Immersed in Evidence

Integrating behavioural data into full-scale healthcare prototypes for evidence-based co-design

Michal Gath-Morad[1], Leonel Aguilar[2], Raphaël Baur[3], Minou Afzali[4], Koen Steemers[5], Kerstin Sailer[6], Ruth Dalton[7], Christoph Hölscher[8]

[1,2] Cambridge Cognitive Architecture, University of Cambridge, UK.
[2,3,8] Chair of Cognitive Science, ETH Zürich, Switzerland.
[4] Swiss Center for Design and Health, Switzerland.
[5,1] Behaviour and Building Performance Group, Department of Architecture, University of Cambridge
[6] The Space Syntax Laboratory, University College London (UCL)
[7] Department of Architecture, Northumbria University
[1]mg2068@cam.ac.uk [2]leonel.aguilar@gess.ethz.ch
[3]raphael.baur@gess.ethz.ch [4]minou.afzali@scdh.ch
[5]kas11@cam.ac.uk [6]k.sailer@ucl.ac.uk
[7]ruth.dalton@northumbria.ac.uk [8]choelsch@ethz.ch

Abstract. Full-scale mock-ups are invaluable in the architectural design process, particularly in healthcare, as they enable stakeholders to collaboratively assess spatial layouts in a near-real environment. However, these mock-ups often lack integration with behavioural data, missing an opportunity to combine empirical insights with full-scale physical prototyping. This study introduces *immersive evidence*, a framework that integrates behavioural data—such as interaction hotspots and visibility analysis—into full-scale prototypes of healthcare environments. A pilot study was conducted in a simulation facility with a 560 m² projection area, supplemented by lightweight construction walls. Participants engaged with spatial data either through screen-based presentations or via 1:1 mock-ups with projected behavioural data. Role-playing simulations provided context for interpreting spatial interactions, while survey results focused on evaluating participants' understanding of behavioural evidence. Findings suggest that *immersive evidence* improves stakeholders' ability to interpret behavioural data, with a medium effect size observed. This study highlights the potential of *immersive evidence* to bridge egocentric and allocentric spatial perspective to facilitate shared understanding of complex design challenges.

Keywords. Healthcare Architecture, Full-Scale Mock-ups, Immersive Simulation, Spatial Data, Evidence-Based Design

ARCHITECTURAL INFORMATICS, Proceedings of the 30th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2025, Volume 4, 407-416.

1. Introduction

Co-design processes in complex environments such as healthcare face the persistent challenge of fostering a shared understanding among stakeholders with diverse expertise and perspectives (Kleinsmann & Valkenburg, 2008). A critical barrier lies in the differences between *egocentric* and *allocentric* spatial representations, which underpin how stakeholders perceive and interpret spatial layouts. *Egocentric* spatial representation encodes spatial relationships relative to the position and orientation of the individual observer, offering a self-centred perspective that updates dynamically with movement. This perspective is critical for clinicians and administrators who rely on their day-to-day navigation of physical environments. In contrast, *allocentric* spatial representation encodes spatial relationships relative to external references or landmarks, providing a world-centred perspective that remains stable irrespective of the observer's position. *Allocentric* representations are integral to architects, who use tools such as 2D plans and diagrams to analyse and communicate spatial configurations (Montello, 1993; Wang & Brockmole, 2003). These cognitive differences may hinder collaboration, as *allocentric* tools may overwhelm non-experts, while *egocentric* perspectives may lack the contextual breadth required for design evaluations.

Full-scale mock-ups have emerged as a promising tool to bridge these gaps, offering stakeholders an embodied, immersive experience of spatial configurations. By presenting 1:1 physical representations of layouts, mock-ups enable users to engage with the spatial scale and adjacencies in real-time. However, traditional mock-ups are typically static, limited to showcasing physical layouts without integrating dynamic behavioural data such as movement patterns (i.e., showing walking traces of different users), interaction hotspots (high-activity zones where face-to-face interactions occur), or visibility patterns (i.e., analysing the inter-visibility afforded by a layout using methods such as isovist analysis or space syntax). This limitation prevents mock-ups from fully aligning the physical experience with the insights provided by evidence-based design.

To address these limitations, this study introduces the *immersive evidence framework*, a novel approach grounded in spatial cognition that combines behavioural data with full-scale mock-ups to bridge *egocentric* and *allocentric* spatial perspectives. By dynamically projecting key insights in the form of planar visualizations—such as interaction hotspots, movement trajectories, and visibility patterns—onto full-scale mock-ups, the framework integrates embodied interaction with data-driven evidence. This hybrid approach strives to enhance spatial cognition by aligning physical immersion with analytical insights to promote shared understanding among diverse stakeholders.

This paper presents findings from a pilot study conducted in a simulation facility (The Swiss Center for Design and Health), where participants from architecture, healthcare, and research engaged with spatial data through either screen-based presentations or full-scale mock-ups augmented with behavioural projections. The study evaluates whether the immersive evidence framework improves participants' ability to interpret spatial and behavioural data, offering preliminary evidence of its potential to align perspectives and support informed co-design in healthcare settings.

2. Relevant studies

Evidence-based design (EBD) has established itself as a pivotal approach in healthcare architecture, emphasizing the use of empirical data to inform design decisions and improve outcomes. Ulrich et al. (2010) provided a foundational framework linking design interventions to measurable results, such as patient well-being and operational efficiency, while Pati (2011) critically examined the criteria for evaluating the quality of evidence in EBD. Despite its strengths, EBD often struggles to effectively communicate its findings in a way that aligns with stakeholders' diverse spatial abilities. For instance, architects typically rely on allocentric tools like diagrams and plans, whereas clinicians and other users depend on egocentric, experience-based perspectives. This disconnect can hinder the practical application of evidence during collaborative design processes.

Participatory design methods, on the other hand, emphasize stakeholder involvement to ensure that spatial configurations meet diverse user needs. A common tool in participatory design is the full-scale mock-up—a 1:1 physical representation of a space using abstract walls and basic furniture. These mock-ups are effective in meeting stakeholders' needs for scale and embodied understanding (Binder et al., 2008). However, Reay et al. (2017) observed, traditional mock-ups are static and fail to incorporate the dynamic behavioural data that EBD generates. Consequently, while participatory methods enable co-creation in real-world settings, they often lack the integration of empirical evidence essential for informed decision-making.

Immersive simulation technologies, such as virtual reality (VR) and augmented reality (AR), offer a means to bridge the gaps in both EBD and participatory design. Grübel et al. (2021) demonstrated the potential of AR to enhance spatial understanding, while Dunston et al. (2011) showed how VR environments allow stakeholders to interact with behavioural data dynamically. These tools combine the benefits of evidence-based insights with a sense of spatial scale; however, they often fail to replicate the physical conditions of the built environment. This limitation is significant, as free motion within a real space is key for self-localization and orientation, processes that contribute to the alignment of allocentric and egocentric perspectives. Without physical immersion, participants are unable to fully engage with the spatial and behavioural dynamics of a design.

The *immersive evidence framework* harnesses the strengths of these approaches by combining evidence-based data, full-scale mock-ups, and dynamic behavioural insights in a physical setting. Using projection technologies, it overlays interaction hotspots, movement trajectories, and visibility patterns onto 1:1 scale mock-ups of healthcare environments, allowing stakeholders to experience and interpret spatial configurations with free movement. By aligning empirical evidence with embodied interaction, the *immersive evidence* framework bridges egocentric and allocentric perspectives, aspiring to promote shared understanding among diverse stakeholders. This approach acknowledges the neurobiological differences between participants, a critical element in evidence-based collaborative decision-making within co-design processes.

3. The Immersive Evidence Framework

The *Immersive Evidence* Framework (Figure 1) is both a conceptual and operational framework designed to bridge the gap between static architectural mock-ups and dynamic behavioural insights, addressing the misalignment between egocentric and allocentric spatial perspectives among diverse stakeholders in co-design processes. The framework consists of three interconnected pillars, each functioning like a modular container where diverse activities and information converge to support co-design processes:

- *Data Integration*: This pillar focuses on synthesizing multiple data streams, including behavioural data (e.g., interaction hotspots, movement trajectories, visibility patterns) and architectural data (e.g., spatial layouts, adjacencies, and flow patterns). The goal is to merge insights from human behaviour and spatial configurations into a unified dataset. These datasets act as foundational inputs for design decisions, ensuring that spatial insights are grounded in evidence. By accommodating diverse data types, this pillar serves as the analytical core of the framework, transforming raw behavioural observations into actionable spatial insights.
- *Projection and Mock-Up*: The second pillar operationalizes the integrated data by dynamically overlaying behavioural insights onto full-scale, life-sized architectural mock-ups using projection technologies. These mock-ups incorporate elements such as lightweight walls, furniture, and key occlusions to simulate real-world conditions. Occlusions are designed to replicate barriers or visual obstructions typical in the built environment, enhancing the realism of the spatial experience. This setup enables stakeholders to physically navigate the mock-up, fostering an embodied understanding of spatial layouts and the interplay of behavioural dynamics.
- *Stakeholder Engagement and Evaluation:* The final pillar focuses on actively involving stakeholders in the design process and evaluating their interactions to ensure that insights derived from data and mock-ups are effectively understood and applied. This includes immersive role-playing simulations, where participants enact scenarios informed by projected data collaborative co-design activities to reconfigure layouts in real time and psychophysiological tools such as surveys, video recordings, eye tracking, and mobile EEG to assess participants' cognitive and emotional engagement.

The *Immersive Evidence* Framework is a general approach designed to integrate behavioural data into full-scale mock-ups during co-design processes. In this paper, we focus primarily on the *Stakeholder Engagement and Evaluation* pillar (Pillar 3), while incorporating aspects of the *Data Integration* and *Projection and Mock-Up* pillars to support this evaluation.

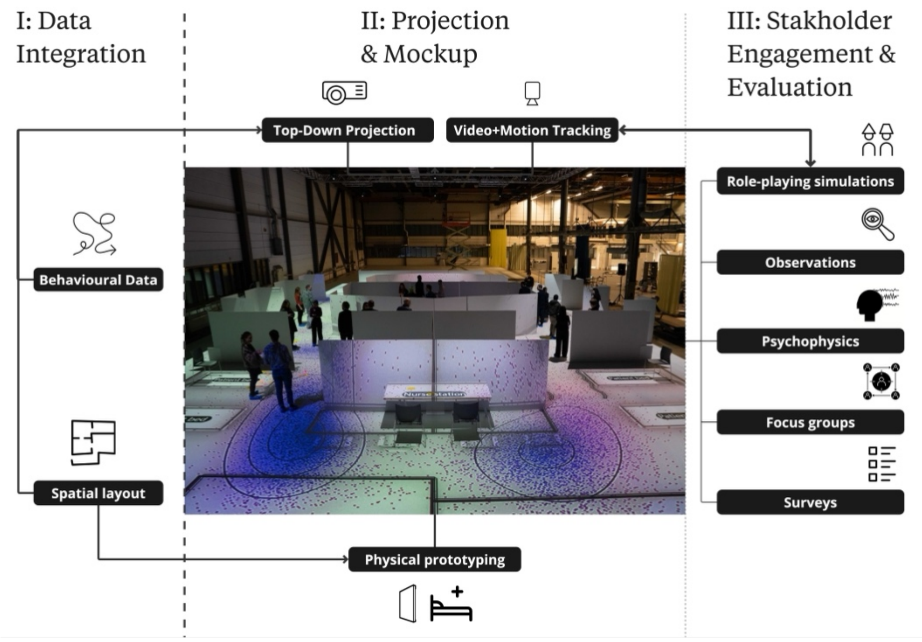


Figure 1: The *Immersive Evidence* Framework comprising three pillars; *Data Integration, Projection and Mock-Up*, and *Stakeholder Engagement & Evaluation*.

4. Methods

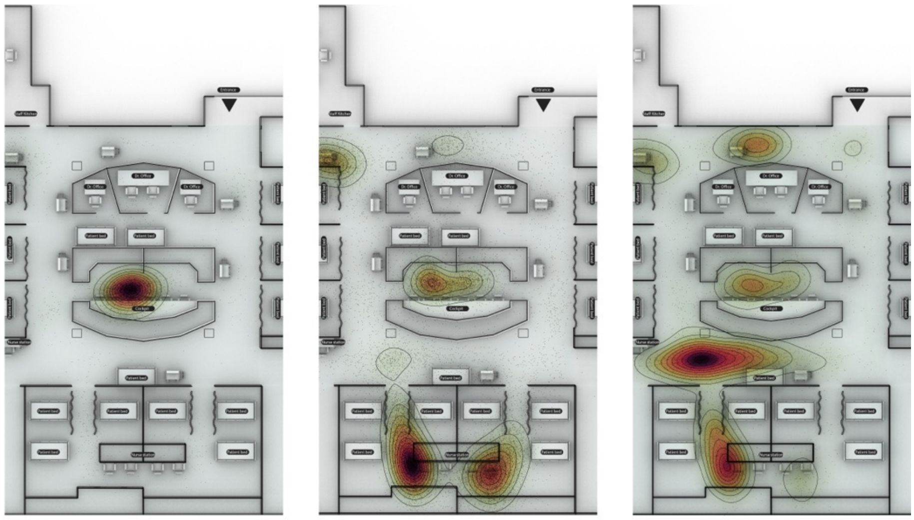
4.1. PARTICIPANTS

The study recruited a convenience sample (n=19), including architects, clinicians, and researchers, to ensure diverse perspectives and expertise in interpreting spatial data. Participants were recruited through professional networks and online outreach. The inclusion criteria required participants to have experience or familiarity with healthcare environments or architectural design. Participants were randomly assigned to one of two groups: the *Screen-Viewing Group* or the *Immersive Group*, ensuring balanced representation of expertise levels across conditions.

4.2. MATERIALS

To evaluate participants' interpretation of spatial data, heatmap projections were developed to visualize interaction hotspots within an Emergency Department (ED) for three key caregiver roles: doctors (Figure 2a), nurses (Figure 2b), and the coordination nurse (Figure 2c). These heatmaps, directly linked to the survey, tasked participants with identifying the caregiver role responsible for the interactions in each hotspot. Participants in the Screen-Based Group reviewed these visualizations on digital devices, while those in the *Immersive Evidence* Group experienced the same heatmaps projected onto a full-scale ED mock-up. This approach enabled a comparative evaluation of how the presentation medium—screen-based or immersive—impacted participants' comprehension and application of spatial data.

The full-scale ED mock-up was constructed to replicate the spatial layout of a university hospital ED in which the behavioural data was collected in two field studies conducted in 2022 and 2023 (Gath-Morad et al., 2025). Key features included life-sized corridors, the cockpit, nurse stations, patient areas, medicine distribution areas, and coordination zones. Heatmap projections highlighted interaction hotspots for the three caregiver roles, illustrating areas with the highest concentration of face-to-face interactions



(a) Interaction hotspots belonging to doctors **(b)** Interaction hotspots belonging to nurses **(c)** Interaction hotspots belonging to the coordination nurse

Figure 2. Heatmap projections showing interaction hotspots in the Emergency Department (ED).

4.3. PROCEDURE

Participants were welcomed and briefed on the study's objectives and methods before providing informed consent. They were then randomly assigned to either the Screen-Viewing Group (Group 1) or the Immersive Group (Group 2). To ensure familiarity with the Emergency Department (ED) layout, all participants reviewed a labelled floor plan highlighting key zones and caregiver roles. Participants in the Immersive Group physically navigated a 1:1 projected floor plan within the mock-up space, while the Screen-Viewing Group accessed the same labelled floor plan on a tablet. This step ensured a consistent baseline understanding of the spatial layout across groups.

After completing a demographic survey, participants were introduced to visualizations of interaction hotspots (see Figures 2a, 2b and 2c) derived from prior studies (Gath-Morad et al., 2025). Group 1 viewed these hotspots on digital screens, while Group 2 explored the same data projected onto the full-scale physical mock-up ((see Figure 1 and Figure 3). Participants in the *Immersive Evidence* group were allowed free movement within the mock-up for one minute, after which an audio announcement instructed them to stop and identify the caregiver roles associated with each interaction hotspot. Screen participants performed the same task on their devices under identical time constraints. Finally, participants engaged in role-playing simulations and co-design activities to explore the ED layout further (results of this part

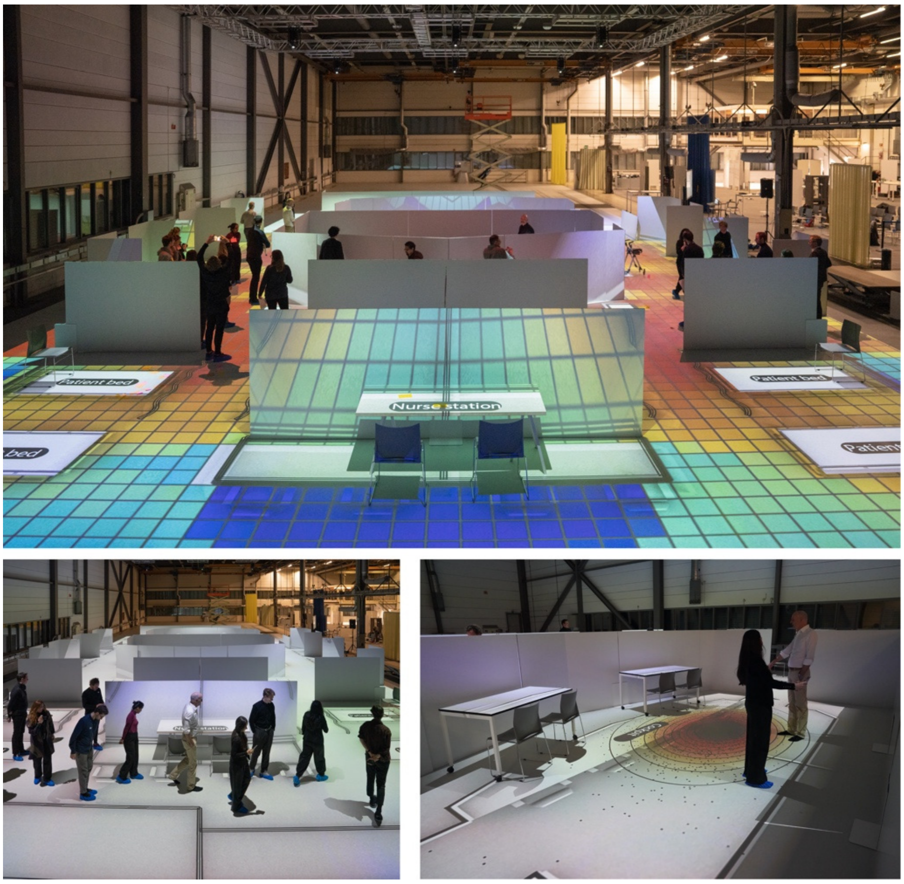


Figure 3. Highlights from the pilot study showcasing the integration of behavioural data and full-scale prototyping in the *immersive evidence* group (credit: Swiss Centre for Design and Health).

not reported in this paper). Top-down video recordings of the sessions, along with qualitative feedback, were collected to evaluate participants' engagement with the presented evidence and its influence on stakeholder interactions and co-design outcomes.

4.4. QUASI-EXPERIMENTAL DESIGN AND ANALYSIS

The pilot study employed a quasi-experimental design, i.e. randomization of a convenient sample of participants in two groups, to evaluate the effect of evidence presentation medium (screen-based vs. immersive) on their interpretation of spatial data. The convenience sampling approach, while limiting the generalizability, was necessary due to the constraints of participant availability and real-world conditions. Participants' ability to accurately identify caregiver roles when immersed in the full-scale mock-up augmented with visualization of healthcare workers interaction hotspots was measured as the number of correct responses (i.e., matching of face-to-face interaction hotspot data with the correct caregiver role). Statistical analysis comprised both descriptive methods (e.g., counts, medians, minimum, and maximum values) and inferential methods. A Mann-Whitney U test, a non-parametric statistical method, was used to compare the number of correct responses between the two groups. To assess the practical significance of the results, the effect size was calculated using Cohen's D. Additionally, a post hoc power analysis was conducted through simulations to estimate the sample size required for future studies to achieve sufficient statistical power.

5. Results

Data was collected from 19 participants, with a balanced gender distribution (10 male, 9 female). Participants represented diverse professional backgrounds and education levels, including Bachelor's, Master's, and PhD degrees, reflecting a well-rounded sample of stakeholders relevant to healthcare and architecture domains (see Figure 4). The results (Figure 4) demonstrated that participants in the *Immersive* group had a higher median number of correct responses, better identifying caregiver roles based on spatial interaction data, compared to those in the *Screen-viewing* group. Despite a medium effect size (Cohen's D = 0.23), a Mann-Whitney U test indicated non-significant results ($p > 0.05$), likely due to the small sample size. A power analysis performed post hoc indicated that a minimum of 60 participants per group would be

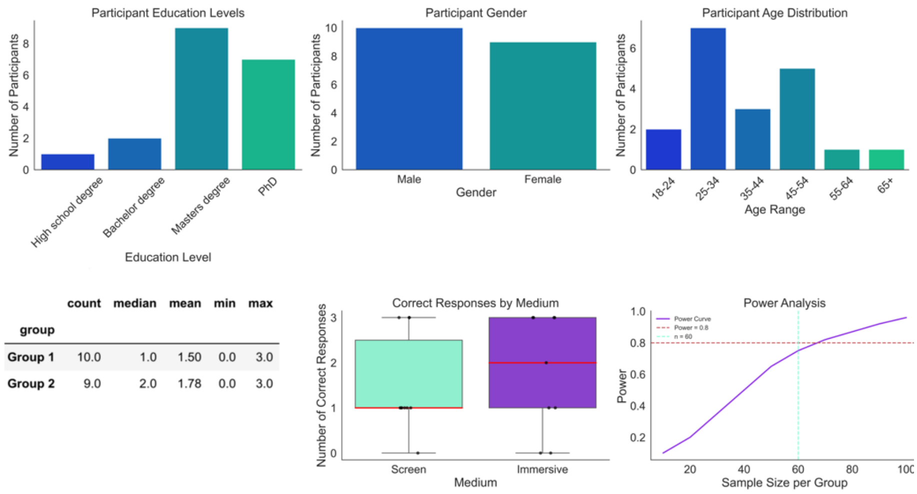


Figure 4. Participant demographics and performance.

required to achieve 80% statistical power for detecting similar effect sizes in future studies. In practice, these results only hint at better performance of the *immersive* group; this would need to be confirmed with a larger sample size or a more contrasting experimental design, e.g. taking further advantage of immersion through, for example, by enhancing immersion with spatialized audio, ambient soundscapes, or interactive sound effects to deepen engagement

6. Discussion

Our findings demonstrate that participants in the *immersive evidence* group were better in identifying caregiver roles based on interaction hotspots compared to those in the screen-viewing group. A medium effect size was observed, suggesting that the *immersive* presentation medium may have a meaningful impact on stakeholders' ability to interpret behavioural data. However, due to the limited sample size, statistical analyses yielded non-significant results. This highlights the potential of *immersive evidence* as a promising method, while raising the need for larger sample sizes to robustly evaluate its effectiveness.

The enhanced performance observed in the *immersive* group may be explained by the cognitive affordances offered by the immersive evidence framework, particularly during the familiarization task. Affordances, a concept introduced by Gibson (1979), refer to the action possibilities that an environment provides, determined by the interaction between the individual's abilities and the properties of the environment. In the *immersive* condition, participants physically navigated the full-scale environment, which included a projected floor plan labelled with different functional areas. We conjecture that this interaction facilitated dynamic spatial updating, allowing participants to form an embodied understanding of the layout.

This movement-based engagement likely enabled participants to explore and internalize the functional relationships between various zones more effectively. For instance, central and static interaction hotspots might have been intuitively associated with doctors, whose roles often involve fixed locations such as workstations or patient areas. Similarly, the dynamic and spatially distributed patterns of interaction typical of nurses may have been more readily interpreted in the *immersive* condition, as participants could directly perceive the nurse station's location and its spatial connectivity to other areas. By integrating movement and visual data in context, the immersive approach provided a richer cognitive framework for understanding and reasoning about the spatial and functional organization of the environment.

In practice, our study highlights that stakeholders can leverage full-scale mock-ups, augmented with behavioural data, as an effective tool for both communicating and understanding complex spatial dynamics. By navigating these environments physically, participants can better grasp the impact of architectural designs on human behaviour and operational workflows. This tangible, embodied interaction fosters a deeper comprehension of how spatial configurations influence behaviour, potentially enabling stakeholders to make more informed collaborative decisions by bridging the cognitive and experiential gaps that often exist in co-design processes.

Future work will build on these findings by leveraging the rich dataset generated from role-playing simulations conducted as part of this quasi-experiment. These simulations explored how spatial configurations influence interactions by simulating a series of events under different design variations. Top-down video data collected during these simulations captured where interactions occurred, between whom, and for how long. In follow-up studies, we aim to address current limitations by including a larger participant pool and incorporating more task-based questions to increase statistical power. Additionally, we will integrate psychophysiological tools such as eye tracking and mobile EEG, inspired by recent state-of-the-art studies combining full-scale mock-ups, behavioural experiments, and psychophysics (UCL, 2024). These tools will enable us to capture cognitive and emotional responses in real-time, providing deeper insights into how different types of evidence presented in different mediums affect design communication and cognition.

References

Kleinsmann, M. and Valkenburg, R. (2008). Barriers and enablers for creating shared understanding in co-design projects. *Design studies*, 29(4):369–386.

Montello, D. R. (1993, September). Scale and multiple psychologies of space. In *European conference on spatial information theory* (pp. 312-321). Berlin, Heidelberg: Springer Berlin Heidelberg.

Gerber, A., Berkowitz, M., Emo, B., Kurath, S., Hölscher, C., & Stern, E. (2019). Does space matter? A cross-disciplinary investigation upon spatial abilities of architects. *Research Culture in Architecture*, 289.

Wang, R. F., & Brockmole, J. R. (2003). Simultaneous spatial updating in nested environments. *Psychonomic bulletin & review*, 10(4), 981-986.

Gibson, J. J. (2014). The theory of affordances:(1979). In *The people, place, and space reader* (pp. 56-60). Routledge.

Ulrich, R. S., Berry, L. L., Quan, X., & Parish, J. T. (2010). A conceptual framework for the domain of evidence-based design. *HERD: Health Environments Research & Design Journal, 4(1), 95-114.*

Pati, D. (2011). A framework for evaluating evidence in evidence-based design. *HERD: Health Environments Research & Design Journal*, 4(3), 50-71.

Binder, T., & Brandt, E. (2008). The Design: Lab as platform in participatory design research. *Co-design*, 4(2), 115-129.

Reay, S., Collier, G., Kennedy-Good, J., Old, A., Douglas, R., & Bill, A. (2017). Designing the future of healthcare together: prototyping a hospital co-design space. *Co-Design*, 13(4), 227-244.

Dunston, P. S., Arns, L. L., Mcglothlin, J. D., Lasker, G. C., & Kushner, A. G. (2011). An immersive virtual reality mock-up for design review of hospital patient rooms. *Collaborative design in virtual environments*, 167-176.

Grübel, J., Gath-Morad, M., Aguilar, L., Thrash, T., Sumner, R. W., Hölscher, C., & Schinazi, V. (2021, June). Fused twins: A cognitive approach to augmented reality media architecture. In *Proceedings of the 5th Media Architecture Biennale Conference* (pp. 215-220).

M. Gath-Morad, R. Baur,L. E. Aguilar, K. Sailer, J. Schmutz,, K. Slankamenac, P. Honegger, R. Dalton, H.Sax,, & C. Holscher., *How the Spatial Design of Emergency Departments Affects Face-to-Face Interactions and Perceived Communication, Collaboration, and Care Outcomes*, 2025. (Manuscript in preparation).

University College London. (2024, September 16). *Large-scale experiment brings real world into lab to design better spaces*. UCL News. Retrieved November 24, 2024, from https://www.ucl.ac.uk/news/2024/large-scale-experiment-brings-real-world-lab-design-better-spaces