Figure 5a, which uses green and red circles, respectively.

Once the positions of the indicators are marked, their orientations are labeled. This is done manually by adding line-segments radiating outward from indicators, representing the viable directions of travel. For example, an indicator placed at the end of a hallway at a T-junction would have three such markers: left, right, and back down the hallway (in Figure 5b, the third marker from the left on the top is an example of this). These markers are differentiated by style (in our case, by using

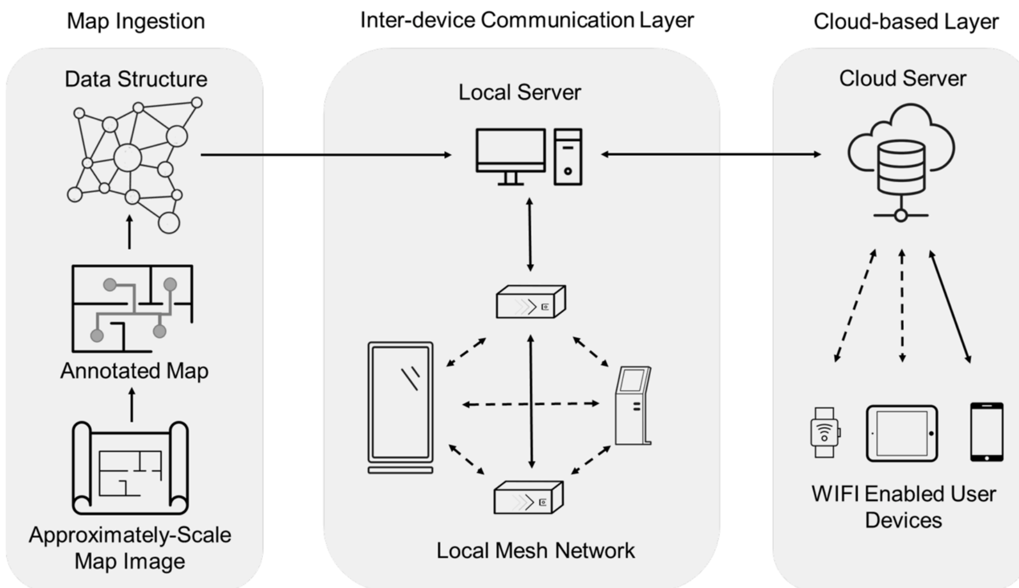


Fig. 4. A diagram showing three layers of the system including map ingestion, inter-device communication, and cloud-based servers. The diagram uses icons of mobile devices, different display units, computers, and data structures to provide an overview of the current and future system using solid and dashed lines.

different colors). The choice of marker style is arbitrary, as long as they are consistent and unique per direction. The markers are then extended with drawn paths, forming a single connected graph between all indicators and navigable locations (see Figure 5c). In our study, map ingestion took ~30 minutes for a ~19,000 sqft floor with 16 indicators servicing 27 navigable locations.

Once the markup step has been completed, a Python script is used to validate the hand-drawn map data by ensuring all edges are connected with no gaps and all markers lie on a valid path. From here, we create a graph data-structure representation, where markers (locations or devices) are nodes and pathways are edges weighted by their distances. The device nodes also contain metadata about their orientation in the space. In the case of wayfinding, we generate an all-pairs-shortest-paths lookup table via Dijkstra's algorithm Dijkstra (1959). For every indicator-location pair on the map, this lookup table provides the quickest direction of travel from the indicator to the location by storing only the directional cue for each indicator in relation to each room (as opposed to storing the whole path). Performing this action as a pre-processing step rather than a real-time calculation allows for low-overhead communication and quicker response times, subsequently reducing the demand on and cost of the indicators.

4.2.2. *Inter-Device Communication Layer*

The devices are connected through a mesh network-enabled microcontroller. A central server maintains knowledge of the system state across all devices, pushes display commands to them accordingly, and serves as the connector between the local mesh and cloud-based devices. At a high level, communication only occurs between devices connected to the system and the server. Devices relay information to the central server regarding their status, any environmental information they may have (*e.g.,* motion sensor data), or any user inputs (*e.g.,* a kiosk interaction), and in turn, the server updates the devices with requests to display the currently appropriate information (*e.g.,* navigational directions). Predicated on a lightweight communications protocol, media is stored locally, can be updated from the server, and display state is sent out as broadcast commands (packet contains state for all displays, increasing size of an individual message, but reducing total number of messages and allowing mesh relay).

4.2.3. *Local Server*

The server monitors the indicators' statuses, listens for navigational requests from devices connected via the mesh network or the cloud server, and signals the indicators to display the appropriate direction to the target room from their positions. The server was run on a laptop with an ESP8266 acting as a communication dongle.

4.2.4. *Indicators*

The prototype indicators themselves are a 5×9 grid of LEDs, controlled by an ESP8266 microcontroller, and powered by a battery pack, all housed within a custom enclosure (Figure 3a-c). These indicators, costing approximately $30 USD each, form a local mesh network and display low-fidelity directional cues based on our formative results and piloting. Meant to be low-cost, easy to construct, and easy to deploy, they are made of readily-available off-the-shelf components. Each device is also outfitted with a Passive Infrared (PIR) motion detector. These sensors allow for some amount of gross user tracking and simple interactions (*e.g.*, displaying directional cues only when a user approaches an indicator rather than at all times). However, these features were not tested during our evaluation. Directions are displayed using a set of animations derived from the formative study (*i.e.,* we selected those that were most commonly suggested by participants with a sample of the remaining suggestions being included in our Supplementary Materials). Animated chevrons provide directional cues, moving across the display in the direction of travel and pausing upon reaching the edge of the display. In this way, we display directions for traveling left, right, forward, and backward, with the last two directions represented by upward and downward chevrons, respectively. Additionally, arrival at a destination is indicated with a pattern that pulses the entire display in a green, shrinking rectangle (Figure 2b) visible at large distances. We aimed to make the indicators unobtrusive in the environment, especially with the use of animation. Figure 6 shows examples from our evaluation of the indicators mounted in a real-world environment.

4.2.5. *Cloud-Based Communication*

The centralized server connects the localized mesh network with internet-enabled devices, which allows users of the system to communicate with the devices (*e.g.,* select a destination for navigation). Internet-enabled devices (*e.g.,* a mobile phone) can provide instructions in a cloud database (such as a Google Sheet), where the centralized server reads and receives them, without the added hardware necessary to connect to the mesh network. The addition of a centralized cloud

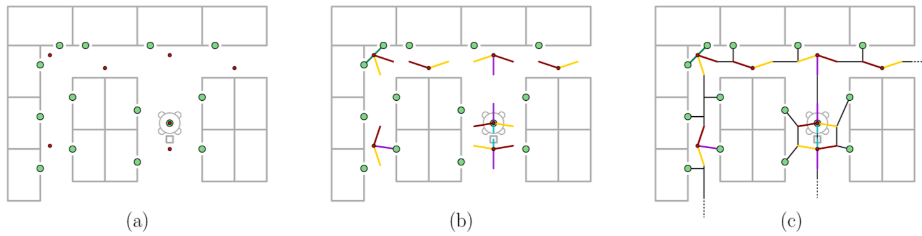


Fig. 5. A simple building layout with two three short halways formined by office spaces used three times being successively labeled with markup left-to-right.

database enables a single mobile application to be shared by multiple buildings and systems, providing seamless experiences across buildings as well.

4.2.6. Mobile Application

For ease, an app was created that offers users the opportunity to select a location from a list of available locations (Figure 3d). Once selected, this location is sent to a cloud-server, changing the system's targeted room and thus the patterns displayed by the indicators. For the purposes of evaluating the effectiveness of the low-fidelity indicators, the mobile application gathers timing information for user tasks but does not provide any navigational information.

5. Study 2: Prototype Evaluation

To evaluate our system, we conducted a controlled experiment (N=18) in which participants were asked to navigate to conference rooms in an office space. We measure performance (*i.e.,* speed of navigation) across six conditions that vary in route complexity and density of displays and gauge user experience.

5.1. Method

We again recruited participants through word-of-mouth and internal mailing lists (see Supplementary Materials). Additionally, survey participants who opted into being contacted about future studies were invited to participate. In total, 21 participants were recruited (11 new, 10 from Study 1). All new participants completed the formative survey, without doing the design activity. Due to technical difficulties, three participants were excluded from the analysis for a total of 18 participants. We deployed the system across one floor on the office campus that no participant frequented.

5.1.1. Study Design

The study employed a 3×2 within-subjects design with factors of *Indicator Density* (None, Low, High) and *Route Complexity* (Simple, Complex) for a total of six conditions. Conditions were counterbalanced using a balanced Latin square. An equal number of participants were randomly assigned to each order.

5.1.2. Room Selection and Route Complexity

In selecting destination rooms for the `Simple` and `Complex` conditions, we considered two criteria: the shortest-path distance to the room and the number of decision points *i.e.,* intersections, along the shortest path. All `Simple` routes were less than 115 feet and contained no more than 7 intersections, while `Complex` routes were over 155 feet with at least 10 intersections. See Figures 7 and 8 for examples of `Simple` and `Complex` routes.

5.1.3. Indicator Placement and Density

Twelve indicators were placed to maximize helpfulness, encounter likelihood, and coverage. The Interconnection Density Index (ICD) proposed by O'Neill (1991) uses intersection degree to measure the complexity of an indoor space. It has been shown that a higher ICD leads to lower wayfinding performance, thus we chose to place indicators at intersections with a greater than average degree. We used betweenness-centrality Freeman (1977) to place indicators in high-traffic locations so that users are more likely to encounter them. The coverage of an indicator is determined, roughly, by its visibility in the space. The greater the area in a space from which an indicator can be seen, the greater its coverage. To balance coverage with cost-effectiveness, we chose to spread our available indicators as evenly as possible across the navigation space. Finally, we supplemented our placement with four additional indicators that were only active during the `High` density condition. These indicators were placed close to other indicators, only minimally increasing coverage, or were located toward the outer extremities of the space. Figure 9 shows the placement of high and low density indicators on the floorplan.

5.1.4. Procedure

Sessions lasted approximately one hour and began by measuring the participant's walking speed. If they had not previously completed the formative survey, they did so at the beginning of their sessions (results included in Section 3). They then received training on the system and corresponding wayfinding application (Figure 1d), which was pre-installed on a provided smartphone. To facilitate tracking our experimental tasks (described in Section 5.1.5), each conference room on the floor was outfitted with a label that contained the name of the room and a four-letter code. Labels were visible from the hallway and always located under the room-name plaque.

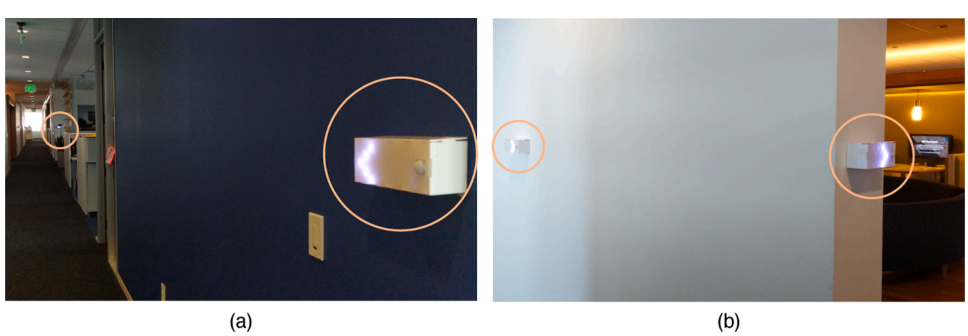


Fig. 6. Two pictures of hallways in the deployment location with pairs of indicators in them. The picture demonstrate the spacing, showing some distance between each (i.e., one is far enough away to be barely observable in the photo).

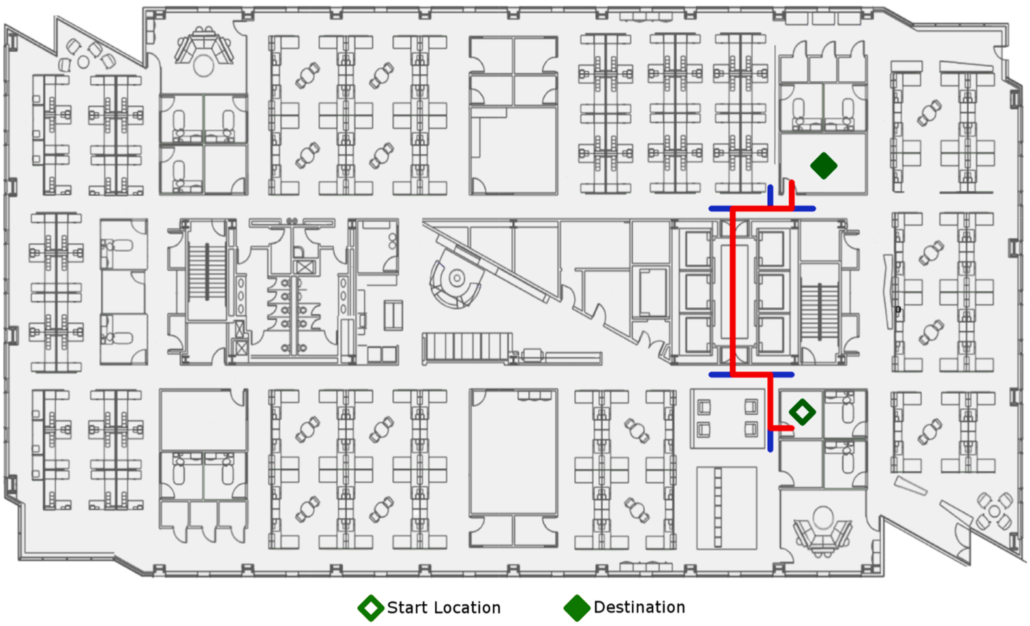


Fig. 7. The actual floor plan of the evaluation site showing long hallways, numerous offices, cubicle areas and a meeting space on a diagonal in the center. Highlighted on the map is a simple route.

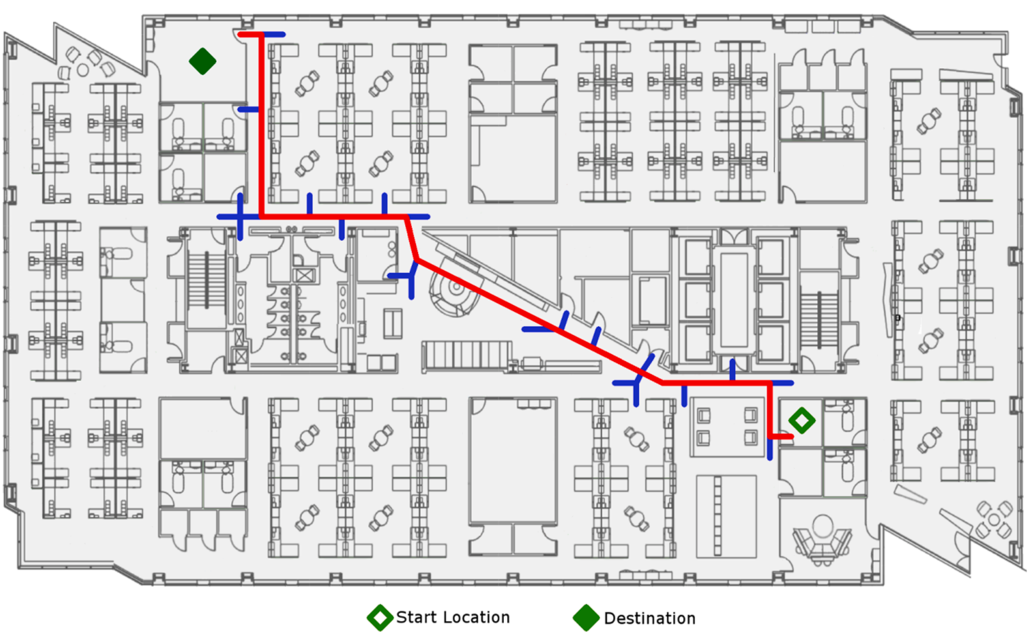


Fig. 8. The actual floor plan of the evaluation site showing long hallways, numerous offices, cubicle areas and a meeting space on a diagonal in the center. Highlighted on the map is a complex route.

All tasks began from the same starting location near the elevators. Participants were instructed to navigate to a specified conference room, at which point they would select the room within the application. They were allowed to use any navigational aids in the environment (*e.g.,* posted maps, LED indicators), but were instructed not to ask others for directions as this experience may vary between participants. Upon reaching the room, they would enter the four-letter code and their timing was logged in the system. Participants were then immediately prompted to complete the NASA Task Load Index (NASA-TLX), proposed by Hart and Staveland (1988), via the app. Participants repeated the task for each experimental condition. At the end of the session, participants completed an exit questionnaire (on paper) containing the System Usability, or SUS, Scale Brooke et al. (1996); Lewis and Sauro (2017, 2009) and a semi-structured debrief interview. Participants were compensated with a $10 Amazon gift card.

5.1.5. Measures and Data Analysis

The time to complete each task was logged using the provided phone app. As the distances to different rooms varied, we normalized the duration of each task by distance to its respective room, thereby calculating the average speed of the participant per task (in miles per hour *mph*, faster is better). The speeds were not normalized by participants' walking speeds as the speeds were compared using a two-way repeated measure ANOVA Fisher (1925). Paper surveys were digitized and Likert responses were analyzed with descriptive statistics. The exit interviews were transcribed and thematically coded.

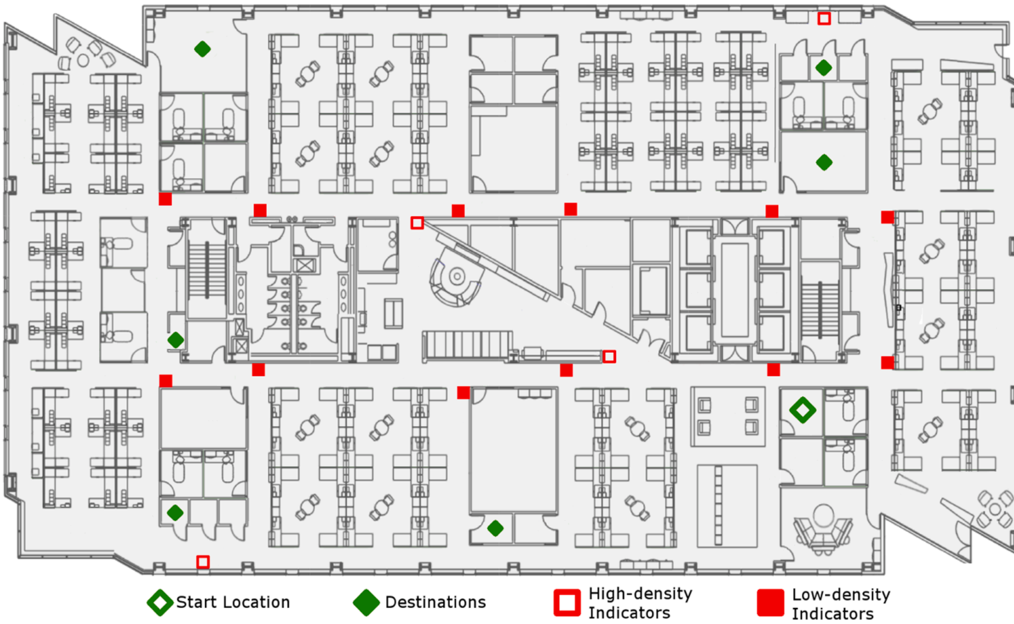


Fig. 9. The actual floor plan of the evaluation site showing long hallways, numerous offices, cubicle areas and a meeting space on a diagonal in the center. Highlighted on the map is all the indicators and destination locations.

5.1.6. Participants

Of 18 participants (12 male, 5 female, 1 preferred not to specify), eight were recruited from the original survey pool, and ten were recruited later. Demographics are reported in Table 1. On average, participants were $67in[170cm]$ ($sd = 4in[10cm]$) tall and walked at a speed of $3.3mph[1.47m\cdot s^{-1}]$ ($sd = 0.32mph[0.95m\cdot s^{-1}]$). All worked on the campus where the study was conducted, but were specifically screened so that none had spent significant time in the building or floor used in the experiment.

5.2. Results

We report on participants' walking speed in each condition, self-reported scoring of task load and usability, and their perceptions of the system in general. Participants are identified by their survey respondent numbers (*e.g.,* the 13[th] survey respondent is identified as P13).

5.2.1. Participant Speed

Overall speed results are shown in Figure 10a. We describe results related to indicator density and route complexity. All speed values are given first in miles per hour followed by meters per second in brackets (e.g., 1.9[0.9]), unless otherwise noted.

Indicator Density. On average, participants were fastest in the `High` indicator density condition ($m = 1.9[0.85], sd = 0.42[0.19]$) versus `None` ($m = 1.61[0.72]$, $sd = 0.56[0.25]$) and `Low` ($m = 1.81[0.81]$, $sd = 0.54[0.24]$), with a significant effect ($f(2, 34) = 3.61$, $p = 0.037$, η_p^2=0.18). Aside from achieving a faster average speed, the `High` density condition had the lowest variance and fewest outliers indicating a more uniform experience when using the indicators. Though a significant effect was found, the effect was not monotonically correlated. Interestingly, participants performed worse on `Low×Complex` and best on `Low×Simple` conditions, indicating fewer lights may be more helpful in simpler routes, but in complex, higher density is more useful.

To further examine the effectiveness of the `High` density condition, our primary factor of interest, we did a post-hoc analysis on the `None` versus `High` conditions only. Using a right-tailed, paired t-test (H_1 = *None* < *High*), we found a significant ($p < 0.05$) *increase* in speed in the `High` density condition.

Route Complexity. On average, participants were significantly faster ($f(1,17) = 14.95, p = 0.001$, η_p^2=0.47) in the `Complex` route condition ($m = 1.930.86$, $sd = 0.510.23$) versus `Simple` ($m = 1.620.72$, $sd = 0.480.22$). This is likely due to routes being farther and participants having longer stretches of walkway to gain speed.

Indicator Density × Route Complexity. A significant ($f(2, 34) = 5.53$, $p = 0.008$, η_p^2=0.25) interaction effect was found. Participants performed best on the `High× Complex` condition ($m = 2.14[0.95]$, $sd = 0.36[0.16]$). Given the prior results, this suggests the number of complex tasks will influence the total number of displays necessary in the system but that fewer displays should be active during simpler wayfinding tasks.

5.2.2. Participant responses to NASA Task-Load Index (NASA-TLX)

The NASA-TLX measures perceived Mental Demand, Physical Demand, Temporal Demand, Effort, Frustration, and Performance for each condition on a scale of 1 to 7. Scores were added to give a cumulative score from 6 to 42 for each task (lower is better). A significant main effect was found for *Indicator Density*, with the `High` density condition performing the best ($m = 8.8, 11.4, 17.6$ for `High, Low, None` respectively, $f(2,34) > 8; p < 0.01$). Similarly, per dimension, significant main effects for *Indicator Density* were found in all six dimensions, with the `High` density conditions requiring significantly less load and higher performance ($f(2,34) > 8; p < 0.01$ for all dimensions). Conversely, *Route Complexity* had no significant main effects in any dimension. A significant interaction effect was found for four dimensions: Mental Load and Effort ($p < 0.01$) and Temporal Demand and Frustration ($p < 0.05$). Participants found the `Low×Complex` condition to be particularly frustrating. Figure 10b shows average responses across the NASA-TLX and a full breakdown by dimension is provided in the Supplementary Materials.

5.2.3. System Usability Scale (SUS)

Participants completed a SUS questionnaire using a 7-point Likert scale. Overall, participants were positive about the system, with most (15/18) agreeing that the system was enjoyable to use ($m = 6.25$) and most (17/18) agreeing that the system was helpful ($m = 6.4$). Notably, many (17/18) felt the system was easy to get started with, disagreeing that many things needed to be learned ($m = 1.65$), and most (16/18) agreed that users would learn the system quickly ($m = 6.25$). Some (13/18) said they would use the system frequently ($m = 5.4$), and most (14/18) felt confident when using the system ($m = 5.5$). On average, the system scored an 80.5 on the SUS, placing it approximately in the 90th percentile for usability Sauro (2011).

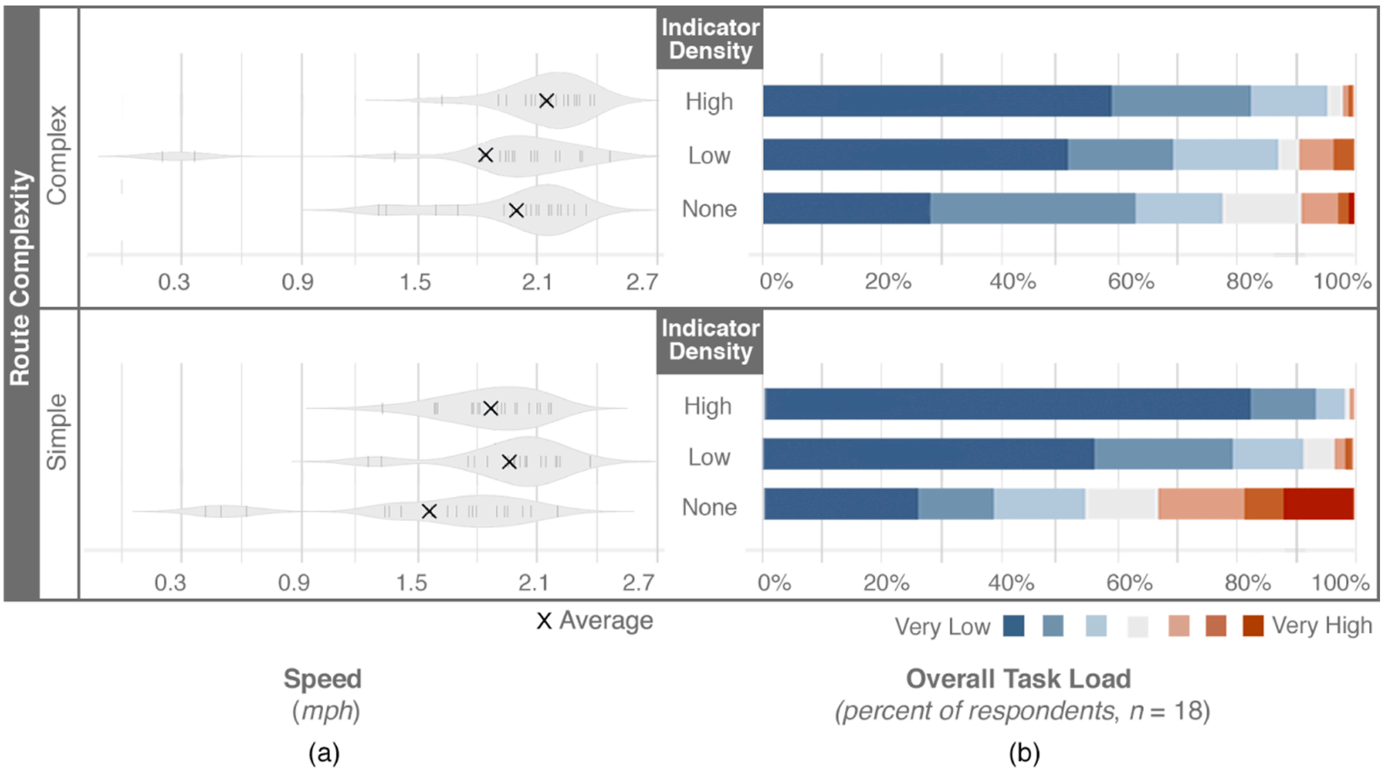


Fig. 10. A four panel table with rows for complex and simple routes and columns for speed and task load.

5.2.4. Post Study Interview

We discuss the perceived benefits and challenges of using systems such as ours.

Benefits. Half of participants commented that the system was intuitive and that it took very little time to understand and learn the signs. They particularly appreciated that the system required a lower overhead than maps (33%) since it eliminated problems of localizing and orienting themselves: *"I liked that I could go out and just follow it. I don't have to find out where I am or type in where I want to go, it just points me"* (P53). Four (22%) explicitly mentioned feeling more confident, assured, or secure with the indicators. In some cases, this was because they trusted the system to guide them: *"I was so confident, I wasn't looking anywhere else but at the lights"* (P45). Others still used the map, but appreciated that the lights confirmed they were on the correct route: *"You feel more confident when you're working with it. Using the maps gives you a rough idea, but not a sense of direction. This fills that gap and helps a lot"* (P55). Finally, participants were enthusiastic about the potential time-savings since route planning would no longer be necessary: *"The first thing I would definitely do is skip looking at pathfinder [an internal wayfinding tool] in emails"* (P15). One participant noted how well the indicators blended into the environment, *"It was just a part of the environment and it was visually pleasing"* (P40).

Challenges. Most challenges participants faced were due to indicator placement (78%). Specifically, participants' frustrations were related to the low density of indicators and confusion when multiple indicators were visible. Several participants would have preferred there be more indicators, in part due to feeling less secure in long stretches of hallway that did not have an indicator. P58 noted, "*when I couldn't see the next indicator while walking I was a bit worried that the next sign was too far or not working, I wondered if I should go back to see the maps.*" Other participants felt that if the next indicator was not always visible, they wondered if *"they were lost"* (P40). In low-density conditions, participants struggled when the indicator was off at intersections.

Participants were also thrown off by being able to see multiple indicators at once. As the indicators were designed to be read as though the user was facing it, participants had difficulty reconciling the directions. P48 explained, "*Once the room was located between two lights that both indicated backward. I knew it was between them, but I found this confusing.*" Additionally, participants expressed worry that they became reliant on the system and the system prevented them from building a mental model of the environment (28%). Some challenges came from protocol frustrations (22%). Because conditions were counterbalanced, those who became reliant on the system in earlier conditions expected them in every condition and were frustrated to find them off.

Privacy. We asked participants specifically how it felt to have navigation information being displayed in such a public and visible way. Half of the participants had no issue with the amount of information that was displayed and felt comfortable using the system. Three noted they were comfortable using the system in specific situations (*e.g.,* conference rooms), but would feel uncomfortable in others (*e.g.,* restrooms). Another three felt mildly awkward. Two participants said they were uncomfortable using the system, either because of social norms or being targeted as a visitor to the building.

Display Feedback. When asked for feedback on the display itself, most participants (72%) thought it was good as-is. Some (17%) particularly appreciated the animation because the movement helped draw their attention. Only two participants suggested improving the *arriving* and *backward* indicators.

Suggestions and Improvements. Participants noted that providing cues such as distance to destination or an overview of the route would be helpful. While giving a map or overview of the route would be difficult on the low-fidelity indicator, this motivates the need for a mixed-device ecosystem which includes large displays and kiosks. Participants also heavily preferred the high-density conditions and suggested having indicators at every intersection and on particularly long stretches of hallways. Participants were also concerned with how the system might scale to handle multiple users.

Applications of Indicators. Almost all participants (94%) thought the indicators would be helpful in an office setting, particularly for visitors, new employees, or anyone unfamiliar with the office layout. Though some (33%) said they would use the system even if they were familiar with the floor plan (for fun or reassurance), the majority would not. One felt the system would be unsuitable for an office environment, as it could be potentially distracting. In terms of specific applications in the office, participants felt the system would be most helpful for locating conference rooms (44%), people's offices or cubicles, or exits.

We asked participants which applications besides navigating office spaces these indicators might be useful for. Many mentioned additional wayfinding applications in other types of buildings, such as in grocery stores, hospitals, and shopping malls. Participants also mentioned the indicators being useful to guide groups of users to large community events or for emergency response (either guiding users to an exit or to guide first-responders to people in distress). Beyond wayfinding, participants suggested the embedded indicators could be used as ambient displays in indoor environments, for example, to display the date and time or coworkers' birthdays. Two suggested using the indicators as a game display: *"Games would be cool, scavenger hunts. Or even like a real-life Pacman"* (P56).

6. Discussion

In this work, we sought to reaffirm that navigational challenges are common in everyday environments, explore perceptions around potential future navigational solutions, and create a low-cost navigation system that would improve both user performance and wayfinding experience while also complementing existing navigational infrastructure and being easy to deploy. Results from our formative study suggest that navigational challenges remain common in modern built environments and that participants were most interested in mobile applications, large-digital displays, and embedded indicators as being the most practical compared to, for example, AR/VR solutions that may require additional personal hardware. Moreover, we found little difference in tenure, reaffirming prior work that these problems do not necessarily go away with time as we might expect Arthur and Passini (1992).

As low-cost, embedded indicators can be deployed quickly to test various deployment factors, we pursued this option as an end-to-end artifact to help realize our ideas around a mixed-fidelity architecture for the built environment. Our evaluation results show that participants found our system to be intuitive and easy to use, that they were able to locate and travel to target destinations more quickly, and were more confident while doing so. By embedding our system in the environment, we created a direct link between the physical space and the navigational cues, reducing the user's need to orient themselves or construct a cognitive map, both tasks that increase the difficulty of wayfinding. Additionally, the combination of ego-centric navigation and environment-embedded cues eliminates the need for precise localization/orientation of users. Extending prior work that looked at performance along a single dimension, we observe a non-monotonic correlation between indicator density and route complexity with respect to performance. Though participants reported feeling more confident when using our indicators, some who encountered the density conditions of *None* or *Low* later in treatments expressed frustration at missing indicators as they had come to expect them (*i.e.,* while individual participants did not repeat overall paths or go to the same destination twice, some hallways segments were re-used to access different destination possibly creating this expectation that an indicator should be on as it was before). While our results may not generalize to all buildings or deployment configurations, they suggest that the number of complex routes in a floor plan will drive the total number of displays necessary but fewer need be active for simple routes—a finding which likely translates to other decision point solutions *e.g.* Möller et al. (2014). Moreover, our formative and qualitative results suggest similar navigational systems would be useful in everyday contexts to support users during navigational tasks with feeling more confident and help to reduce cognitive load if not always delivering measurable performance increases.

6.1. Adherence to Design Goals

We began the design process by defining a set of four design goals. In creating our prototype system we did our best to adhere to these goals, however, due to logistical constraints, there is room for improvement.

6.1.1. Lightweight Deployment

Map ingestion is a quick and straightforward process. Setting up the prototype for our evaluation took no more than half an hour to capture and annotate the necessary map data. The addition of custom mapping tools/aids, such as icon packages for vector graphics programs, would allow for even easier drag-and-drop-style markup. The control server and prototype LED indicators required no existing infrastructure. Together they formed a local mesh-network for communication and the indicators ran on battery power for the duration of our multi-day evaluation.

6.1.2. Modular Ecosystem

The exploratory system created makes use of a simple, cloud-based communications interface, allowing for the easy integration of further devices. However, as the system was designed with low-fidelity indicators in mind, the transmitted information is relatively simplistic, comprised solely of the necessary directional cues. To fully leverage the capabilities of additional devices, a richer communications protocol would need to be established.

6.1.3. Minimal Cognitive Load

Participants found the system easy to use and understand. Several commented that it was very intuitive and that the chosen visual cues were clear and direct, with the exception of *backwards* (a downward chevron)—viewed as unclear by some. Frequent and well-thought-out indicator placement helped to maintain participant confidence, particularly in high-density tests. In the low-density cases and in one particular location where a mural prevented the installation of an indicator, participants found the lack of indicators made them feel uneasy. A more rigorous set of placement guidelines and testing would be useful for helping to understand exactly how and when this unease occurs and how best to mitigate it.

6.1.4. Low Buy-in

Participants used a mobile application during the evaluation, though this app was mainly used to record timing for the experiment data. In practice, these interactions could easily be moved to an *in-situ* kiosk or other devices. Beyond this, the remainder of the user-facing portions of the system were integrated into the environment, with all indicators affixed to walls; in the future, such indicators could be embedded into the wall during construction. The addition of low-cost indicators provides for greater coverage of the system, allowing for an increase in scale while keeping overall costs low. These indicators bring the unit cost down by an order of magnitude, costing tens of dollars rather than hundreds or thousands, as larger digital displays often do. They could be made cheaper still via mass production.

6.2. Human Building Interactions and Other Applications

A focus on smart buildings is becoming more prevalent, but generally, such systems are designed with building management in mind (*e.g.,* HVAC, security, structural health) and/or to gather usage data. While our indicators were created with navigation in mind, there is very little in their design that would preclude them from other use-cases that could foster novel, new interactions with buildings Alavi et al. (2019, 2016). Even within the realm of navigation, there are other uses to be explored. Perhaps they could be used to guide users to exits during an emergency or aid first-responders, who often work in unfamiliar environments and under time pressure Ibrahim et al. (2016); Ramirez et al. (2009). Beyond navigation, several participants suggested the indicators could be used to display public messages similar to Kray et al. (2008) or even for augmented reality games. Despite their enthusiasm, some were concerned that they may become too reliant on the system and may struggle without it, yet participants reported rarely needing the indicators when returning from their target room. This implies a growing familiarity with the space, despite reliance on the system, mitigating this concern.

6.3. Design Recommendations.

Here we discuss three key design recommendations for future indoor navigation systems similar to ours.

6.3.1. Technology

Many wayfinding solutions rely on user-specific hardware/software, such as mobile applications. However, users of mobile applications are notoriously fickle. Roughly 40% of abandoned apps are uninstalled within one day Li et al. (2015), while about 93% survive less than a week. The expectation that users would install and retain navigational apps seems optimistic, especially if each space requires its own app. Successful applications will likely need to service multiple spaces and handle various user preferences (*e.g.,* privacy). As a result, our system is not meant to replace other solutions such as mobile applications, digital signage, or posted maps but augment them, giving users choice in solutions that best suit them.

6.3.2. Indicator Placement

Several of our test participants expressed some level of unease when the next indicator on their route was not visible. Conversely, some participants became confused when they could see too many indicators. These indicators offered alternate paths based on their positions, but to participants this appeared to be contradictory information. Thus, care must be taken when selecting the number of indicators and their placement, taking into consideration how many indicators are visible to a user at any given time.

6.3.3. Minimize Distraction

Several participants were concerned with the system's potential to be distracting as we ran our experiment on an occupied and active floor during business hours. While we received no complaints, one should take care when designing and deploying such a system. By designing a relatively small, low-power display rather than large digital signage, we attempted to minimize our impact on the visual landscape.

6.4. Limitations and Future Work

The limitations of this work include: (i) a limited participant pool drawn from employees of a single software company which resulted in a gender skew toward male participants and overlapping participants across studies (*i.e.,* which may have resulted in more positive sentiment toward the system used in our evaluation), (ii) self-selection bias from volunteer-based studies, (iii) implementation of only one prototype and text-only descriptions for alternative solutions used in the formative study, (iv) a lack of generalizability across indoor environments, as tests were conducted on a single office floor, and (v) only investigating using our system to complement posted maps as the primary available existing navigational infrastructure. In addition to addressing these issues, future work should also investigate:

6.4.1. Indicator Design.

Some users found that the *backward* direction was confusing and took more time to understand *in situ* than other patterns, despite the forward direction (up arrow) posing no problem. One participant pointed out that every day signage often uses arrows to convey direction (*e.g.*, on roadways), with the exception of downward arrows, which are relatively rare. This confusion was enough that one participant failed to find a room at all, instead giving up and returning to the study administrator. Further work should be done to either find a better representation of this direction or determine a method of routing that does not require such a direction. Additionally, given that small screen displays are becoming increasingly low-cost it may be possible to move away from LED-type displays to higher fidelity ones in the future which would open up the design space for display content to include text, localized maps, as well as instructions for multiple users while still maintaining cost parity (at scale) and aesthetic qualities.

6.4.2. Localization

Our system does no real-time localization of the user. This frees us from having to strike the delicate balance between a high-cost, high-accuracy system and a less accurate yet more economical one. However, the addition of user-localization (*e.g.,* using cameras and additional sensing) could allow the system to be further tailored to a user, only activating indicators within their line of sight, allowing, for example, multiple users in different areas to use the system simultaneously. This integration would be critical in scaling up the system to larger spaces with concurrent users.

6.4.3. Multi-user Support

The system as developed only supports a single user, but adding support for multiple concurrent users is a necessary next-step for real-world deployment. In addition to support for user localization, multi-user support would require methods for managing several simultaneous routes, displaying information to more than one user at a time, and a server allowing concurrent user inputs. As previously mentioned, some of these display elements could be achieved by exploring additional lost-cost and higher-fidelity display technologies. However, there are several possibilities even with the current platform. For example, participants suggested using different colors to code instructions and support multiple users. Additionally, work by Rukzio et al. (2009) uses a combination of indicators built into the environment in conjunction with users' mobile phones to tackle multi-user support by way of time slicing worth investigating further. Moreover, additional cameras or tighter integration with mobile devices (*i.e.,* without the use of purpose built applications) could offer additional solutions if privacy and cost concerns can be addressed. With more robust user tracking, indicators could display only for the nearest user and with mobile device integration, users could initiate directions (e.g., tap an indicator with their phone) as needed.

6.4.4. Map Ingestion

Our map ingestion method made system deployment quick and efficient but there is room for improvement. The map markup step requires adherence to certain rules such as co-locating positional markers with line segment endpoints. Doing so in a vector graphics program not intended for this task is not difficult but can be tedious if the space is large. A lightweight or minimalist tool that would automatically enforce markup requirements would make the process faster, easier, and would help to prevent errors.

6.4.5. Usage Statistics

The deployment of a building-wide system provides an opportunity for gaining a greater understanding of how a space is being utilized. What are the most common destinations? Which routes see the most traffic? Does usage change at different times of day or during different seasons? Analyzing this data could lead to further insights into how users interact with the built environment.

6.4.6. Targeted Route Planning

With a better understanding of how a space is used comes a better understanding of how to use it. Load-balancing, for example, can be done when a space is particularly crowded, sending users along alternate routes to help relieve congestion similar to Kataoka et al. (2016). Similarly, occupants can be encouraged to visit points-of-interest that they may not otherwise see while nearby displays provide them with relevant information or behavioral nudges, similar to Rogers et al. (2010), increasing enjoyment of or engagement with a space while also, for example, reinforcing daily step goals or other healthy behaviors.

6.4.7. Personalization

Rather than taking the shortest route, users may wish to customize certain routing options, such as taking a more scenic route or passing by amenities. Frequent users could store their preferences making future interactions quick and easy while also allowing for personalized route and point-of-interest recommendations.

6.4.8. Maintenance and Power

As has been noted by others, such as Gleason et al. (2018), maintaining IoT systems in the field is difficult and there are elements of our current design that make long-term deployment an open challenge. Our indicator design was not meant to be the sole, canonical version, but instead an exemplar. Our intent is to show the efficacy of a low-cost, easy to deploy system, leaving the choices and trade-offs related to powering and maintenance up to the system owner. For some, this means embedding indicators into a building during construction/retrofits and connecting them directly to building power which may impact the ease of replacement. Others may prioritize battery powered indicators that can be quickly deployed or moved (*e.g.,* for short-term hotspot mitigation during large events). A low-cost modification to our system would allow for both power options, increasing system utility and robustness. However, long-term deployment issues and mitigating solutions are worth further exploration.

7. Conclusion

To evaluate how an open architecture of mixed-fidelity devices can utilize low-cost indicators to help users better navigate indoors, we conducted a multi-stage study in an active office environment. Beginning with a survey study (N=58) to determine and reaffirm existing navigational challenges, we then designed a prototype navigation system and evaluated it using a mixed-methods approach, including a controlled user experiment (N=18) that examined the interaction of display density and route complexity. Our results show that our system of networked LED indicators can improve both wayfinding performance and experience, boosting confidence and consistency among users while delivering similar benefits as high-cost digital alternatives. As result, the main contributions of our work include: (i) a low-cost system for indoor navigation with a lightweight and open deployment paradigm as well as a novel map ingestion mechanism, (ii) a formative study that explores current perceptions of existing navigation solutions while also reaffirming the need for additional navigational support in everyday buildings, (iii) a controlled study that evaluates performance and the interaction of display density and route complexity against an existing baseline, and (iv) design recommendations for deploying such systems in the built environment to foster new interactions in buildings.

CRediT authorship contribution statement

Philip Dasler: Conceptualization, Methodology, Software, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Sana Malik:** Supervision, Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Matthew Louis Mauriello:** Supervision, Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests

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Supplementary material

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