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Evaluating the impacts of color, graphics, and architectural features on wayfinding in healthcare settings using EEG data and virtual response testing

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ABSTRACT

Wayfinding difficulties in healthcare facilities have been shown to increase anxiety among patients and visitors, to reduce staff operational efficiency, and to increase operational costs. There is evidence that wayfinding-oriented interior design features can mitigate these problems, but the robust evaluation of wayfinding design strategies is hindered by the unique nature of each building and the expense of testing different navigational aids. The current study implemented a novel testing approach using virtual reality and EEG data to evaluate the effects of three different interior designs, using altered color patterns, graphics, and architectural features intended to enhance wayfinding in a specific hospital facility. Multiple sources of data including self-reported responses, behavioral metrics, and measurements of neural activity in wayfinding-relevant brain regions were collected. The results indicated that the most extensive wayfinding design was associated with improvements in some orientation behaviors and with greater neurological activation in the brain regions of interest. However, these findings did not translate into improved wayfinding times or reductions in self-reported stress, fatigue, or confusion. The authors discuss the implications of these findings and make extensive recommendations for the future directions of evidence-based pre-construction design testing. The streamlined testing platform and data-analysis approach that was developed in this work can make this evidence-based approach more feasible for other researchers and professional designers, eventually leading to a broad comparative data-set incorporating a wide range of buildings and participants.

1. Introduction

Wayfinding enhancement strategies in interior design—signs, color-schemes, and similar features intended to aid in navigation—can strongly contribute to the comfort and wellbeing of patients, visitors, and staff members in healthcare settings (Carpman, Grant, & Simmons, 1990; Foxall & Hackett, 1994; Nelson-Shulman, 1983; Peponis, Zimring, & Choi, 1990; Ulrich et al., 2008; Zimring, 1990). Unfortunately, these design features are frequently treated as an "afterthought" rather than as an integral part of the architectural design process (Devlin, 2014). The lack of attention to up-front wayfinding design can lead to significant problems in the long term; in a study conducted in 1990, the annual cost of maintaining an ad-hoc wayfinding system in a tertiary-care hospital was calculated to be more than $220,000 per year ($448 per bed per year), and the researchers found that direction-giving by hospital employees other than information staff occupied more than 4500 staff hours per year (Zimring, 1990). Difficulties in wayfinding due to inadequate design features have been shown to be a significant source of stress for hospital patients (Devlin, 2014), as well as a significant burden on hospital employees and an obstacle to operational efficiency (Peponis et al., 1990). In contrast, research has shown that effective hospital wayfinding systems can improve patient experiences, promote the

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efficiency of medical staff, and contribute to better emergency management (Pati, Harvey, Willis, & Pati, 2015; Ulrich et al., 2008).

There is a growing body of research focused on determining the most effective cues for helping people find a path through the physical environment (Levine, 1982; Levine, Marchon, & Hanley, 1984; Ophir, Nass, & Wagner, 2009; Pollet & Haskel, 1979; Sharma et al., 2017; Weisman, 1981). However, logistical factors make it very difficult to carry out any kind of rigorous, comparative studies of wayfinding features in the context of constructed healthcare facilities (Ulrich et al., 2008). Some of the most frequently used wayfinding design strategies in healthcare settings include developing a distinct color scheme for each unit, adding prominent pictograms and recognizable icons, and adjusting architectural features to highlight destinations and facilitate move/stop behavior (Carpman, 1993; Huelat, 2004; Kalantari & Snell, 2017; Passini, Pigot, Rainville, & Tétreault, 2000; Pati et al., 2015; Rooke, Koskela, & Tzortzopoulos, 2010; Ulrich et al., 2008). The relative effectiveness of these different design interventions and the mechanism under which they impact human wayfinding has not been empirically tested to any great extent. Furthermore, the utility of any given wayfinding strategy is likely dependent on the manner in which it is implemented in the overall design of a particular building, which means that the small number of existing research studies in this area may not be readily generalizable to new facility designs.

The current research project addressed the need for an effective pre-occupancy evaluation method that can be used during the design development process to test and optimize specific wayfinding design features in built environments. The goal was to evaluate the ease of wayfinding in specific facility designs, catch potential problems prior to construction, and enable evidence-gathering to support (or refute) more innovative and creative wayfinding design strategies. This was accomplished through the use of an immersive high-resolution virtual reality (VR) platform, which allowed the study of participant behavioral and neural responses during wayfinding tasks under different design conditions. Using the VR approach makes it possible to simply switch out different signs, color-patterns, and other wayfinding features (without incurring any construction costs), thereby evaluating the likely success of these designs for hospital users and tweaking them to remove problem spots.

This approach follows a general call in the design field for the greater use of VR studies as a form of pre-construction testing (Hölscher, Meilinger, Vrachliotis, Brösamle, & Knauff, 2006; Jansen-Osmann, Schmid, & Heil, 2007; Jansen-Osmann & Fuchs, 2006; Jansen-Osmann & Wiedenbauer, 2004; Tang, Wu, & Lin, 2009; Werner & Schindler, 2004). In addition to better isolating design variables for rigorous experimental testing, the VR setting makes it easier for researchers to use physiological sensors that would be unwieldy or distracting (or simply technologically infeasible) in a real-world hospital environment. The collection of physiological data creates an additional layer of empirical feedback about human responses to designs (Banaei, Hatami, Yazdanfar, & Gramann, 2017; Kalantari et al., 2021; Round et al., 2020). Part of the motivation for the current project was to introduce such physiological data into analyses of participant responses during wayfinding tasks, via electroencephalography (EEG) and motion-tracking technology. The collected physiological data can be triangulated against the participants' subjective feedback, and synchronized chronologically to their actions and movements within the VR environment. For example, we can evaluate whether or not a participant looked at a particular sign, how long they looked at it, changes in brain activity while looking at the sign, how quickly and accurately they then moved toward the target destination, and their conscious feedback about the sign's effectiveness.

The successful implementation of physiological and neuroscientific measures in the behavioral sciences has attracted the attention of environmental psychologists who seek to investigate human EEG correlates of spatial navigation (Banaei et al., 2017; Djebbara, Fich, & Gramann, 2021; Lin, Chiu, & Gramann, 2015a, 2015b). In addition to helping researchers better understand the mechanisms underlying wayfinding behavior, physiological and neuroscientific techniques can reveal reactions that users may not be inclined to divulge in feedback surveys (such as feelings of irritation or confusion), or that may not enter users' conscious awareness, or that they may not be able to verbalize (Furl et al., 2018). Spatial orientation is a complex behavior that requires many perceptual and processing capabilities. The use of psychophysiological techniques can help in analyzing these diverse phenomena, and thus lead to improved predictions of users' behavior and interactions with the built environment, compared to research that relies only on behavioral observation and self-reported measures (Banaschewski & Brandeis, 2007; Furl et al., 2018; Plassmann, Venkatraman, Huettel, & Yoon, 2015).

In the current research we conducted a study to evaluate different wayfinding designs, including color patterns, signage enhancements (e.g., pictograms), and architectural features, in a healthcare facility that was being designed and built by our industry partner. The study analyzed self-reported metrics (mental fatigue, stress, and confusion), behavioral metrics (efficient orientation behaviors, and time taken to reach a destination), and EEG features associated with spatial awareness and navigational processing, across three design conditions. Condition A was a baseline design, Condition B added a color scheme to highlight signs and destinations, and Condition C added new architectural features as well as enhanced color and graphics to promote wayfinding. In addition to testing specific hypotheses about these design conditions, the research emphasized the creation of a streamlined data-collection protocol to consistently synchronize the EEG signals with behavioral observations and subjective feedback in the VR system. This protocol and testing platform makes neurological data-collection more accessible, and can empower other researchers and design professionals to use this approach in evaluating their own wayfinding designs in various buildings.

2. Conceptual background and overview of related research

Wayfinding in healthcare facilities can be a challenging task. Hospitals are large and complex, and to most people they are unfamiliar environments (Devlin, 2014; Mollerup, 2009). Furthermore, spatial issues often develop and/or are exacerbated over time as hospitals are renovated and new additions are built (Cheng & Pérez-Kriz, 2014; Mollerup, 2009; Rousek & Hallbeck, 2011). The population that has to navigate through these complicated buildings typically includes a large number of first-time and infrequent visitors, as well as individuals who may be in a state that impairs their judgment, perception, or mobility (from sickness, anxiety, injury, urgency, etc.) (Carpman & Grant, 2016; Berger, 2009). Elderly patients in particular have been identified as encountering negative impacts from wayfinding difficulty in hospital environments, as such experiences can contribute to general cognitive disorientation and an increased likelihood of tripping or falls (Rousek & Hallbeck, 2011).

Prior studies on hospital wayfinding have sought to identify disparate features that may help or hinder individuals in finding their destinations. The factors that have emerged in this literature are fairly intuitive, and include topics such as logical floorplans, clearly understandable directional signs, highly visible landmarks, and architectural designs that prompt movement toward information areas and patient and visitor destinations (Ahn, 2006; Apelt, Crawford, & Hogan, 2007; Baskaya, Wilson, & Özcan, 2004; Bauer & Mayer, 2009; Calori & Vanden-Eynden, 2015; Carpman, 1993; Jamshadi et al., 2020; Huelat, 2004; Mollerup, 2016; O'Neill, 1991; Passini, 1984; Passini et al., 2000; Pati et al., 2015; Rodrigues, Coelho, & Tavares, 2019; Rooke et al., 2010; Scialfa, Laberge, & Ho, 2004; Ulrich et al., 2008; Weisman, 1981). Despite these general areas of agreement, however, wayfinding continues to be a problem in healthcare environments, and designers often struggle with uncertainty about the best way to implement wayfinding features in a particular facility. Specific implementations of wayfinding design are rarely user-tested in any kind of robust fashion prior to their construction (Bubric, Harvey, & Pitamber, 2021; Short, Reay, & Douglas, 2019). Post-occupancy studies evaluating hospital wayfinding designs also relatively rare, and the conclusions in this literature rely primarily on self-reported evidence and behavioral observations, with no clear generalizability beyond the specific design implementations in the buildings that were studied. The expense of conducting such studies, along with the unique nature of each facility, makes it unlikely that extensive rigorous comparative studies of hospital wayfinding strategies will ever be carried out in real-world contexts (Kalantari & Snell, 2017).

We also know very little about the specific mechanisms through which environmental wayfinding cues are processed in the human cognitive system. Many of the seminal studies on wayfinding in urban environments relied on the concept of "mental maps" or "cognitive maps" (Lynch, 1960; Siegel & White, 1975; Toman, 1932), and sought to determine the best way to aid users in building such maps. A cognitive map has been defined as an internal spatial representation of the environment that includes Euclidean information, spatial layout, and structural features relevant to navigation (Kitchin, 1994; Moore & Marans, 2010; Weisberg & Newcombe, 2016). These mental representations are thought to incorporate two types of information: skeletal information at the global scale, and context-rich route information at the local scale (Pati et al., 2015). Siegel and White (1975) linked the concept of cognitive maps to landmarks, which they described as the primary reference points for navigational decisions. Weisman (1981) similarly describes a taxonomy of features for wayfinding that focused on lines of sight and architectural differentiation as a means of promoting the formation of cognitive maps. Much more recently, Carlson, Hölscher, Shipley, and Dalton (2010) developed a theoretical framework for wayfinding that combined the concept of cognitive maps with objective building features and individual skills and strategies. This framework was further refined by Kuliga et al. (2019) argued that the "cognitive map" component should cover a cognitive selection processes that determines which environmental information to encode into short-term or long-term memory. However, the precise neurological correlates of these cognitive maps have not been widely studied.

The overall results from the design literature indicate that wayfinding success in hospitals is likely linked to the structural features of buildings (floor-plans, room shapes, sightlines) as well as to overlaid directional cues (landmarks, signs, color schemes) (Marquardt, 2011). The mutual impact of these factors is reminiscent of Carpman and colleagues' (1985) influential view that architectural design is a combination of environmental affordances (what the structure suggests can occur) and manifest cues (overlaid indications of what should occur). An interesting hospital design study by Vilar, Rebelo, Noriega, Duarte, and Mayhorn (2014) placed environmental affordances in terms of corridor width and brightness in direct competition with manifest cues—signs that directed participants in a non-intuitive direction. The results indicated that visitors in emergency situations tended to rely more strongly on the manifest cues, whereas those arriving for more mundane tasks were more likely to attend to the environmental affordances. Again, little is known regarding the underlying cognitive/neural processes that occur during such wayfinding behaviors, or about how the construction of mental maps is related to other involved neural processes such as decision-making and mobility (Passini, 1996).

In recent years researchers have started to investigate some of these complex neural activities. EEG studies have been able to show that the retrosplenial complex (RSC) is active during wayfinding, though the extent of the activity appears to depend on various contextual factors such as the type of mobility response and the level of active engagement with the environment (Avraamides, Loomis, Klatzky, & Golledge, 2004; Klatzky et al., 1998; Ehinger et al., 2014; Gramann et al., 2010; Lin et al., 2015a, 2015b). In this study, we focused specifically in the occipital cortex during the active simulated navigation in VR. Previous studies demonstrate that naturalistic navigation reveals strong theta synchronization in the RSC during navigation phases that require head movement (Klug & Gramann, 2020), and theta synchronization in parietal regions associated to salient landmark recognition (Rounds, Cruz-Garza, & Kalantari, 2020). A network involving the RSC (Vann, Aggleton, & Maguire, 2009), occipital, and parietal cortices work in translating visual-spatial information into decision making in active navigation settings (Do, Lin, & Gramann, 2021). This experiment was designed specifically to evaluate the influence of design elements in navigation efficiency of participants, for which we selected the visual processing component for further investigation.

Neural activity is often studied in terms of alpha-band desynchronization (i.e., perturbations in neurological signals in the 8–13 Hz frequency range), which is widely regarded as indicative of heightened cognitive processing (Pfurtscheller & Da Silva, 1999). Gramann et al. (2010) analyzed EEG data for participants who were navigating through a virtual tunnel passage and found significant alpha-band desynchronization in parietal and occipital areas. Lin et al. (2015a, 2015b) similarly found perturbations of the alpha-band in the RSC associated with navigational activities. While this prior research overall provides a good indication of relevant brain regions and signal activities associated with navigation, the studies have tended to generalize wayfinding tasks, for example by not making a clear distinction between orientation behaviors, path selection, movement activation, and course-corrections. Furthermore, prior EEG-based studies have not focused on the impact of environmental variables on neurological activation or on the efficiency of wayfinding behaviors. In the current research we examined how interior design alterations intended to help with wayfinding were related to alpha-, beta-, and theta-band activity in occipital areas.

3. Methods and hypotheses

3.1. Facility design conditions

The VR testing environment was based on an actual healthcare facility that was being designed by our industry partner. This facility was the Corner Brook Acute Care Hospital, located in Corner Brook, Newfoundland, Canada, and it was in the design development phase during the time of this study. Two specific parts of this large hospital complex were selected to be used in the study, and design details about those portions of the facility were imported into our virtual testing platform. Drawing from the prior literature of healthcare wayfinding design—particularly the concepts of environmental affordances and manifest cues (Devlin, 2014)—we adjusted the virtual environment to create three distinct wayfinding design conditions:

- Condition A (Baseline): Standard signage, and minimal contrast between the destination, the signage, and the overall environment.
- Condition B (Enhanced Color): Added color to highlight destinations and to increase the contrast of signage against the overall environment. In this condition all destination areas (e.g., elevators, reception desks) used contrasting colors to help them stand out from their surroundings. These types of color cues have been frequently used in wayfinding designs; they are theorized to improve "salience" (thus drawing attention) and to prompt the formation of "anchor points" in cognitive maps (Jansen-Osmann & Wiedenbauer, 2004; Pati et al., 2015).
- Condition C (Enhanced Color, Graphics, and Architectural Features): This condition included the same color changes as Condition B, along with added architectural features and graphics. These features were designed to further highlight destinations and signs, prompt or deter movement, and signal functional changes between different areas of the building (Pati et al., 2015). For example, changes in ceiling height and the addition of wood pattern were used to draw participants' attention to destination areas, while recognizable graphics linked signage to destination decors **(Figs. 1 and 2).**

In addition to testing some of the wayfinding design strategies that are most commonly recommended in the design literature, our goal in

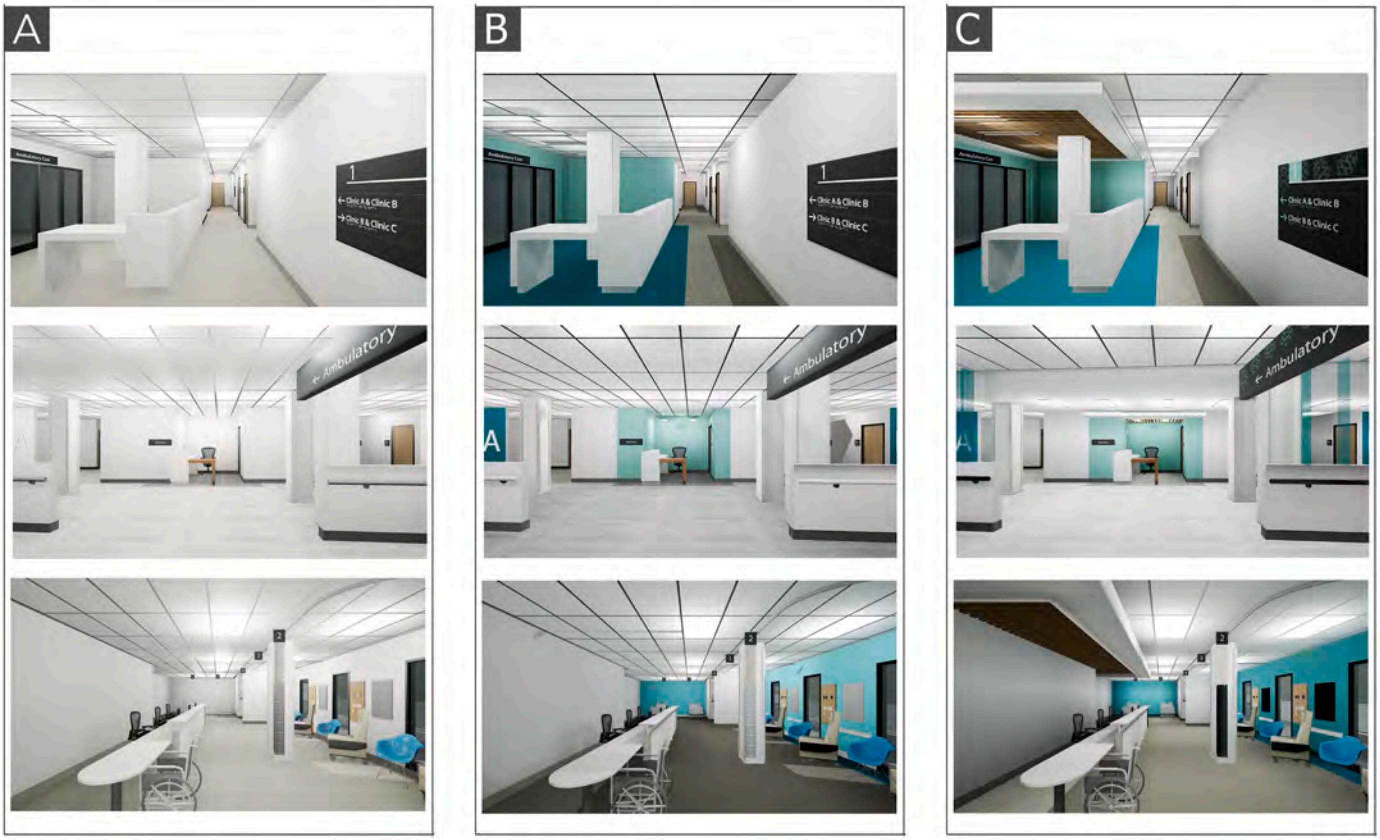


Fig. 1. Screen-captures from the VR environment showing examples of the wayfinding design features in the Baseline Condition (A), the Enhanced Color Condition (B), and the Enhanced Color, Graphics, and Architectural Features Condition (C). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

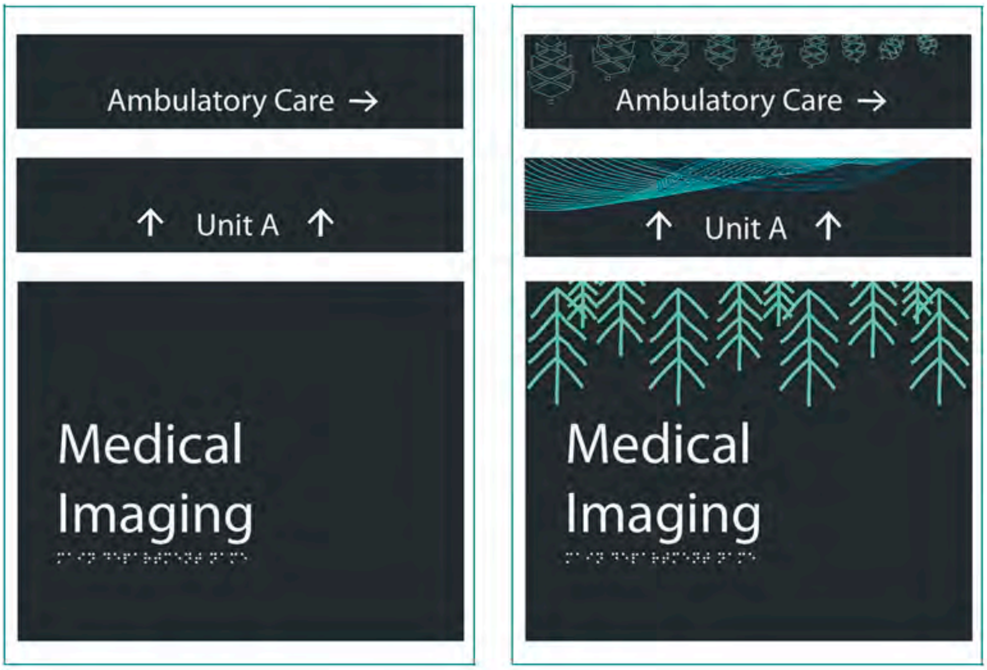


Fig. 2. Example of the thematic graphics that were added to signage in Condition C (at right), compared to Condition A (at left).

dividing up the experimental conditions in this way was to analyze the use of color alone vs. color in combination with graphics and architectural features. The latter design strategies that were added in Condition C require a much higher construction cost compared to using color changes alone. Thus, we wanted to determine if these additions of graphics and architectural features would provide additional wayfinding benefits sufficient to justify their financial cost.

3.2. Hypotheses

Participants in the study were randomly assigned to one of the three design conditions and were asked to complete a series of wayfinding tasks in the VR environment while behavioral and physiological data was collected synchronously. The data were statistically compared between the three design conditions to test the study hypotheses:

H1. Behavioral metrics related to successful wayfinding will be significantly higher among participants who complete the tasks in the hospital design with enhanced color (Condition B), compared to the baseline design (Condition A). These behavioral metrics include:

H1a. Lower self-reported mental fatigue, stress, and confusion.

H1b. Less time required for wayfinding task completion.

H1c. More efficient and accurate orientation behavior and the correct choice of direction.

H2. Behavioral metrics related to successful wayfinding will be significantly higher among participants who complete the tasks in the hospital design with enhanced color, graphics, and architectural feature condition (Condition C), compared to the other two design conditions (Conditions A and B). These behavioral metrics include:

H2a. Lower self-reported mental fatigue, stress, and confusion.

H2b. Less time required for wayfinding task completion.

H2c. More efficient and accurate orientation behavior and the correct choice of direction.

H3. Neural patterns associated with spatial awareness and navigational processing (e.g., alpha, beta, and theta band EEG in occipital areas) will be heightened when participants complete the tasks in the hospital design with enhanced color condition (Condition B), compared to the baseline design (Condition A).

H4. Neural patterns associated with spatial awareness and navigational processing (e.g., alpha, beta, and theta band EEG in occipital areas), will be heightened when participants complete the tasks in the hospital design with enhanced color, graphics, and architectural feature (Condition C), compared to the other two design conditions (Conditions A and B).

3.3. Virtual reality development

The creation of the virtual hospital environment was carried out by importing architectural design documents into Epic Games' Unreal Engine (www.epicgames.com). Most of the modeling and UV-mapping took place within Autodesk 3ds Max (www.autodesk.com). The Unreal Engine uses Blueprint scripting, allowing for a quick learning curve on the part of researchers and designers who may want to expand or replicate our work. All of the front-end interaction and user interactivity in our testing environment also leverages the Blueprint platform.

The camera height was fixed at 1.70 m (corresponding to the average human eye-height), but participants were otherwise allowed to move freely throughout the environment and to alter the camera angle (looking up or down). Custom interactive widgets allowed self-reported Likert-scale responses to be collected directly in the VR environment. The hospital designs were presented to study participants using an HTC Vive Pro head-mounted display, through a gaming desktop with a resolution of 1440 × 1600 pixels. The Vive Pro provides a 110-degree horizontal field of view with a 90 Hz refresh rate, and can be adjusted for participants with different inter-pupillary distances. Some additional examples of two-dimensional screen captures from the virtual environment are shown in Fig. 3.

3.4. Participants

All participants gave informed written consent prior to the

Fig. 3. Screenshots from the participants' view in the virtual environment. The bottom two images show our integrated Likert-scale widgets that simplify the collection of subjective feedback. The integrated software platform also helps to keep track of the duration of the wayfinding tasks, the position of the user in the environment, and the times at which the user looks at certain signs or other selected environmental features.

Table 1
Inpatient wayfinding tasks.

Task	Origin	Destination	Condition A	Condition B	Condition C
Pre-task	"Imagine a beloved member of your family is going through a high-risk surgery, and you are late for the patient visit. You are in a big hospital and you want to visit your family member as quickly as possible. Please try your best to complete the following tasks as quickly as possible."				
Task 1	Hospital main entrance	Information desk	Information desk with a sign indicating "Information" and the name of hospital.	Condition A + the information desk background was highlighted in blue.	Condition B + the information desk area was defined with a lower ceiling and wooden rafters.
Task 2	Info desk	Elevator	The shortest path included walking through the main entrance hallway with furniture on the left side, then seeing the sign for "Ambulatory Care" with directions to turn right at the first intersection, and then seeing a T-shape intersection with the sign "Medical Imaging" in front. After turning right participants could see the sign of "Main Elevator" at the end of the hallway.	Condition A + the right side of the main hallway used blue tempered glass, and key signs including "Medical Imaging" and "Main Elevator" had a blue accent color added. The background for the large icon of "Floor 1" was also highlighted in blue.	Condition B + the ceiling of the sitting area was lower, thus better defining the walking area versus sitting area. All signs in the route had distinguishable graphic patterns. The destination ceiling area was defined by lower ceiling with a rectangle shape.
Task 3	Elevator	Nurse station in Unit A	The shortest path included pressing a button to go up, leaving the elevator and seeing a white wall with the icon "Floor 5," seeing T-shape intersections on both the right and left, seeing a sign with information about Unit A, and going through the corresponding corridor to reach the destination at a center of an H-shape intersection with a sign "Unit A – Care Station."	Condition A + the first wall when individuals come out of the elevator was highlighted with a dark blue color, and the border of the care station was also defined with a blue color in the carpeting and walls.	Condition B + all signs had distinguishable graphics, and the background wall with the floor number and Care Station decor had similar graphics. The open area in front of the elevator and the Care Station were also better defined with a lower ceiling and wooden rafters.
Task 4	Nurse station in Unit A	Patient room #5A-511	The shortest path included reading the sign listing patient room numbers, taking the appropriate corridor, and finding the appropriate room in the corridor.	Condition A + all entrances of the patient rooms were highlighted in blue, and all patient room number signs had a blue bar underneath.	Condition B + the patient room areas were better defined with lower ceilings.
Task 5	Patient room #5A-511	Elevator	Same environment as described in Tasks 3 and 4.		
Task 6	Elevator	Hospital main entrance	Same environment as described in Tasks 1 and 2.		

Table 2
Outpatient wayfinding tasks.

Task	Origin	Destination	Condition A	Condition B	Condition C
Pre-task	"Imagine that you are feeling ill and need immediate treatment. You just want to find the fastest way to get to the room where you will complete your medical exams. Please try your best to complete the following tasks as quickly as possible."				
Task 7	Hospital main entrance	Ambulatory care reception desk	Same environment as described in Tasks 1 and 2. After seeing the sign "Ambulatory Care" individuals will turn right and see another hallway with the sign "Ambulatory Care Reception Desk" in front of them.	Condition A + the reception area was highlighted using blue color.	Condition B + the reception area had a lower wooden rafter ceiling defining the border of the area.
Task 8	Ambulatory care reception desk	Treatment chair #4 in Section C	The shortest path included seeing three corridors with the large icons "A," "B," and "C" on the walls, then going through the appropriate hallway past room number signs on both sides, passing an intersection with information about Clinic C, then reaching the appropriate chair.	Condition A + all relevant signs were highlighted in blue, the reception area at clinic C had highlighted blue wall decor, and the background for all treatment chairs included blue highlights.	Condition B + all relevant signs included a distinguishable graphic pattern, and the reception desk in clinic C had a lower wooden rafter ceiling.
Task 9	Treatment chair #4 in Section C	Back to the ambulatory care reception desk	Same environment as described in Task 8.		
Task 10	Ambulatory care reception desk	Cafeteria cashier	The shortest path included seeing the sign in the front corridor describing the direction to Medical Imaging, Cafeteria, and Ambulatory Care, then turning left, reaching a T-intersection, and seeing the cafeteria located to the right.	Condition A + all relevant signs were highlighted in blue, and the cafeteria cashier area was also highlighted in blue.	Condition B + the cafeteria cashier area was defined by lower ceiling and the relevant signs included distinguishable graphics.
Task 11	Cafeteria cashier	Hospital main entrance	The shortest path back to the hospital entrance included reaching the main hallway then following a short corridor to the information desk, then turning to the right.	Condition A + the information desk background was highlighted in blue.	Condition B + the information desk area was defined with a lower ceiling and wooden rafters.

experiment, and the overall study protocol was approved by the Institutional Review Board at Cornell University. We conducted an a-priori analysis of the required sample size using G*Power (Version 3.1.9.3.). For an effect size of dz = 0.50, a 0.01 probability of error, and a power of 0.90, the necessary sample size was 75. The effect size of dz = 0.50 was estimated based on Kuliga and colleagues' (2019) results for wayfinding performance. Accordingly, a total of 81 research participants were recruited using a convenience sampling method (word-of-mouth and announcements on departmental e-mail lists). These participants were divided among the three environmental conditions, using a randomized between-subjects study design. Ten of the participants had to be excluded due to technical problems during the wayfinding tasks, and an additional 8 participants had to be excluded due to technical problems in the data-recording (missing/incomplete data and excessive motion artifacts). This was a greater attrition rate than we had expected, but with the remaining 63 participants distributed fairly evenly among the three conditions (21 in Condition A, 23 in condition B, and 19 in Condition C), we were still able to achieve a statistical power of 0.75 (dz = 0.50, $\alpha = 0.01$).

The participants ranged in age from 18 to 55 years ($M = 20.72$, $SD = 4.57$). The majority were undergraduate university students (n = 52), with a smaller number of graduate students (n = 8) and faculty members (n = 3). In terms of their gender, 38 participants reported as female, 23 reported as male, and 2 preferred not to answer. Regarding ethnicity, 26 participants reported as Asian, 8 as Latinx or Hispanic, 1 as Black, and 28 as White. All of the participants were associated with Cornell University, representing the departments of Design, Psychology, Computer Science, Music, Biology, Marketing, Communications, Architecture, Human Development, Policy Analysis and Management, Development Sociology, Hotel Administration, Economics, Mechanical Engineering, Food Science, City Planning, Nutritional Sciences, and Chemistry.

We collected a variety of background data from the participants, which were not analyzed as prospective moderator variables but are included here as an overall snapshot of the study sample. A majority of the participants (n = 43, 68%) reported that they had experienced a hospital environment within the previous six months, either as a patient or as a visitor. On a Likert scale (1 = not at all; 10 = extremely), participants expressed moderate familiarity with hospital environments ($M = 5.14$, $SD = 2.59$), and indicated that such environments were moderately stressful and confusing ($M = 4.83$, $SD = 2.34$). Post-experiment surveys indicated that the participants on average were reasonably comfortable when wearing the VR headset ($M = 3.22$, $SD = 1.70$; 1 = comfortable, 10 = uncomfortable) and the physiological sensors ($M = 2.96$, $SD = 1.83$; 1 = comfortable, 10 = uncomfortable). Participants also reported that they felt the VR environment was reasonably realistic in both the inpatient areas ($M = 6.17$; $SD = 2.12$; 1 = not similar to reality, 10 = very similar to reality) and the outpatient areas ($M = 5.91$; $SD = 1.99$; 1 = not similar to reality, 10 = very similar to reality). In regard to sleep levels, 35% percent reported getting eight or more hours of sleep the previous night, 46% reported six to 7 h of sleep, and 19% reported four to 6 h of sleep. None of the participants were aware of having current neurological conditions, and none reported the recent use of psychoactive substances (excluding caffeine).

3.5. Procedures

All of the experiment sessions took place at the same physical location in the Design and Augmented Intelligence Laboratory, at Cornell University. Sessions were conducted for one participant at a time. During each session, after providing consent, and filling the demographic survey, the participant was carefully fitted with the physiological sensors by trained research team members. To establish resting-state data, after sensor fitting and quality checking the participant was asked to sit quietly facing a blank computer monitor for 1 min, and then to sit quietly with eyes closed for 1 min. Once the resting-state data were

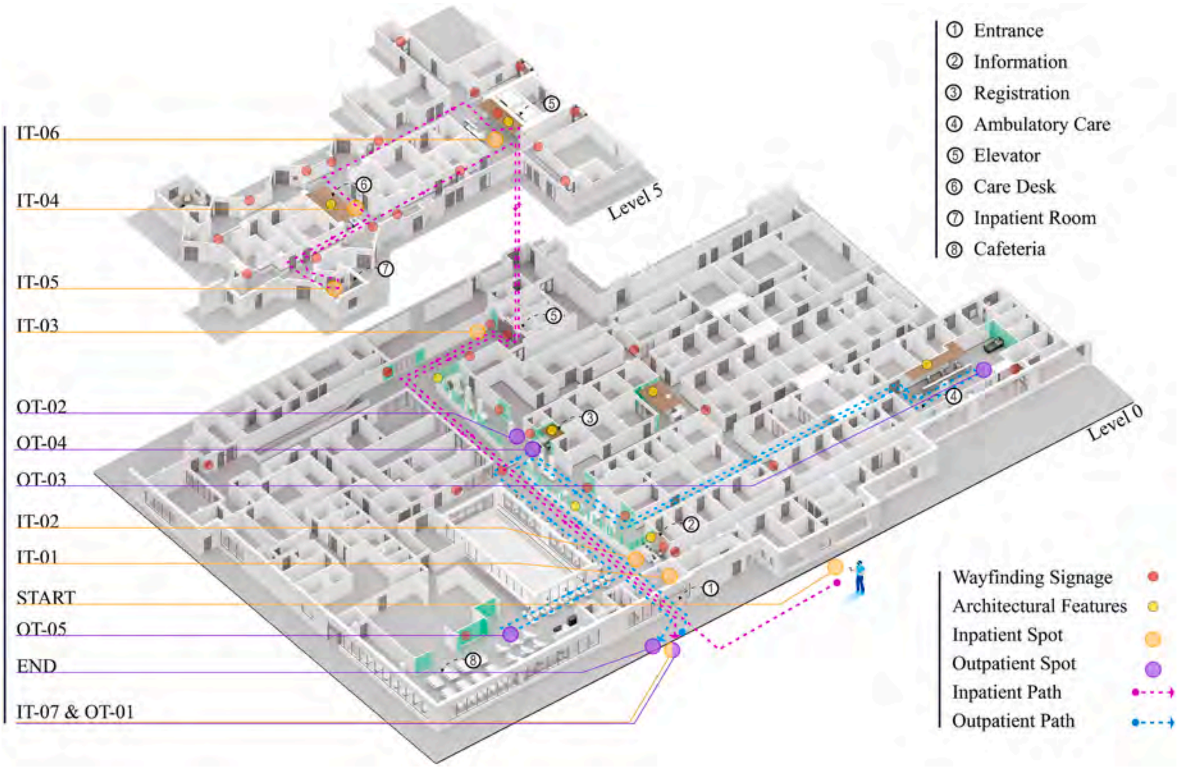


Fig. 4. Navigational inpatient tasks (IT) and outpatient tasks (OT) as shown on hospital plans.

collected, the participant was fitted with the VR headset and entered the virtual environment. An initial 5-min "free" period in the VR allowed the participant to become familiar with the navigational tools and to explore the platform. Two blocks of navigational tasks were then assigned: an "inpatient" block consisting of six wayfinding tasks, and an "outpatient" block consisting of five wayfinding tasks. All participants completed the same navigational tasks in the same sequence. To promote greater immersion, each task-series began with the presentation of a written scenario, asking the participant to imagine themselves in a moderately stressful medical situation, followed by doing navigation tasks and answering the self-report questions in the immersive virtual environment. In total participants spent around 20–30 min in the simulation, completing the navigation tasks and answering the questions. The total time for the whole experiment was around 90–120 min including the EEG set-up and filling out a short survey before and after the VR simulation (**Table 1**, **Table 2**, **and Fig. 4**).

3.6. Data collection

A non-invasive EEG cap was used to record electrical brain activity. The EEG signals were recorded at 512 Hz for 128 channels, using the Actiview System (BioSemi Inc., Amsterdam, Netherlands) with Ag/AgCl active electrodes (Fig. 5). This system uses a common mode sense (CMS) active electrode and a driven right leg (DRL) passive electrode (Biosemi EEG, 2021), which form a feedback loop and drive the average potential (the Common Mode voltage) as close as possible to the ADC reference voltage, effectively reducing the line noise by a factor of 100. The CMS electrode was used as the recording reference.

We developed a custom technique to synchronize physiological, self-reported, and behavioral data as participants completed the wayfinding tasks. The design of the VR environment included a small box that was out of the participants' field of view but could be seen in the observing monitor of the researcher's computer and the associated video recording. This box changed color according to events happening during the experiment, for example when the participant's gaze crossed a designated signage area in close enough proximity for the sign to be legible. To code this, a "gaze collision area" was defined in the VR file 10% larger than the size of the sign. When participants were within reading distance (between 4 and 7 m, depending on the sign's font size), the trigger for that sign was activated and it began to monitor for gaze information. The event markers were then activated if the center of the VR field-of-view continuously overlapped with the sign's collision box for more than 1500 ms. (This time limit was defined based on pilot testing to distinguish sign-views from momentary overlaps due to unrelated head movements.) The VR log file automatically recorded the number of signs seen, the identity of the signs seen, the duration of each sign view, and the time stamp for each view, all synchronized with the EEG data. At the end of each experiment, this log was hand-checked. A member of the research team went through the screen-recording video and verified each marker to confirm that it represented an actual sign-seen event, and also to check for any sign-seen events that may have been missed. Questionable cases were treated as non-events. This system was used to extract all behavioral event markers, including not only sign views but also direction changes, stationary periods, and task completion. The resulting data was exported into an MS Excel spreadsheet for further analysis. The use of Camtasia (www.techsmith.com) video-editing software allowed the researchers to confirm event markers with millisecond accuracy.

3.7. Behavioral data analysis

We established an exploratory behavioral analysis for session events, which included: (a) the number of times a participant started traveling in the wrong direction, (b) the total time spent traveling in the wrong direction (in seconds), (c) the number of times the participant viewed a sign, (d) the total time spent viewing signs, and (e) the number of times participants traveled in a correct direction after viewing a sign. We also calculated a relative variable of (f) "sign efficacy" as the number of times participants traveled in the correct direction after viewing a sign divided by the number of times the participant viewed a sign. The selection of these factors as wayfinding behavioral metrics was based on common practice in the research literature, under the assumption that they are indicative of the successful formation and use of cognitive maps (Carlson et al., 2010; Kuliga et al., 2019). Self-reported data in terms of fatigue level, stress level, and confusion level were provided by the participants at the end of each task using the integrated Likert-scale widgets ("Please indicate your stress level," "Please indicate your mental fatigue level," and "How confused did you feel during this task," all on a scale of 1 = "not at all" to 10 = "extremely"). These behavioral and self-reported metrics were statistically compared across the different design conditions A, B, and C.

3.8. EEG data analysis

Neural signals were aggregated and statistically compared across the three design conditions for the time-periods when participants were viewing navigational signage and making decisions about their next move. We extracted 5-s EEG data epochs from all participants, from 1 s prior to 4 s after observing wayfinding signs (i.e., all "sign seen" events in each design condition). The motivation for selecting 5-s epochs around sign-views was to ensure that we were evaluating neural activity during wayfinding cognition. The average time for participants actively looking at each signage was 2.35 s ($SD = 0.96$). Hypothetically, the sign-view events could represent the visual perception of environmental cues, information processing, and motor execution actions right after seeing a sign. Sign-views are indisputably part of the wayfinding process, and since the signs were adjusted between each design condition (A, B, and C), we can be certain that sign-views represent an interaction with the altered environmental variables. Overall, each participant experienced an average of 24 sign-view events during the experiment (including all inpatient and outpatient tasks).

Brain dynamics were analyzed using independent component analyses (ICA) on high-density EEG data (see Appendix A). The independent components (ICs) were projected to their equivalent dipole location within a boundary element head model based on the MNI (Montreal Neurological Institute, Quebec, Canada) brain. Scalp EEG data at the electrode level records the sum of projected activities from multiple sources in the brain, including potential non-brain signals. Performing ICA allowed us to assess the brain dynamics at effective brain sources (Makeig et al., 2002; Klug & Gramann, 2020), in areas hypothesized to be involved in the experimental task. A relevant IC cluster, obtained through 10,000 optimization iterations for the region of interest (Gramann, Hohlefeld, Gehrke, & Klug, 2021; Do et al., 2021), was localized to Brodmann Area 18 (BA18), a part of the brain associated with the processing of visual information. ICs clustered to the visual association area BA 18, were compared between the different design conditions across all participants.

Log-scaled EEG data for this cluster were evaluated using one-way ANOVA to compare the different design conditions at a significance level of $p < .05$ and $p < .01$ for five EEG frequency bands: delta (1–4 Hz), theta (4–7 Hz), alpha (8–12 Hz), beta (13–30 Hz), gamma (30–40 Hz) (Kontson et al., 2015). Following a significant one-way ANOVA test, the post-hoc Tukey HSD method for multiple comparisons was applied to evaluate which frequency bands per condition were significantly different, using the *multcompare* function of the MATLAB Statistical Toolbox.

Event-related spectral perturbations (ERSPs) for the ICs in the selected occipital cluster were calculated using the *newtimef* function in EEGLAB. The significance levels of the ERSP were tested by bootstrap resampling method, with 3000 permutations. Statistical significance for contrast between design condition pairs were obtained by using EEGLAB's default unpaired t-tests at a significance threshold of p-value $< .003$; Bonferroni-corrected from $p < .05$ and fifteen comparisons (three design-pair comparisons and five frequency bands). Statistically significant values were plotted and analyzed.

4. Results

4.1. Self-reported stress, mental fatigue, and confusion (H1a & H2a)

The self-reported data were averaged across all wayfinding tasks for each participant and compared among the three design conditions. (For example, the mental fatigue ratings provided by all participants after all tasks in design Condition A were averaged together.) One-way ANOVAs were then conducted to compare the different design conditions. No significant differences were found in the reported levels of stress, mental fatigue, or confusion between conditions A, B, and C. Therefore, H1a and H2a were not supported.

4.2. Time required for task completion (H1b & H2b)

The time required for task completion was averaged across all wayfinding tasks in each design condition. One-way ANOVAs were used to compare the different design conditions. No statistically significant differences were found for task completion time. Based on these findings, H1b and H2b were not supported.

4.3. Orientation behavior and correct choice of direction (H1c &H2c)

One-way ANOVAs were used to compare the behavioral metrics

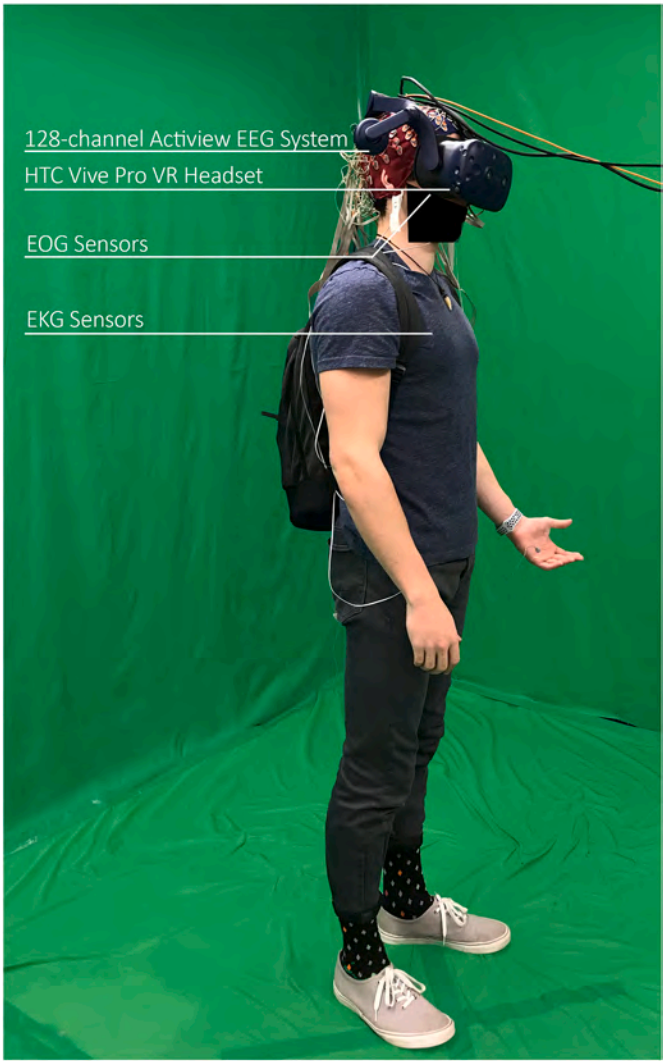


Fig. 5. A study participant wearing the physiological sensors and VR display helmet.

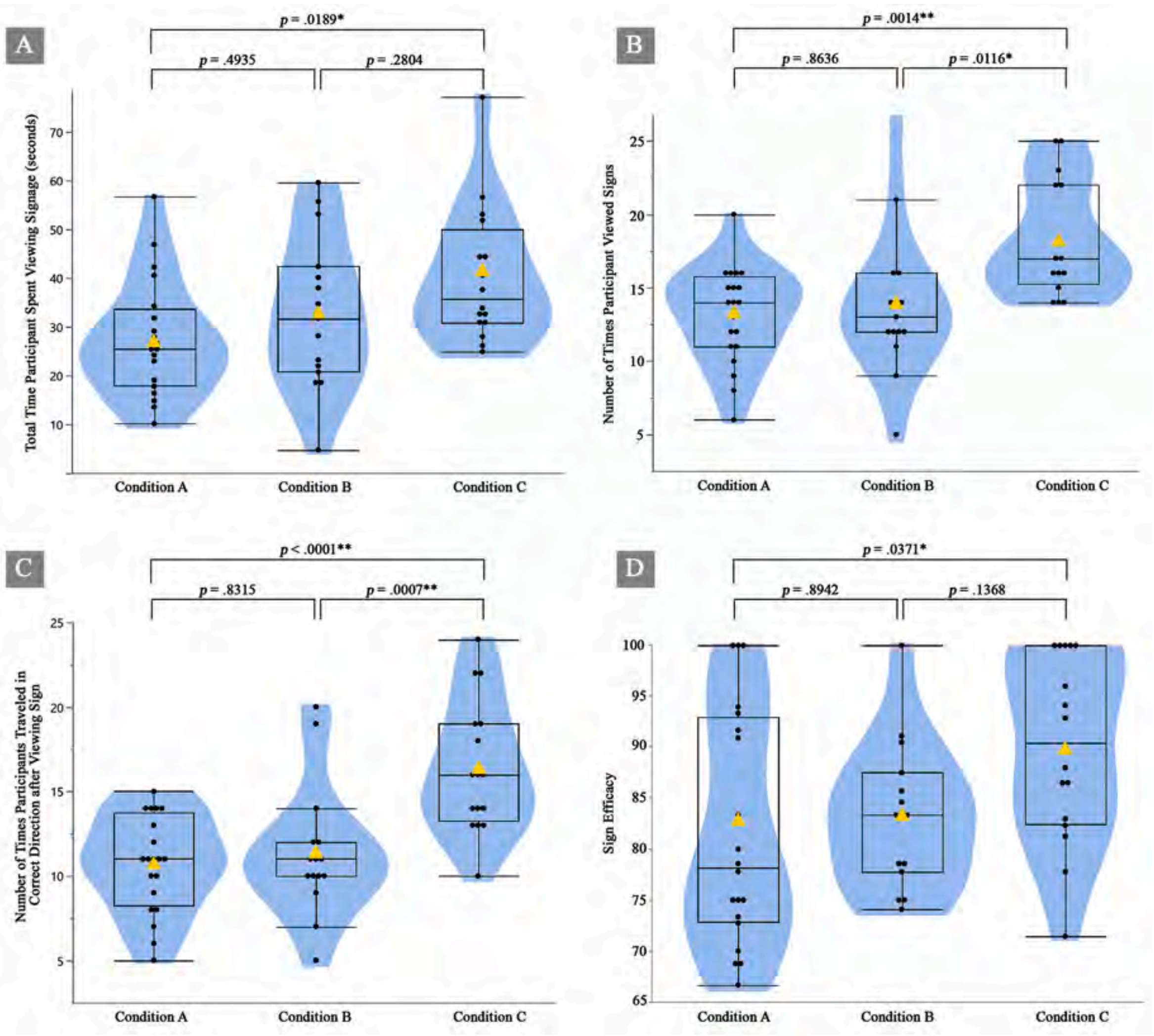
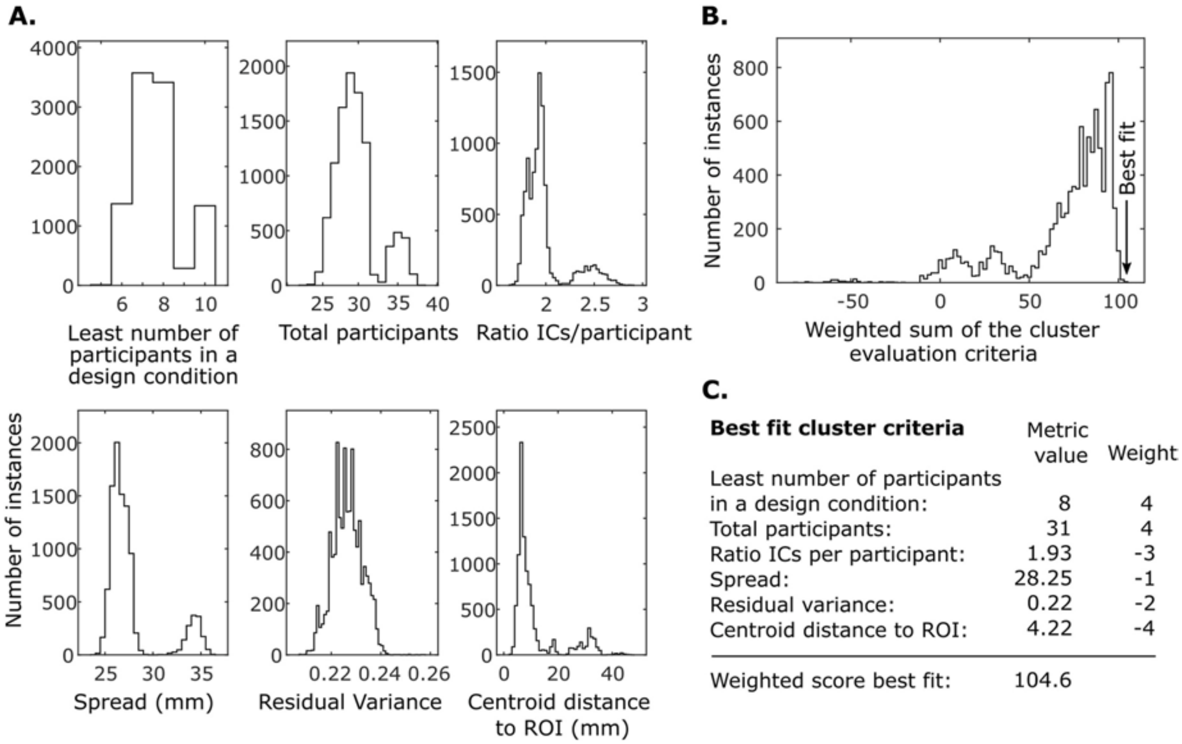


Fig. 6. Results of Tukey HSD tests for (a) the amount of time participant spent viewing signs, (b) the number of times participants viewed signs, (c) the number of times participants traveled in the correct direction after viewing signs, and (d) the "sign efficacy" (number of times participants traveled in the correct direction after viewing a sign divided by the number of times the participant viewed a sign). Design Condition C showed significant advantages over the baseline Condition A in all of these categories, while Design Condition B did not. Yellow triangles show the mean. (*$p < .05$; **$p < .01$). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

across design conditions A, B, and C. No significant differences were found for the overall number of times participants started traveling in the wrong direction, or for the total time spent traveling in the wrong direction. However, the number of times that participants traveled in the *correct* direction *after viewing a sign* was significantly different across the three conditions (F (2, 48) = 13.15, $p < .01$, $\eta^2_p = .35$). Post-hoc results using the Tukey HSD test indicated that participants in Condition C ($M_C = 16.43$, $SD_C = 3.91$) were significantly more likely to orient themselves in a correct direction after viewing a sign, compared to participants in Condition B ($M_B = 11.40$, $SD_B = 3.90$, $p < .01$) and Condition A ($M_A = 10.70$, $SD_A = 2.86$, $p < .01$). There were no significant differences in this variable when comparing between Condition B and Condition A. This finding seems to suggest that adding color highlights was not enough to increase participants' wayfinding success after viewing a sign, but that the combined effect of enhanced color, graphics, and architectural features together improved the outcomes of navigational choices after participants stopped to read a sign.

The number of times that participants viewed signs was significantly different across the three design conditions (F (2, 48) = 7.78, $p < .01$, $\eta^2_p = .24$). Post-hoc results using Tukey HSD test indicated that participants in Condition C ($M_C = 18.25$, $SD_C = 3.87$) viewed significantly more signs compared to those in Condition B ($M_B = 13.86$, $SD_B = 5.05$, $p < .05$) and Condition A ($M_A = 13.15$, $SD_A = 3.31$, $p < .01$). The same pattern held in regard to the total time that participants spent viewing signs (for the ANOVA, F (2, 48) = 3.96, $p < .05$, $\eta^2_p = .14$). Post-hoc results using Tukey HSD test showed significantly higher total sign-viewing time in Condition C ($M_C = 40.33$, $SD_C = 13.86$) compared to Condition A ($M_A = 27.41$, $SD_A = 11.88$, $p < .05$). However, comparisons of sign-viewing time between Condition C vs. Condition B and Condition B vs. Condition A showed no significant differences. Overall, these results indicate that graphics and architectural features (Condition C) were important in drawing building users' attention to navigational signs, and that better color alone did not accomplish this purpose.

Finally, the analysis of the "sign efficacy" variable using the one-way ANOVA test showed significant differences across the three conditions (F (2, 48) = 3.50, $p < .05$, $\eta^2_p = .12$). The post-hoc Tukey HSD test indicated that the wayfinding signs in Condition C ($M_C = 89.96$, $SD_C = 9.21$) were significantly more efficient compared to Condition A ($M_A = 81.72$, $SD_A = 11.43$, $p < .05$). Comparisons of Condition C vs. Condition B and Condition B vs. Condition A showed no significant differences. These results again indicate that the enhanced color, graphics, and architectural features added in Condition C helped to improve navigational



Best fit cluster criteria	Metric value	Weight
Least number of participants in a design condition:	8	4
Total participants:	31	4
Ratio ICs per participant:	1.93	-3
Spread:	28.25	-1
Residual variance:	0.22	-2
Centroid distance to ROI:	4.22	-4
Weighted score best fit:	104.6	

Fig. 7. The EEG independent component cluster selection was based on six weighted criteria. The images here show (a) the distribution of cluster selection criteria among 10,000 random initializations, (b) distribution of the weighted sum of the six cluster evaluation criteria, and (c) the score of the best fit cluster on the basis of the specified criteria and corresponding weights.

effectiveness in a way that better color alone did not accomplish. The hypothesis H1c was not supported by these results, but H2c was supported (Fig. 6 and Supplementary Table 3).

4.4. Neural signatures of spatial awareness, recall, and cognitive engagement (H3 & H4)

The optimal IC cluster that we identified was located with a centroid at Talairach coordinates [$x = -21.7$, $y = -88.7$, $z = 10.6$], in Brodmann Area 18 (see Appendix A). This cluster contained data from at least 8 participants in each design condition, including 31 total participants (14 from Condition A, 9 from Condition B, and 8 from Condition C) (Fig. 8b), with an overall average of 1.93 ICs per participant. There was a 28.25 mm average distance of each IC to the centroid (spread), and a 22% average residual variance. The centroid was located 4.22 mm from the pre-defined region of interest (ROI) (Fig. 7c). The positive value-sided skewness of the weighed sum score from the individual criteria (Fig. 7a and b) indicates that the automatic clustering algorithm found consistently at least one IC cluster around the original ROI.

The optimal cluster selection only represents a marginal increase in the specified criteria, further validating the robustness of the IC characteristics found around the ROI. The power spectrum density, converted to dB through $10*\log10(\mu V^2)$, in the selected cluster showed differences in power spectral density among the three design conditions for all frequency bands: delta $F(2, 753) = 34.45$, $p < .001$, $\eta^2_p = .08$; theta $F(2, 753) = 23.31$, $p < .001$, $\eta^2_p = .06$; alpha $F(2, 753) = 15.22$, $p < .001$, $\eta^2_p = .04$; beta $F(2, 753) = 11.09$, $p < .001$, $\eta^2_p = .03$; gamma $F(2, 753) = 10.40$, $p < .001$, $\eta^2_p = .03$. There was consistent broadband desynchronization (less power) in design conditions C, compared to the baseline design Condition A (Fig. 8a).

In this averaged power-spectrum density across the epoch time, there were no significant differences between conditions A and B [e.g. beta band statistics (dB): $M_A = -19.34$, $SD_A = 0.30$, $M_B = -20.62$, $SD_B = 0.38$, $p = .34$], which does not support H3.

There was a statistically significant difference across all frequency bands between Condition A and Condition C [e.g. beta band statistics (dB): $M_A = -19.34$, $SD_A = 0.30$, $M_C = -21.96$, $SD_C = 0.38$, $p < .001$], supporting H4.

A significant difference was found only in the delta and theta band when comparing Condition B with Condition C (Fig. 8c) [e.g. theta-band statistics (dB): $M_B = -20.35$, $SD_B = 0.38$, $M_C = -22.40$, $SD_C = 0.39$, $p = .014$], supporting H4.

The temporal dynamics of neural features can provide additional information about wayfinding success. To examine changes in the EEG signals over time, the power spectrum dynamics of the selected IC cluster were analyzed through 5-s time epochs associated with gazing at specific wayfinding signs in the VR hospital environment. As shown in Fig. 9, statistically significant broadband desynchronization was seen in the comparison between Condition B vs. the baseline Condition A (particularly in the frequency range of 25–35 Hz), and also in the comparison between Condition C vs. the baseline Condition A (particularly at 1–12 Hz and 25–35 Hz). The comparison between Condition C vs. Condition B shows a much smaller area, and lesser intensity, of statistically significant desynchronization, located mostly in the 1–8 Hz range.

The analysis of design Condition C, when compared against both conditions A and B, shows a pattern of theta-band desynchronization that begins about 1s after looking at a wayfinding sign, continues until about the 2s mark, then disappears for about half a second, before returning again at 2.5s. The ERSP comparisons between conditions show statistically significant differences in the intensity of neural responses between the three design conditions, supporting both H3 and H4. These differences occur in the occipital cortex in the form of beta-band desynchronization between Conditions A and B (H3), and additional oscillating theta-band desynchronization between Conditions A and C (H4).

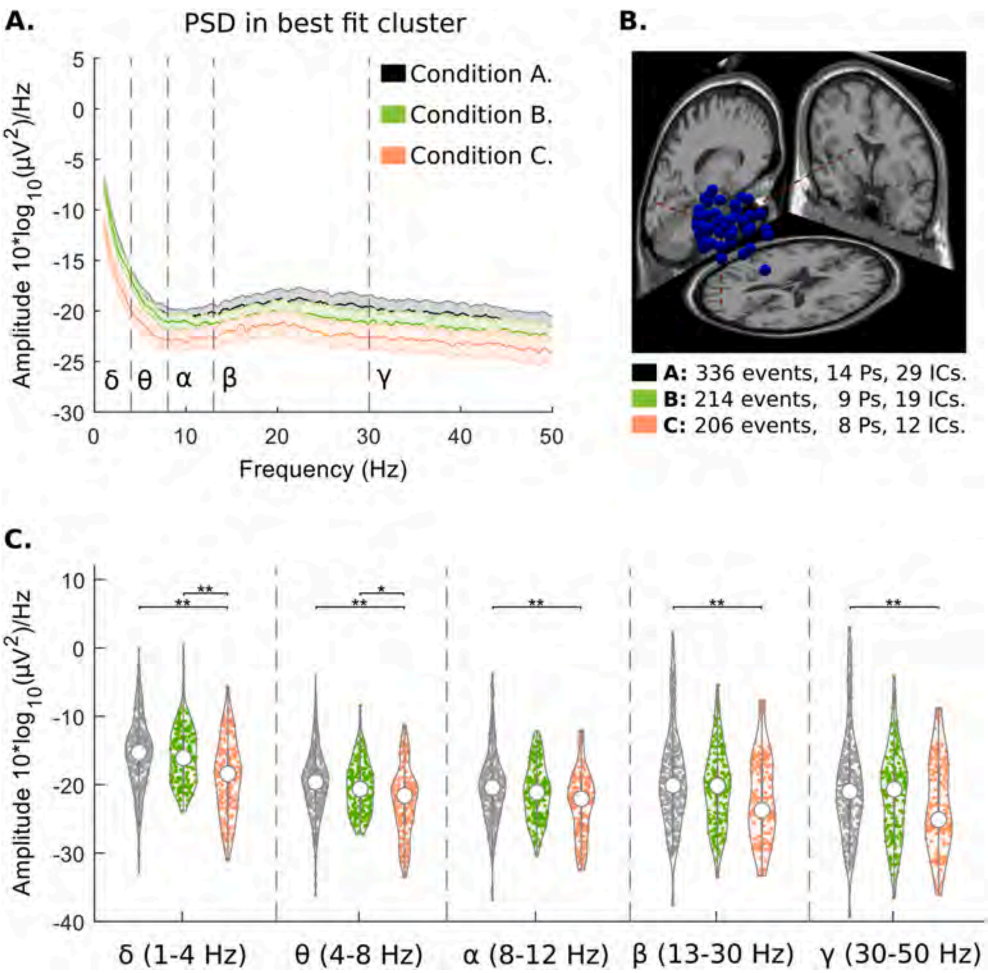


Fig. 8. Attributes of the selected occipital lobe independent component cluster: (a) comparison between design conditions for power spectral density with 99% confidence intervals, (b) cluster dipoles and distribution among participants, and (c) comparison between design conditions for frequency band-power distribution, Tukey HSD statistical significance for: **p < .01, *p < .05.

5. Discussion

The findings in this study regarding self-reported and behavioral data were mostly inconclusive, with a few notable exceptions. The participants did not report any significant differences in their stress levels, mental fatigue levels, or confusion levels after completing wayfinding tasks in the different hospital designs. There were also no significant differences in the time that was required for them to complete the wayfinding tasks. The data did indicate, however, that some orientation behaviors when viewing signs were more effective in design Condition C (enhanced color, graphics, and architectural feature) compared to Condition B (enhanced color) and Condition A (baseline). The participants who completed navigational tasks in Condition C looked at navigational signs more often and for longer periods of time, and were more likely to proceed in the correct direction after viewing a sign, compared to those who navigated through the other two hospital designs.

We speculate that our navigational tasks may not have been difficult or extensive enough to show the effects of the design variations on the stress/fatigue/confusion variables and on the time required for wayfinding. Furthermore, features of the VR environment, such as the absence of noise and the lack of other people in the scenarios, may have also contributed to making wayfinding tasks easier to complete than they would be under real-world conditions. It is worth considering that even slight improvements in wayfinding experiences, which are suggested by the findings of improved orientation behaviors in Condition C, would have a long-terms benefit over the course of many thousands of trips during the life of a healthcare facility. However, more research needs to be carried out to determine if the improvements in orientation behaviors shown in the current study will actually translate to faster navigational times and reduced stress under more challenging wayfinding conditions.

The EEG data taken from time-segments during which participants were viewing navigational signs and decision making right after viewing the sign further supported the behavioral findings that indicated better orientation and direction-choice after viewing signs in design Condition C. Frequency band-power analysis indicated significantly greater neural processing occurring in the occipital cortex when participants viewed signs and decided the next move in Condition C and Condition B, compared to the baseline Condition A (Fig. 8). A temporal analysis of ERSPs likewise showed significant desynchronization, indicating higher levels of cognitive engagement, when participants looked at signs in Conditions B and C compared to the baseline Condition A (Fig. 9). These findings appear to indicate that neural feature associated with navigation were more highly engaged, presumably encoding stronger mental maps or navigational conclusions, when signs were viewed under design Condition C, corresponding to the finding of improved orientation behaviors after viewing signs in this design condition. The ERSP analysis also showed a potentially oscillating behavior for the theta-band desynchronization in the seconds after participants viewed a navigational sign. The theta-band desynchronization difference between Condition C and Condition B was found to be most prominent at 1s and 2.5 s

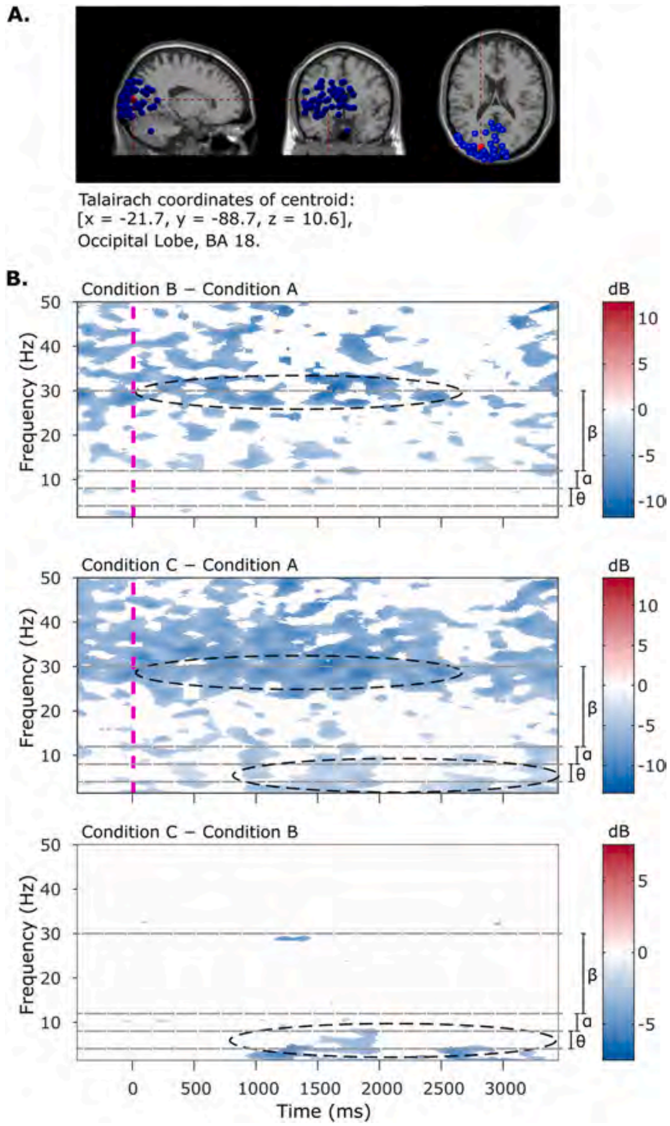


Fig. 9. Event-related spectral perturbation from −1 to 4 s after a "wayfinding sign seen" event during the navigational tasks. The brain images (a) show the occipital cluster distribution of IC equivalent dipoles among participants (blue) and the cluster centroid (red) in the brain region Brodmann Area 18. The graphs (b) show ERSP comparisons in dB between the three design conditions. The dotted ovals indicate comparisons with the largest effect size. White-colored areas mask non-statistically significant effects, at a p-value < .003. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

after the "sign-seen" event, and in each case was sustained for approximately 1s. Based on prior research (Rounds et al., 2020) this may indicate that the participants were cognitively integrating a relatively broader array of environmental information after viewing the signs in design Condition C. The differences observed in the oscillatory activity between the design conditions could potentially be explained by differences in the visual processing of information, which again may indicate that participants were responding in a different cognitive and behavioral fashion to the different wayfinding designs.

Taken together, these findings suggest that the enhancement of environmental affordances in the hospital design (adding architectural features and textures to highlight destinations and adding distinguishable patterns to signs) served to improve some aspects of navigational cognition and orientation behaviors, in a way that enhanced color alone did not accomplish. It is important to remember that design Condition C included *both* manifest cues and environmental affordances, and to recall that prior work (Vilar et al., 2014) has shown a heightened reliance on manifest cues in emergency situations. These results are thus generally commensurate with prior work in hospital wayfinding design (based mostly on anecdotal findings and static-image preferences) that have recommended incorporating both environmental affordances and manifest cues (Carpman, 1993; Devlin, 2014; Huelat, 2004; Marquardt, 2011; O'Neill, 1991; Passini et al., 2000; Pati et al., 2015; Rousek & Hallbeck, 2011; Ulrich et al., 2008). However, a strong note of caution is introduced by the finding that improvements in some orientation behaviors and a greater neurological activation in a wayfinding-related brain area did *not* translate into significant reductions in wayfinding times or reduced self-reported stress, fatigue, and confusion. More research is definitely needed in this area to determine if broader and more congruent wayfinding impacts can be identified, or if the lack of correspondence between these different wayfinding metrics is a consistent phenomenon. Fortunately, due to the advantages of the VR testing platform, the possibilities are nearly endless for future testing of additional design variations and participant populations.

Advancing our understanding of the neural activations associated with different types of wayfinding tasks may help to further develop cognitive map theory and explain the "correspondence" (Carlson et al., 2010) between building components and the cognitive map. Findings from the current research, along with other recent studies of brain dynamics of wayfinding in natural settings (Do et al., 2021; Djebbara et al., 2021), could contribute to the understanding of the neurological feature associated with information processing and decision making, that could better explain the cognitive map shaping process in the human mind. Neurological and behavioral metrics could also be an effective tool for understanding the individual differences (e.g., Gramann et al., 2010; Lin et al., 2015a, 2015b), which could also contribute to explain "skills and strategies" (Kuliga et al., 2019) of wayfinders in different contexts.

5.1. Limitations

The use of virtual reality for design testing purposes allows for pre-construction testing of design effectiveness, and for rigorous comparative tests that would not be feasible to carry out in real-world environments. However, there are some limitations in the use of VR for behavioral studies, since the bodily motions, sensory immersion, and physiological responses to VR contexts may not precisely mirror real-world experiences. In the current study we encountered some episodes of "teleportation behavior" in the VR system (where participants would jump immediately from one position to another without a fluid transition). This glitch in the system's realism may have impacted the wayfinding outcomes and the participants' reaction to the environment. In a similar fashion, realism was reduced in the virtual environment due to the absence of any other humans or visual and aural clutter in the hospital building. Typical hospital distractions that may affect wayfinding outcomes (noise and conversation, carts moving down the hallways, etc.) were not present.

The EEG analysis in this study was limited to a particular region of interest in the occipital cortex. Activity in this brain region has been robustly associated with wayfinding cognition, but it is not the *only* brain region involved in wayfinding. The process of parsing an environment, selecting navigational cues, making decisions, activating motion, and evaluating/correcting the results is neurologically complex. The selection of observed information during wayfinding can also lead to different attentional mechanisms that in some cases elicit a different motor responses (Djebbara et al., 2021; Gallivan, Chapman, Wolpert, & Flanagan, 2018). The VR context, in which motion in the environment is initiated with hand-held controllers, may add further wrinkles to these neurological processes. In the current study we focused on visual attention (occipital cortex) as a correlate of motor execution action (Brown, Friston, & Bestmann, 2011). This metric is well-supported for evaluating differences in wayfinding cognition, but a more robust neural picture could be obtained by investigating interplay between brain regions associated with sensory integration, planning, and decision-making.

As one of the first studies using VR immersion with physiological sensors as a method of wayfinding evaluation, it is perhaps unsurprising that a relatively large number of participants had to be excluded due to technical issues in data-collection. One of the problems that we encountered was that possible pathways in the hospital complex were quite numerous, and thus allowing the participants to move freely required the use of a very "heavy" VR file. This lead to the VR system crashing several times during the experiment, which necessitated the exclusion of the affected participants. Our research team is continuing to work on this aspect of the VR simulation tools, and we expect the overall state of the technology to continue to rapidly advance in upcoming years. The other major reason for participant exclusion was corrupted EEG data, primarily due to participant motions that resulted in the loss of signal channels. This technological concern will also likely be reduced in future studies by emerging advances in mobile EEG systems. It may also be mitigated by the use of a wireless EEG system and the careful fitting of appropriate cap sizes for diverse participants.

Finally, it is important to recall that in this study we examined only one possible implementation of wayfinding design principles. As discussed in Section 2 above, the effectiveness of a wayfinding strategy very likely depends on how it is implemented in a specific building, and it may also be affected by a variety of confounding/external variables (user demographics, user capabilities, task urgency, etc.). In addition, the current study used a convenience sample comprised mostly of undergraduate students, located in an entirely different geographical area than that of the planned hospital facility. Thus, great caution would be needed when generalizing the study findings. In a broader sense, however, the project's goal was to demonstrate the exciting potential of VR immersion with physiological sensors as a method of pre-construction testing, and to show how it can be used to optimize wayfinding design outcomes in specific facilities. The streamlined testing platform and data-analysis approach that was developed in this work can make this evidence-based approach more feasible for other researchers and professional designers, eventually leading to a broad comparative data-set incorporating a wide range of buildings and participants.

5.2. *Future directions*

One near-future expansion of this research will involve the analysis of neural features during a wider and more complex array of wayfinding tasks. The current study only analyzed EEG data for brief time-periods after participants gazed at navigational signs. Additional design insight may be gained by looking at other wayfinding events, for example times when participants have taken a wrong direction and need to correct their wayfinding mistake. The neurological analysis may also be expanded to additional brain regions, and it may be triangulated with additional physiological data such as heart rate or skin conductance (as measurements of stress). Expanding and broadening the study population is a strong priority for future work, with the goal of considering demographic variables as a factor in responses to wayfinding design.

The difficulty of the wayfinding challenges in the study may be increased even within the system's current technological capabilities by using a smaller number of more lengthy wayfinding tasks, and by adding visual and aural clutter to the simulation. In combination with larger sample sizes, this may lead to a greater ability to detect subtle variations in wayfinding outcomes. One of the great advantages of this research platform is that it allows for the easy incorporation of new wayfinding design strategies and additional facility plans. Expanding the number of designs tested is an important priority in generating more conclusive findings. This is particularly exciting in that it provides an opportunity to test new and innovative wayfinding design strategies that might otherwise struggle to gain adoption.

5.3. *Implications for practice*

The current study was undertaken in collaboration with Parkin Architects, and it evaluated actual wayfinding designs being considered for one of their healthcare facility projects. The outcome of this research includes specific findings about the proposed design of this facility; but perhaps more importantly, it also advances a new and tangible pre-construction testing method that can be directly applied to a wide variety of buildings. The testing and optimization of wayfinding designs prior to their implementation can help in selecting efficient designs and prevent the need for costly changes after physical construction. On a broader level, the optimization of wayfinding systems can improve the experiences of patients, visitors, and staff members in healthcare settings, potentially reducing anxiety and ensuring that people get to their appointments on time (Davis & Ohman, 2016; Jamshidi & Pati, 2020; Mollerup, 2009; Rousek & Hallbeck, 2011). The testing platform that we have created will lay the foundation for developing a larger body of knowledge in this area and conducting pre-construction design testing that would not otherwise be possible to carry out. Ultimately the use of rigorous virtual testing will help to promote the adoption of evidence-based principles in the industry, with the benefit of substantial cost savings and an improved environment for the public.

6. Conclusion

This study applied a novel approach using VR and EEG to evaluate wayfinding success under different interior design conditions in a healthcare facility. Multiple types of data were collected and analyzed, including self-reported responses, behavioral metrics, and measurements of neural activity in wayfinding-relevant brain regions. Three variations of an interior hospital environment were created: a baseline design with standard signage and minimal environmental contrast (Condition A), a design featuring added color to better highlight destinations and signs (Condition B), and a design that included the enhanced color from Condition B along with improved architectural features and graphics (Condition C). Participants for the study were recruited using a convenience sampling method and were randomly assigned to complete navigational tasks in one of the three interior design conditions. The findings indicated that orientation behaviors and wayfinding cognition were significantly improved in Condition C, compared to the other two interior hospital designs. Few differences in wayfinding metrics were found between Condition B and Condition A, indicating that adding color to highlight destination and increase the contrast of signs may not be adequate to promote better wayfinding. These findings regarding the advantages in Condition C tentatively support the value of adding both color and broader environmental affordances to support wayfinding in these types of facilities. However, the study did not find evidence that improvements in orientation behaviors and wayfinding cognition translated into faster navigational times or reductions in stress, mental fatigue, or confusion. More research is needed to evaluate the potential discrepancy between these different wayfinding metrics. Since each facility design and user population is unique, caution should be used in generalizing any of the outcomes of this study to other healthcare settings. However, the virtual testing platform that we developed in this project can make it relatively easy for other researchers and designers to carry out their own studies of various under-development facility designs, which has the potential to lead to a larger corpus of findings and a deeper synthesis across them.

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Author contributions

SK designed the experiment, collected the data, and conducted the behavioral analysis. VT, JK, and JDR curated the data and contributed to the behavioral analysis. JGCG curated the data and conducted the EEG data analysis. AM developed the virtual environment. RS was involved in the experimental design and provided the hospital floor plans. SK and JGCG wrote the manuscript. All authors approved the manuscript for publication.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2021.101744.

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