

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Design review in immersive Virtual Reality: End-User involvement and  
Cognitive Fit

SHAHIN SATEEI

Department of Architecture and Civil Engineering

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2026

Design review in immersive Virtual Reality: End-User involvement and Cognitive Fit

SHAHIN SATEEI

ISBN 978-91-8103-440-0

Acknowledgements, dedications, and similar personal statements in this thesis, reflect the author's own views.

© SHAHIN SATEEI, 2026.

Doktorsavhandlingar vid Chalmers tekniska högskola

Ny serie nr 5897

ISSN 0346-718X

Department of Architecture and Civil Engineering

Division of Construction Management and Engineering

Chalmers University of Technology

SE-412 96 Gothenburg

Sweden

Telephone + 46 (0)31-772 1000

Cover:

End-users and other stakeholders engaging with building design proposals through immersive Virtual Reality. The images show collaborative design review sessions across healthcare and school building projects, including multi-user interaction, multi-scale views, and combined immersive and non-immersive user-interfaces. See Section 3.2 for further details.

Chalmers Digitaltryck

Gothenburg, Sweden 2026

*“Yesterday I was clever, so I wanted to change the world. Today I am wise, so I am changing myself.”*

*- Rumi (13<sup>th</sup>-century Persian poet)*



SHAHIN SATEEI

Department of Architecture and Civil Engineering  
Chalmers University of Technology

## Abstract

Design decisions in healthcare and educational facilities have long-term consequences for everyday work. During design review, end-users are typically expected to evaluate architectural proposals using conventional formats such as 2D drawings, which require mental reconstruction of three-dimensional space and may constrain the use of their operational knowledge. Immersive virtual reality has therefore gained attention as an alternative format enabling full-scale exploration of proposed designs. However, studies in real-world projects remain limited, and it is unclear how immersive formats influence cognitive load, identification of design issues, and end-users' ability to communicate their operational knowledge. This matters because facilities that fail to reflect end-user work practice can compromise operational efficiency, safety, and well-being for years after construction.

To address this need, this thesis investigates how immersive virtual environments can support end-user involvement, including Co-Design, during building design review. The research draws on four empirical studies in ongoing healthcare and educational building projects involving end-user groups such as building occupants, facility planners, and client representatives. It combines qualitative analyses of design review sessions with quantitative measures of cognitive load and issue identification, and draws on Cognitive Fit Theory, Collaborative Virtual Environment research, and participatory design theory.

The findings show that immersive virtual environments enable end-users to explore proposed designs at full scale and assess spatial layouts in relation to operational work practices. Immersive review supported identification of workflow- and layout-related design issues across design phases and was most effective when combined with conventional 2D drawings and overview-based formats. Interactive features such as multi-user interaction, object interaction, and multi-scale views further supported communication of operational knowledge within representations of the facilities in focus.

The thesis makes three contributions. First, it provides empirical evidence that immersive virtual environments can support higher levels of end-user involvement, including Co-Design, when interactive features such as multi-user collaboration and object interaction are available. Second, it extends Cognitive Fit Theory into collaborative design review, arguing that individual cognitive fit is a necessary precondition for higher collaborative involvement. Third, it offers practical implications for combining immersive and conventional formats to support end-user involvement during design review, helping ensure that facilities support the daily work of building occupants.

**Keywords:** Cognitive Fit Theory, Cognitive Load, Collaborative Virtual Environment, Design review, End-user involvement, Participatory Design, Virtual Reality (VR)



# Acknowledgement

The work presented in this thesis was conducted at the Division of Construction Management and Engineering at Chalmers University of Technology between October 2020 and June 2026. The research was financially supported by the Swedish Research Council for Sustainable Development (FORMAS), whose support is gratefully acknowledged.

I would like to begin by expressing my sincere appreciation to my supervisors Mattias Roupé, Mikael Johansson, and Viktoria Sundqvist. I owe them a debt of gratitude, as their timely, thorough, and continuous feedback helped me make considerable improvements throughout this research journey, not least through their extraordinary patience in helping me develop as an independent researcher. Each of you has, in your own way, contributed significantly to my development as a researcher.

I am deeply grateful to Mattias Roupé for believing in me from the very beginning and for giving me the opportunity to pursue this PhD in the first place. Your support, encouragement, and ability to remind me to believe in myself during periods of doubt have meant more than you probably realize. I would also like to thank Mikael Johansson for constantly challenging me to think more deeply and to ask better questions whenever I felt stuck. Your guidance pushed me to develop a more critical and reflective approach to research, and your persistence in solving problems is admirable. Finally, I greatly value Viktoria Sundqvist for encouraging me to embrace the broader context of my research and for continually challenging me to consider new perspectives. Your insights and thoughtful feedback have been essential in shaping not only this thesis, but also how I think about and relate to research more broadly. The discussions, supervision, and collaboration with all three of you have been fundamental to completing this work. Thank you.

I would also like to thank my colleagues at the Division of Construction Management and Engineering for their support, encouragement, and for contributing to a stimulating and enjoyable research environment throughout these years. In addition, I am sincerely grateful to all the healthcare staff, facility planners, architects, and other project participants who generously shared their time, experiences, and expertise throughout the various studies included in this thesis. Without your engagement and willingness to participate, this research would not have been possible.

Finally, I would like to thank my family, friends, and especially my girlfriend for their patience, support, and understanding throughout this journey. Thank you for standing beside me through the stress, the uncertainty, the long evenings, and everything in between. Josefin, my love, you are my biggest inspiration, and having you next to me has made me appreciate life even more fully. Self-trust and vulnerability come easily with you next to me. You are my heartland. Thank you for being you.

Shahin Sateei,  
Gothenburg June 2026



# List of publications

This thesis is based on the work contained in the following papers:

## Paper I

From informative to Co-Design: the role of immersive Virtual Reality for user-involvement in healthcare facility design

*Sateei, S., Roupé, M., and Johansson, M. (2025)*

Published in: Journal of Information Technology in Construction (ITcon), May 2025.

## Paper II

Collaborative Design Review Sessions In Virtual Reality: Multi-Scale And Multi-User

*Sateei, S., Roupé, M., and Johansson, M. (2022)*

Presented at: 27<sup>th</sup> International Conference of the Association for Computer Aided Architectural Design Research in Asia (CAADRIA) 2022. Vol. 1, p.29-38, April 2022.

## Paper III

Transitioning from 2D to VR in design review – Resistance to Engagement

*Sateei, S., Roupé, M., and Johansson, M. (2023)*

Presented at: 23<sup>rd</sup> International Conference on Construction Applications of Virtual Reality, CONVR 2023. Vol. 23, p. 85-96, November 2023.

## Paper IV

How Representation Format Affects End-User Design Review: Cognitive Load and Task Performance in 2D drawings and immersive HMD Virtual Reality

*Sateei, S., Gustafsson, M., Roupé, M., and Johansson, M.*

Under review in Journal of Virtual Reality, submitted January 2026.

## Contributions

For all appended papers, the co-authors contributed with conceptualization, reviews and continuous scientific advice. The author of this thesis made the following contributions:

**Paper I:** Conceptualization, methodology, literature review, data collection, data analysis, visualizations, and writing and editing the manuscript.

**Paper II:** Conceptualization, methodology, literature review, data collection, data analysis, visualizations, and writing and editing the manuscript.

**Paper III:** Conceptualization, methodology, literature review, data collection, data analysis, visualizations, and writing and editing the manuscript.

**Paper IV:** Conceptualization, methodology, literature review, data collection, data analysis, visualizations, validation, data curation formal analysis and writing and editing the manuscript.

## **Additional publications not included in this thesis.**

### **Peer-reviewed conference papers:**

1. **Sateei, S.**; Eriksson, J.; Roupé, M.; Johansson, M.; Lindahl, G. How Virtual Reality is used when involving healthcare staff in the design process. *In Proceedings of the 38th CIB W78 Conference on Information Technology for Construction, Luxembourg, 13–15 October 2021; pp. 419–428*
2. **Sateei, S.**, Roupé, M., Johansson, M. (2022). An ontological approach for a recommendation system of a requirement tool: the case of a national standard framework for hospital design. *Proceedings of the European Conference on Computing in Construction.*
3. **Sateei, S.**, Sundquist, V. (2022). Knowledge Integration Through Resource Combining: The Case of a National Standard Framework for Hospital Design. *Proceedings 38th Annual ARCOM Conference: 73-82*
4. **Sateei, S.**, Gustafsson, M., Roupé, M., Johansson, M. (2025). Evaluating Cognitive Load and Sense of Presence in Design Review of Healthcare Facility Design: 2D Versus Immersive VR. In: Noroozinejad Farsangi, E., Rasouli, A.H., Dawood, N., Morrison, G. (eds) *Construction Applications of Virtual Reality, Volume I. CONVR 2024. Lecture Notes in Civil Engineering, vol 683. Springer, Singapore*
5. Gustafsson, M., Roupé, M., Johansson, M., **Sateei, S.**, Disney, O. (2025). Evaluating Design Review Efficiency and Cognitive Load: 2D vs 3D vs Immersive. In: Noroozinejad Farsangi, E., Rasouli, A.H., Dawood, N., Morrison, G. (eds) *Construction Applications of Virtual Reality, Volume I. CONVR 2024. Lecture Notes in Civil Engineering, vol 683. Springer, Singapore.*

### **Licentiate thesis:**

Sateei, S. (2023). Virtual Collaborative Design Environment: Information Structure and Interfaces. Department of Architecture and Civil Engineering, Chalmers University of Technology

### **Report:**

**Sateei, S.**, Roupé, M., Johansson, M., (2024) Kollaborativ informationsstruktur i sjukhusbygge

# Terminology

In this research project, the following terms, definitions, and abbreviations are used:

<b>Term</b>	<b>Definition</b>
VR	Virtual Reality. A computer-generated environment that users perceive as a three-dimensional space.
HMD	Head-Mounted Display. A wearable display that presents a stereoscopic view of a virtual environment with positional tracking.
Immersive HMD VR	Virtual Reality experienced through a head-mounted display (HMD), presenting the building design at 1:1 scale with positional tracking.
BIM	Building Information Model. A digital representation of a building used as the source model for the VR environments in this thesis.
CVE	Collaborative Virtual Environment. A shared virtual space in which multiple users can interact with the model and with each other simultaneously.
ViCoDE	Virtual Collaborative Design Environment. A multi-interface CVE system combining immersive HMD VR, a multitouch top-view table, and a shared projector screen.
Co-Design	A level of end-user involvement where end-users act as members of the design team and shape design solutions together with the design team.
PD	Participatory Design. A level of end-user involvement where end-users share and influence design decisions but do not become part of the design team.
End-user	A stakeholder who will use the finished building, including building occupants, client representatives, and facility planners.
Building occupant	A type of end-user whose daily work practice takes place inside the building, such as healthcare staff or teachers.
Design review	A structured session in which stakeholders evaluate a design proposal and identify issues before construction.
Cognitive Fit Theory	Alignment between how information is represented, the cognitive demands of the task, and the user's domain knowledge and prior experience.
Cognitive load	The mental effort required to process information during a task; measured in this thesis using NASA-RTLX.
NASA-RTLX	NASA Raw Task Load Index. A self-report instrument used in Paper 4 to assess perceived cognitive load.

Object interaction	Selecting, moving, and rotating objects in the virtual model while preserving their shape.
Multi-user feature	Multiple users simultaneously present in the same virtual model, able to perceive each other's presence and actions.
Multi-scale feature	A toggle within the same VR model between a full-scale (1:1) view and a miniature overview view.
Egocentric frame of reference	A self-centered viewpoint, experienced from inside the space at full scale.
Allocentric frame of reference	An external, environment-centered viewpoint such as a 2D plan or overview view.
Task-based scenario	A structured work-practice activity carried out within a design review, such as simulating a clinical workflow or testing equipment placement.
RIBA Plan of Work	A standard framework dividing the architectural design process into phases (e.g., concept design, technical design).
RDS	Room Data Sheet. A project document specifying the equipment and functional requirements for each room.



# Table of contents

Abstract .....	I
Acknowledgement .....	III
List of publications.....	V
Terminology.....	VII
Table of contents.....	X
1 Introduction.....	1
2 Related work .....	5
2.1 Design layout affecting building occupants' work practice.....	5
2.2 End-user involvement in the building design process .....	6
2.3 Spatial understanding in representational formats .....	9
2.4 Interactive features in VR for collaborative design review .....	12
2.5 Collaborative Virtual Environments .....	13
3 Research methodology .....	19
3.1 Research approach .....	19
3.2 Multiple case study research .....	20
3.2.1 Healthcare building projects .....	22
3.2.2 School building projects.....	25
3.3 Data collection .....	27
3.3.1 Design review setting.....	29
3.3.2 CVE systems and VR-model preparation .....	30
3.3.3 Data types collected .....	31
3.4 Data analysis .....	32
3.4.1 Qualitative analysis .....	32
3.4.2 Quantitative analysis .....	32
3.5 Research process .....	33
3.5.1 Research timeline .....	33
3.6 Cross-case synthesis and analytical strategy.....	34
3.6.1 Operationalization of analytical dimensions.....	39
3.6.2 Contaminating differences and plausible rival interpretations .....	43
3.7 Reflections on research quality .....	43
4 Results and summary of appended papers .....	47

4.1	Overview of how the papers are related .....	47
4.2	Summary of Appended Paper I .....	48
4.2.1	Background and aim .....	48
4.2.2	Methods .....	48
4.2.3	Results .....	49
4.2.4	Contribution to thesis .....	49
4.3	Summary of Appended Paper II .....	50
4.3.1	Background and aim .....	50
4.3.2	Methods .....	50
4.3.3	Results .....	50
4.3.4	Contribution to thesis .....	50
4.4	Summary of Appended Paper III .....	51
4.4.1	Background and aim .....	51
4.4.2	Methods .....	52
4.4.3	Results .....	52
4.4.4	Contribution to thesis .....	52
4.5	Summary of Appended Paper IV .....	53
4.5.1	Background and aim .....	53
4.5.2	Methods .....	54
4.5.3	Results .....	54
4.5.4	Contribution to thesis .....	55
5	Discussion .....	57
5.1	End-user involvement and Co-Design in immersive design review .....	57
5.2	Interactive features and collaboration in immersive design review .....	60
5.3	Cognitive fit and end-user expertise .....	62
6	Conclusions .....	67
7	Future research .....	71
	References .....	73
	Appended Papers .....	87



# 1 Introduction

Design decisions made during the early phases of the design process have long-lasting consequences for how buildings function in everyday work. Early design choices about spatial layout, visibility, and room relationships influence how building occupants, such as healthcare staff, teachers, move, communicate, and carry out their daily tasks (Lawson, 2013; Bjørn et al., 2021; Elf et al., 2024). This is particularly evident in operationally demanding environments such as healthcare facilities and educational buildings, where spatial design directly affects safety, workflow coordination, and operational performance (Joseph and Rashid, 2007; Ulrich et al., 2008; Frelin and Grannäs, 2021). When design issues affecting layout, visibility, or workflow are identified late in a project, they often lead to costly redesigns, compromises in how spaces are ultimately used, or persistent operational challenges such as inefficient workflows, communication difficulties, or safety-related constraints that are difficult to correct once the building is completed (Gomes and Tzortzopoulos, 2018).

Because building design sets the frame and conditions for how building occupants carry out their work, involving operational end-users in design review is important, as their practical knowledge helps identify design issues that might otherwise be overlooked. In this thesis, the term end-users refers to stakeholder groups who will work in or use the building once it is completed. These groups include building occupants such as healthcare staff and teachers, as well as representatives such as facility planners or client representatives who participate in design review on behalf of operational units. Involving these groups in design review helps ensure that building designs reflect how spaces are actually used, rather than relying only on assumptions about future use (Johansson et al., 2002; Simonsen and Robertson, 2012; Caixeta et al., 2019). At the same time, end-users rarely form a homogeneous group. Differences in professional background (e.g., building occupants, representatives, facility planners), domain expertise, and familiarity with spatial representations can influence how design proposals are understood as well as the conditions for participation in design review (Elf et al., 2024; Nazeer et al., 2024). These differences in expertise can make it difficult to support participation in practice and ensure that end-user input meaningfully informs design decisions across stakeholder groups. Still, despite the recognized importance of end-user involvement, achieving such involvement during design reviews remains challenging.

A key challenge is how design proposals are presented during design review. Architectural design review with end-users has traditionally relied on representational formats such as conventional 2D drawings, including plans, sections, and elevations. While these representations are standard within professional design practice, they can be challenging for stakeholders such as building occupants who are not trained in interpreting conventional drawings. Understanding a future building from drawings requires mentally reconstructing three-dimensional space from abstract symbols and fragmented views, a process shown to increase cognitive load and limit stakeholders' ability to identify design issues (Kosslyn, 1994; Shi et al., 2020; Umair et al., 2022; Foroughi Sabzevar et al., 2025; Gustafsson et al., 2025). The cognitive effort required to interpret conventional representational formats can therefore limit building occupants' ability to identify design issues linked to work practice and to actively contribute during design review.

An alternative to conventional representational formats is immersive virtual reality (VR), particularly immersive head-mounted display (HMD) systems, which convey spatial depth,

scale, and how close things are to each other more directly than conventional drawings. By allowing users to experience a proposed building at full scale and from a first-person perspective before construction begins, immersive VR supports spatial understanding through perception and movement rather than through abstract mental reconstruction. Users can explore layouts, assess visibility, and evaluate how spaces may support everyday work situations during design review (Paes et al., 2017; Wolfartsberger, 2019; Nikolić and Whyte, 2021). Studies indicate that immersive VR can improve identification of spatial and workflow-related design issues, particularly in healthcare facilities and other operationally demanding environments (Heydarian et al., 2015; Roupé et al., 2020; Shultz and Jha, 2021). Recent developments in collaborative virtual environments also allow multiple stakeholders to explore and evaluate the same virtual design together, manipulate design elements (e.g., furniture placement, equipment layout, spatial configurations) and jointly evaluate alternative design solutions in real-time (Johansson and Roupé, 2022). Such interaction can support articulation of operational knowledge directly within the representational format and help align different stakeholder perspectives during design review (Arias et al., 2000; Snowdon et al., 2001; Fischer et al., 2005). Taken together, studies suggest that immersive environments with interactive features can support more direct end-user involvement during design review. At the same time, the availability of immersive and interactive design review features does not necessarily result in active end-user involvement in practice. It is therefore important to better understand the conditions under which immersive environments influence end-user involvement and design review outcomes in real-world projects.

However, research on immersive HMD VR as a design review tool remains limited, particularly when compared with conventional 2D drawings in professional design settings. Existing comparison studies are often conducted in controlled experimental settings with student participants performing simplified tasks such as basic modelling exercises (Tastan et al., 2026), navigation tasks (Chrastil and Warren, 2013), or identification of predefined design issues (Umair et al., 2022; Gustafsson et al., 2025), rather than reviewing design proposals from ongoing projects, which raises questions about ecological validity. While such studies provide useful insight into spatial perception or evaluation of VR system usability, they do not fully reflect the complexity of design review in professional practice, where domain knowledge, a professional stake in review participation, and familiarity with the operational setting influence how designs are interpreted and evaluated (Shi et al., 2020; Han and Leite, 2021). As a result, there is still limited understanding of how immersive HMD VR affects end-users' interpretation of design proposals and their ability to engage in design review under conditions relevant to professional design practice.

A related issue concerns how end-users cognitively interpret different representational formats during design review. To explain how representational format may influence design review, this thesis draws on Cognitive Fit Theory (Vessey, 1991), which proposes that task performance, such as identifying design issues, improves when the way information is presented aligns with users' prior experience, including domain knowledge of work practice, and the cognitive demands of design review tasks (Vessey, 1991; Vessey and Galletta, 1991). Applied to design review, the theory suggests that the usefulness of conventional drawings or immersive HMD VR depends largely on how well they support end-users' mental models of the space being reviewed, their professional expertise, and their familiarity with interpreting spatial representations. These cognitive and human factors are difficult to capture in controlled experimental studies but strongly influence how design proposals are interpreted and

understood by end-users in real-world projects. This complexity is further reflected in design review practice, where multiple representational formats are often used together rather than drawings and immersive VR being treated as separate alternatives (Wingler et al., 2019; Buchanan et al., 2023), which can influence how design proposals are interpreted and how design issues are identified. End-users' ability to interpret representations and identify design issues therefore forms an important basis for how actively they can contribute during design review. This ability is shaped both by their domain experience of work practice and by the mental models they develop of the space being reviewed. While existing frameworks describe different forms and levels of user involvement in the field of building design (Caixeta et al., 2019), they provide limited insight into how design review activities are carried out in practice, particularly in relation to the representational formats used to support user interpretation. Understanding how such representational formats influence users' ability to interpret and evaluate design proposals is therefore important for assessing how immersive HMD VR may support end-user involvement during design review in real-world projects.

Still, immersive HMD VR is not the only configuration available for design review, and not all VR systems are equally suited to all design review tasks or different types of end-users. Alternatives include CAVE systems, desktop VR, and hybrid setups that combine HMD VR with shared displays or multitouch tables. Each configuration carries trade-offs. CAVE systems support co-located viewing but typically track only one user with correct stereoscopic perspective, which constrains multi-user use (Agrawala et al., 1997; Coburn et al., 2017). Desktop VR is widely accessible but offers limited spatial cues and weaker sense of presence (Slater & Sanchez-Vives, 2016). Hybrid setups, such as combining an HMD with a multitouch top-view table, can support both immersive evaluation and shared overview but require users to switch attention between user-interfaces and coordinate across different views of the same model (Roupé et al., 2020). Within immersive HMD VR itself, evidence is mixed. While it can reduce cognitive load by externalizing spatial reasoning, highly detailed or information-rich virtual environments can also increase cognitive load relative to simpler representations. Which configuration fits best therefore depends on the design review task, the end-users involved, and the conditions of the project (e.g., design phase, availability of hardware and trained facilitators). The work presented here focuses on immersive HMD VR and HMD-based hybrid configurations, including the ViCoDE setup that combines HMD VR with a multitouch table and a shared projector view. The focus reflects both the technical maturity and accessibility of HMD VR in current professional practice and its growing presence in real-world projects, conditions that also shaped which configurations were available in the cases studied. The thesis therefore does not claim that HMD VR is the optimal configuration in all design review situations; rather, it examines the conditions under which HMD VR and HMD-based hybrid configurations support end-user involvement in real-world projects.

Against this background, the thesis investigates how immersive virtual environments support end-user involvement during building design review. Particular attention is given to how end-users interpret building design proposals presented through different representational formats, including drawings, immersive VR, and combinations of these, and how they identify design issues. The research is based on real-world projects involving different types of end-users reviewing proposed building layouts using both conventional drawings and immersive HMD VR. By combining empirical studies of design review practice with theoretical perspectives from collaborative virtual environments, end-user involvement frameworks, and Cognitive Fit

Theory, the thesis examines the conditions under which immersive virtual environments support end-user involvement in design review.

## 1.1 Aim and research questions

The aim of this thesis is to investigate how immersive virtual environments can be used in practice to support end-user involvement, including Co-Design, during building design review. Specifically, the thesis examines how immersive environments influence levels of end-user involvement, collaborative interaction between end-users and other stakeholders, and the cognitive conditions under which end-users interpret and evaluate design proposals.

To address this aim, the thesis investigates three research questions that together explore how immersive virtual environments influence design review from three complementary perspectives: end-user involvement, collaborative interaction in the virtual environment, and cognitive conditions for evaluating design proposals.

### **RQ1: How can immersive virtual environments support higher levels of end-user involvement, including Co-Design, during building design review?**

End-user involvement is widely considered important in building design, particularly in environments such as healthcare where users possess critical knowledge about daily operations. Yet design proposals are often reviewed through representations intended for design professionals, such as technical drawings, which can be difficult for non-experts to interpret. This raises the question of whether alternative representational formats, such as immersive virtual environments, can better support meaningful end-user involvement during design review, and whether such formats can also enable higher levels of involvement, including Co-Design.

### **RQ2: How do interactive features in virtual environments shape collaboration during immersive design review?**

Levels of involvement are not determined by immersion alone, but also by how participants interact within the shared virtual environment. Design review typically involves discussions between multiple stakeholders, where collaboration is mediated not only through verbal communication but also through the interactive capabilities of the virtual environment itself. Features such as navigation, object manipulation, or the exploration of alternatives may influence how participants direct attention, communicate observations, and develop a shared understanding of the design proposal. RQ2 therefore moves from involvement as an outcome to the interactive features that shape collaboration between end-users and other stakeholders during immersive design review.

### **RQ3: How does cognitive fit between representational format, task demands, and end-user expertise influence end-user performance and involvement during design review?**

Collaborative review depends on what each participant is able to contribute individually, which in turn depends on whether the representational format allows them to interpret and evaluate the design within the cognitive demands of the task and their own domain expertise. With traditional 2D drawings, this often involves mentally transforming abstract representations into spatial understanding, which can demand considerable cognitive effort, particularly for non-experts. Immersive environments present spatial information in a more experiential format, potentially changing how users interpret and evaluate design proposals. RQ3 therefore turns from the collaborative dynamic to the individual cognitive conditions that make meaningful contribution to design review possible.

## 2 Related work

### 2.1 Design layout affecting building occupants' work practice

The building design has a direct impact on how work is carried out by end-users, affecting operational efficiency, safety, and communication. In settings like healthcare and education, where work practice is tightly linked to physical space, layout and design choices influence daily routines, collaboration, and the ability to respond to unexpected situations or fluctuating operational demands (Mourshed and Zhao, 2012; Frelin and Grannäs, 2021, 2022). In healthcare, for example, studies have shown that single-room layouts can reduce nurses' peripheral vision and awareness of patients and colleagues, which has been linked to reduced collaboration among healthcare staff due to physical separation (VanHeuvelen, 2019; Pruijsten et al., 2024). Another example is how during the COVID-19 pandemic, healthcare staff faced difficulties in quickly separating infected and non-infected areas, as well as adapting existing spaces for intensive care, making it harder to manage patients safely in overcrowded environments (Capolongo et al., 2020; Navaratnam et al., 2022). Similarly, studies exploring the effect of school building design on end-users have shown that classroom layout can significantly influence teachers' ability to collaborate with each other and supervise students (Frelin & Grannäs, 2022; Grannäs & Stavem, 2021). In adaptable classroom layouts featuring shared teaching zones with open sightlines or partial partitions, teachers have reported more frequent team-teaching, easier coordination of student groupings, and the ability to step in and assist each other during instruction without formal planning (Niemi, 2021; Fletcher et al., 2025; Grannäs et al., 2025). Still, other studies have found that in fully open-plan classrooms, high noise levels and the absence of defined instructional areas can make it difficult to maintain student attention during whole-class teaching, while traditional enclosed layouts often limit teachers' ability to monitor students working simultaneously in separate groups (Byers et al., 2018; Rance et al., 2023).

These examples highlight the need to design buildings in ways that support the work practice of the people who use them. This is especially important for building occupants such as healthcare staff or teachers, whose work depends on how physical space supports task flow, communication, and safe movement through their environment. Yet involving building occupants in the design process can be difficult, as they often have detailed knowledge of their own work practice but limited experience interpreting the design proposal via traditional representational formats such as conventional 2D drawings (Shi et al., 2020; Buchanan et al., 2022; Foroughi Sabzevar et al., 2025). Additionally, healthcare professionals and teachers often face time constraints due to demanding clinical workloads, rigid teaching schedules, and limited organizational support for participation during working hours, making it difficult for them to attend design review sessions (Pirinen, 2016; Støre-Valen, 2021; van Houwelingen et al., 2023). This becomes even more difficult because healthcare facilities and schools must accommodate complex operational requirements while also complying with regulatory and functional constraints (Azzopardi-Muscat et al., 2020; Soliman-Junior et al., 2021). They are also expected to support future needs, for instance, the integration of digital monitoring systems in healthcare facilities or the shift toward floor plan layouts that promote physical activity among young students (Huang et al., 2013; Brittin et al., 2015; Memari et al., 2022, 2025). In sum, these spaces directly shape how staff move, communicate, and carry out their tasks, design decisions about layout, visibility, and room placement can significantly influence the quality and

efficiency of day-to-day operations (Elf et al., 2015; Bjørn et al., 2021; Frelin and Grannäs, 2021).

Yet, project teams must coordinate input from multiple stakeholders and not only end-users, including, among others, architects, engineers and facility managers, each of whom brings different priorities and constraints to a building project (Daniels et al., 2019; Støre-Valen, 2021; Carroli et al., 2025). Still, it is end-users who have the real-world operational experience that other stakeholders do not have, resulting in many design issues being overlooked as they are only visible to end-users (Shultz and Jha, 2021; Lu et al., 2022). Moreover, as work practices change over time (e.g., development and use of new medical technology, shift towards student-centered teaching) (Naamati-Schneider and Alt, 2024; Aguilar-Moya et al., 2025), the knowledge of current building occupants is critical to make sure the building design fits how things work today, not based on assumptions on how they may have worked in the *past* (Leggat, 2008). This consideration also applies to stakeholders who previously worked in operational roles but now contribute in other capacities (e.g., facility planners or user representatives), as their earlier experience may not fully reflect current needs or challenges (Arthur Jr. et al., 1998; Vlasblom et al., 2020). In addition, the literature describes a disconnection between decisions made during early phases of the design process and end-user (e.g., healthcare staff) outcomes, such as workflow efficiency and staff working conditions (Lawson, 2013; Elf et al., 2024). At the same time, end-users are not always familiar with a project's regulatory, structural or budgetary constraints (Carthey, 2021; Young and Cleveland, 2022). As a result, functional building designs tend to emerge only when other project stakeholders who understand these constraints provide input during design review, ensuring that the building functions as intended (Simonsen et al., 2022). Therefore, a more accurate and shared understanding of the final building design requires the involvement of all relevant stakeholders, particularly end-users.

## **2.2 End-user involvement in the building design process**

In architectural design, involving end-users has long been promoted as a way to create spaces that work well for their everyday activities and fit the specific conditions of the project. This idea gained momentum with the participatory design (PD) movement in Scandinavia during the 1960s and 1970s, which aimed to give unions and workers influence over decisions about their work environments. Instead of leaving workers to simply accept design decisions made by designers and management, the PD approach recognized that while workers are not design professionals, they have unique knowledge of their daily tasks (e.g., task sequence, workflows, ergonomic needs) that is needed to design workplaces that improve work conditions (Johansson et al., 2002; Sundblad, 2011; Simonsen and Robertson, 2012). Over time, these ideas shifted from a workplace setting to building design, where involving end-users became a way to ensure that spaces support real activities rather than preconceived assumptions (e.g., how nurses circulate between patient rooms and supply areas, or how office workers collaborate in shared spaces) (Granath et al., 1996; Sfandyarifard and Tzortzopoulos, 2011; Caixeta et al., 2019; Caixeta and Fabricio, 2021; Olsson et al., 2022). In practice, engaging users early helps identify critical aspects of a space that directly affects how the building design can be used (e.g., logistical flows, room sizes, sightlines, adjacency needs). Doing so ensures that layouts and design solutions reflect how spaces are actually used, rather than how project stakeholders, such as designers, facility planners, or project leaders, assume they will be used based on generic formulations in design guidelines (Carthey, 2013; Soliman-Junior et al., 2021), previous design review experience (Thyssen et al., 2010; Olsson et al., 2022), or oversimplified interpretations

of end-user needs (Kujala, 2003; Stern et al., 2003; Tampio et al., 2022). In other words, end-user involvement can help bridge the gap between the technical expertise of architects and planners (responsible for e.g. building codes, design guidelines, project requirements), the priorities of project leaders (responsible for e.g. budgets and schedules), and the lived experience of building occupants who use these spaces on a daily basis (Eriksson et al., 2015; Carthey, 2021; Larsen et al., 2021).

In this setting, end-user involvement is not only about collecting end-user feedback, but also, actively incorporating end-users in decision-making throughout the design process. Specifically, an active involvement of end-users has been described as important to close the gap during design review between the intention of involving end-users and the realization of their contributions in practice (Caixeta et al., 2019; Olsson et al., 2022; Åsgård et al., 2024). Still, terminologies such as end-user involvement and participation are widely used, and as highlighted by earlier studies, used arbitrary and interchangeably (Carpentier, 2016; Caixeta et al., 2019; Räisänen et al., 2024). With the lack of conceptual consensus on what end-user involvement can mean, arguments have been made that involvement risks taking place on the premise of false expectations (Choguill, 1996). As a result, end-users may be viewed as alibis in the design process, with their involvement becoming passive rather than an active one (Christiansson et al., 2011; Nazeer et al., 2024).

To address the lack of conceptual consensus on terminologies used to describe end-user involvement, efforts have been made to develop classification models for different levels of involvement in building design. One of the earliest and most influential examples is Arnstein's (1969) "*Ladder of Citizen Participation*", developed as part of citizen participation in urban planning and with the aim of showing that involvement is dependent on who holds decision-making authority. Arnstein (1969) illustrated involvement as eight rungs on a ladder, ranging from non-participation where involvement is used as a façade to legitimize decisions (manipulation and educating users), to symbolic forms (users are consulted or informed but have no decision-making authority to influence outcomes) and finally to shared decision-making (partnership, delegated power, citizen control). The ladder analogy emphasized that involvement varies by how much decision-making authority is shared with citizens. Later, Wulz (1986) adapted Arnstein's idea to architectural design, framing involvement as a scale that shifts between two poles: from architect-led design (representation, where the architect interprets user needs and makes all decisions) to user-led design (self-decision, where the user acts as a designer, making all planning and design decisions). Also building on Arnstein's (1969) ladder, Choguill (1996) argued that the highest level of participation is not always the most desirable or achievable. Instead, she emphasized that the "best" level of participation is determined by the broader setting in which participation takes place and critiqued the assumption that higher levels of involvement are always preferable. Davidsson (1998) further added to the point of choosing an appropriate level of involvement, using Arnstein's (1969) classification as a reference, but, instead of a ladder-based shape, developed a wheel-shaped classification. This was done to highlight that the goal is not to reach the top, but to identify and agree on the most appropriate type of participation for each project. Unlike Arnstein (1969) and Choguill (1996) who argued that user-involvement is mainly determined by project leaders or authorities, Davidsson (1998) places greater emphasis on collaborative decision-making. Davidsson (1998) argued that decisions about the appropriate form and level of user involvement should be jointly discussed and agreed upon by project leaders and participants in the design process. Otherwise,

if decisions about involvement are not made collaboratively, projects may end up offering only information to users, with little opportunity for active involvement.

More recently, Caixeta et al. (2019) reviewed existing classifications of user-involvement in both architectural and non-architectural fields, examining how different levels of involvement are defined and include the above studies by Arnstein (1969), Wulz (1986), Choguill (1996) and Davidsson (1998). They found that although user-involvement is widely discussed, studies differ in the selected criteria used as metric (e.g., decision-making power, user roles) to distinguish levels of involvement and how different levels of involvement are defined. For example, representing and informing users (Wulz, 1986; Damodaran, 1996) or participatory design and Co-Design (Granath et al., 1996; Sanders and Stappers, 2008; Ho and Lee, 2012). Based on their findings, Caixeta et al. (2019) present a new classification for user involvement in a building design setting: Informative, Consultative and PD/Co-Design. In the Caixeta et al. (2019) study, each level of involvement is distinguished by the range of influence that users or their representatives have over the final products (Bergvall-Kåreborn and Ståhlbrost, 2008; Caixeta et al., 2019). At the Informative level, users share their needs, preferences, and requirements with the design team and are informed about the building design in return. The Consultative level corresponds to an increased level of involvement and is described as when users give feedback on a set of predefined design options. Lastly, PD and Co-Design are set at the highest level of involvement and separated based on what the focus of the user-involvement is. PD refers to users actively involved throughout the design process, while Co-Design emerges when users act as members of the design team and revise and develop design solutions together with other project members (e.g., architects, engineers) or independently. As described in their study, Caixeta et al. (2019) argue that Co-Design is appropriate when users' *experiences and knowledge are pertinent to the design action*.

To this end, the classification of Caixeta et al. (2019), although contributing with a contextual understanding of user-involvement within building design, does not answer the question of *how* these design actions are done, i.e., methods used for involvement (2D drawings, rendered images, immersive VR etc.). Nor is it clearly explained whom *users* refers to, although it is implied that it is end-users, but not what type of end-user (e.g., building occupant, client representative). During a design review session both choice of method and type of user participating are considered key factors that set the conditions for user-involvement, and specifically, intended level of involvement (Wulz, 1986; Sfandyarifard, 2013; Nazeer et al., 2024; Åsgård et al., 2024). Even though the importance of method choice during user-involvement is well documented in both early and later research, few studies have evaluated how different methods for involvement influence end-users' ability to express their wants and needs about the design proposal (Dulgeroglu, 1977; Luck, 2003; Eriksson et al., 2015; Kim et al., 2016; Caixeta and Fabricio, 2021). Instead, the few studies that have evaluated method choices' influence on end-user involvement have focused on user experience (e.g., perceived usefulness, method preference) rather than actual design review performance (e.g., number and time needed to identify issues) (Payne et al., 2015; Kim et al., 2016; Tampio et al., 2023; Byci Jakupi and Xhambazi, 2024). As such, studies suggest that end-user involvement is likely to remain at an informative level when there is a mismatch between the intended level of involvement and the method used to support it (Eriksson, 2013; Soikkeli et al., 2023). Taken together, for end-user involvement to be collaborative and allow participants to be more actively involved during design review, especially at higher levels such as PD and Co-Design, it is important that all involved project members have a shared understanding of the building design

and the issues to be resolved (Loyola, 2019; Dane et al., 2024; Jouppila, 2025; Vasarainen et al., 2025). Shared understanding is shaped by how information is conveyed, whether through 2D drawings, physical mock-up rooms, or immersive VR. The choice of representational format, and the degree of spatial understanding it provides for each participant, can therefore have a significant impact on how actively users are able to contribute during design review.

### 2.3 Spatial understanding in representational formats

Among end-users involved in design review, building occupants (e.g., healthcare staff) typically focus on understanding how a proposed building design will affect future work practices (e.g., spatial layout, visibility, proximity). In contrast, other stakeholders involved during design review, such as facility planners and design team members, often prioritize building code compliance, project requirements, feasibility constraints, and project budget. These different perspectives mean that design review typically becomes a negotiation process between end-users and other types of involved stakeholders (Caixeta et al., 2019; Jouppila, 2025). Specifically, decisions about the building design must not only comply with regulatory and technical constraints but also support the operational needs of those who will work in the building (Carthey, 2021; Jouppila, 2025).

In practice, however, design review is often organized around a limited number of sessions involving multiple stakeholder groups (Stichler, 2016). During these sessions, end-user feedback is typically documented and later interpreted and incorporated by the design team in subsequent design iterations rather than being resolved within the session, unless it can be addressed without requiring trade-offs across stakeholder priorities (Luck, 2007; Jouppila, 2025). As a result, design issues that require negotiation across operational needs, regulatory constraints, and project requirements are commonly addressed in later sessions. Under these conditions, there is a risk that attention shifts toward resolving already identified issues, while other design issues that could have been identified by building occupants remain unnoticed, increasing the risk of rework after construction is completed (Yap et al., 2016; Taghizadeh et al., 2021).

In time-limited design review sessions, the extent to which design risks are identified is closely linked to how easily end-users, and building occupants in particular, can understand and evaluate the design proposal (Souza et al., 2023; Nazeer et al., 2024). When representational formats impose high cognitive demands, a substantial portion of the available time and mental resources may be spent on interpreting the representation itself rather than on identifying design issues or collaboratively exploring alternative solutions. From a cognitive load perspective, this reduces the mental capacity available for higher-level reasoning, discussion, and decision-making during design review (Zimmerer and Matthiesen, 2021; Lavrsen and Daalhuizen, 2024). This is particularly relevant in situations where end-users must mentally reconstruct spatial relationships or anticipate how proposed layouts will support everyday work activities. When a large share of cognitive resources is allocated to interpreting the representation itself, fewer resources remain for identifying design issues, reflecting on operational implications, or contributing to collaborative design discussions (Higuera-Trujillo et al., 2021; Gustafsson et al., 2025). Such demands are especially evident when representational formats require users to infer spatial and functional implications from abstract or fragmented information. When the representational format aligns poorly with the demands of the design review task or with end-users' prior experience of the work environment, the conditions for developing a shared

understanding of the building design are weakened. This misalignment can be understood in terms of cognitive fit (Vessey, 1991; van der Land et al., 2013), and is particularly critical for building occupants whose contributions depend on being able to quickly relate the design proposal to their work practice experience (Andrews et al., 2023; Souza et al., 2023).

Yet, these design reviews are typically conducted using 2D drawings, a representational format widely regarded as limited in its ability to support the spatial understanding required for end-users to accurately interpret and identify design issues during the early phases of the design process (Dadi et al., 2014; Shi et al., 2020; Paes et al., 2021; Foroughi Sabzevar et al., 2025). Studies have shown that end-users without architectural training, such as building occupants, often struggle to interpret drawings, which rely on abstract lines and symbolic representations and require prior familiarity with reading such materials. From a cognitive load perspective (Krukar and Schultz, 2025; Park et al., 2026), interpreting 2D drawings requires stakeholders to mentally reconstruct fragmented spatial information into a coherent three-dimensional understanding of the space, placing demands on working memory that may reduce the cognitive resources available for identifying design issues. Comparison studies using three-dimensional desktop models suggest that such representational differences can influence cognitive load and task performance, with participants identifying more predefined design issues in 3D model reviews than when using 2D drawings (Umair et al., 2022; Gustafsson et al., 2025). Cognitive load in these studies is commonly assessed using the NASA Task Load Index (NASA-TLX) questionnaire (Hart, 2006), a widely validated multidimensional subjective workload measure that captures mental demand, effort, frustration, and related factors across a wide range of tasks.

Notably, studies using the NASA-TLX indicate that cognitive load and performance are not always directly related, and that higher perceived workload does not necessarily imply reduced task performance (Hart, 2006; Grier, 2015). Research further suggests that there is no universal threshold for an ‘optimal’ level of cognitive load. Performance may decline when workload becomes excessive, yet high perceived effort does not automatically lead to reduced performance and can, in some cases, be maintained or even improved under high cognitive load depending on task characteristics and expertise (Paas et al., 2003; Das Chakladar and Roy, 2024). Conversely, performance can also deteriorate when task demands are very low and engagement decreases (Hart, 2006; Grier, 2015). Together, these findings indicate that the relationship between representational format, cognitive load, and design review performance varies across different design review situations. From a cognitive fit perspective (Vessey and Galletta, 1991; van der Land et al., 2013), such effects can be understood in terms of how well representational formats align with task demands and users’ prior experience, particularly domain knowledge of work practice. This alignment is critical in building design review, where building occupants must quickly relate abstract design representations to operational scenarios and ensure that design issues affecting their work practice are not overlooked. As a result, when representational formats impose high cognitive demands or do not align with users’ expertise, building occupants may overlook design issues that affect work practices, which has motivated increasing interest in alternative representational approaches that better support spatial understanding during design review (Wingler et al., 2019; Buchanan et al., 2023).

A promising representational format for design review is immersive virtual reality (VR). Through VR, users can explore a 1:1 scale computer-generated environment that simulates real-world perception (Paes et al., 2017, 2021; Wolfartsberger, 2019; Nikolić and Whyte, 2021). The degree to which this simulated experience is achieved is referred to as *immersion*, which

depends on technological factors such as field of view, real-time motion tracking, and user interaction with virtual objects (Slater and Sanchez-Vives, 2016; Triberti et al., 2025). Real-time tracking allows natural body movements—such as turning or bending—to influence perception of space. In head-mounted display (HMD) systems, users are visually enclosed by the headset, which can reduce conflicting spatial cues compared with other immersive VR systems such as CAVE projections, where parts of the physical environment may still be visible (Castronovo et al., 2013; Cummings and Bailenson, 2016). Higher immersion enhances the sense of presence, the feeling of ‘being there’ in the virtual environment, which supports spatial understanding and allows users to evaluate design features as if physically in the space (Prabhakaran et al., 2022a, b).

In regard to cognitive fit, immersive virtual environments have been shown to support design review by presenting information in a form that better aligns with the spatial demands of design review tasks, thereby facilitating individual understanding of design proposals (van der Land et al., 2013). However, the immersive nature of these environments and the way users interact with them may also introduce additional cognitive load during collaborative evaluation. This suggests that the benefits of immersive VR depend not only on representational alignment, but also on whether cognitive resources are spent evaluating design implications rather than interpreting the environment itself. Such effects are reflected in empirical studies showing that, from a cognitive load perspective, immersive HMD VR can reduce perceived cognitive load during design review tasks compared with conventional 2D drawings and non-immersive 3D desktop environments, often accompanied by improved identification of predefined design issues (Han and Leite, 2021; Umair et al., 2022; Gustafsson et al., 2025; Tastan et al., 2026). These effects are commonly assessed using the NASA Task Load Index (NASA-TLX), a widely used multidimensional measure of perceived workload (Hart, 2006). At the same time, findings are not consistent. Some studies suggest that highly detailed or information-rich immersive environments may increase cognitive load, particularly when environmental details do not directly support the review task (Schrader and Bastiaens, 2012; Im et al., 2025). Other studies indicate that the ability to directly perceive and interact with spatial information can support more active information processing, potentially offsetting increased sensory input (Pimentel & Teixeira, 1993). In design review sessions, the influence of environmental detail and representational fidelity on cognitive load remains underexplored (Im et al., 2025; Joo et al., 2025), although recent studies suggest that even limited visual cues can influence perceived spatial qualities such as room size and sightlines (Kitamoto and Yamada, 2026). These findings are particularly relevant to research examining how immersive VR affects the identification of design issues during review tasks.

Prior studies show that immersive HMD VR improves end-user task performance during design reviews by enabling detection of spatial and workflow-related issues difficult to assess in 2D drawings. In healthcare projects for example, immersive HMD VR has helped staff identify design flaws, test workflows, and assess visibility and equipment placement in real time, rather than interpreting them from static representations (Roupé et al., 2020; Shultz and Jha, 2021). Similarly, studies related to classroom design highlight how use of VR can help architects better understand teachers’ needs and requirements for classroom layout that support multiple pupil activities (Piroozfar et al., 2022). In sum, end-users, as well as other types of involved stakeholders, can via immersive HMD VR reason for spatial qualities (e.g., room size, sightlines, and workflow) through perception and movement rather than abstract mental transformation. Nevertheless, while visual immersion alone increase spatial understanding among end-users,

recent research suggests that interactive features (multi-user, object interaction, free exploration etc.) not only support more rapid identification of design issues (Truong et al., 2021; Johansson and Roupé, 2022), but also allow end-users to make direct changes to the design proposal (Roupé et al., 2020; Nikolić and Whyte, 2021; Whyte and Nikolić, 2024), and thereby accelerate the design review cycle loop. As a result, end-users can be more actively involved during design review than with static virtual representations alone.

## 2.4 Interactive features in VR for collaborative design review

While immersive HMD VR already supports spatial understanding by presenting the design at full scale and from a first-person perspective, the addition of interactive features further enables end-users to interact directly with the virtual representation of the building design. These interactive features can also create better conditions for other stakeholders, such as design team members and facility planners, to understand for example how the design proposal being reviewed, influences for example, updated work practices among building occupants (e.g., teaching, providing healthcare) (Wingler et al., 2019; Jouppila, 2022), or how project constraints related to building codes and requirements can be satisfied (Alghamdi et al., 2017; Foroughi Sabzevar et al., 2025).

In this thesis, interactive features such as object interaction and exploration are defined according to what LaViola et al. (2017) describe as fundamental interaction tasks. These tasks are considered necessary for users to accomplish objectives in a 3D environment and include object selection, object manipulation, travel, and system control. Specifically, object interaction encompasses both object selection (identifying and selecting objects) and object manipulation (adjusting an object's position and rotation). LaViola et al. (2017) further define exploration as a subclass of the travel task, where users do not have an explicit movement goal but instead navigate the environment to gather spatial information, observe objects, and develop an understanding of the virtual space. For multi-user functionality, this thesis adopts the definition by Churchill & Snowdon (1998), which describes a Collaborative Virtual Environment (CVE) as a computer-based, distributed virtual space where people can meet and interact with others, agents, or virtual objects. Immersive HMD VR is not inherently a CVE; rather, it can function as one when specific features supporting collaboration review are added, such as shared virtual space, embodied avatars, awareness cues, and synchronous interaction with shared objects.

Depending on the set of interactive features available in the virtual environment, end-user involvement can range from individuals freely exploring and evaluating different design layouts (Hahm et al., 2007), to collaborative design processes in which end-users, architects, and other stakeholders make real-time changes, thereby accelerating the design cycle (Roupé et al., 2020; Ehab et al., 2023).

For example, research has shown that when users are able to freely navigate virtual environments, they are more likely to identify spatial issues and provide detailed feedback on layout and functionality (Chrastil and Warren, 2013; Huang, 2023). The argument is that exploring the building design freely allows for a more thorough understanding, as all points of interest (i.e., unidentified design issues) are not necessarily known in pre-defined walkthroughs or static representational formats (e.g., conventional 2D drawings with fixed viewpoints, 3D view on a flat screen) (Berg et al., 2017; Haahr and Knak, 2022). Similarly, multi-user feature has shown to accelerate the overall lead time during design review, as the shared frame of reference and use of non-verbal cues (e.g., gesturing, pointing at objects) in the virtual

environment allows for immediate and more accurate real-time feedback between different involved stakeholders doing design review (Truong et al., 2021; Johansson and Roupé, 2022).

Lastly, object interaction as an interactive feature, such as adjusting an object's position and rotation or adding and deleting objects in the virtual environment (LaViola et al., 2017), has been shown to help end-users identify design issues that are difficult to detect in visual-only virtual environments (Wolfartsberger, 2019). In addition, when combined with multi-user functionality, object interaction enables end-users and other involved stakeholders, such as design team members, to collaboratively explore alternatives and develop new design solutions within the virtual environment (Roupé et al., 2020). As a result, faster consensus on design changes can be made while jointly identifying and developing design solutions that adhere to both project requirements and building occupants' needs and wants (Roupé et al., 2020). Still, few studies focus on object interaction as a variable in design review (Paes and Irizarry, 2018). This can be due to technical factors, such as software limitations and interoperability constraints. In addition, non-technical factors, including traditional workflows in which design changes are typically made using non-immersive representational formats by design team members, affect the conditions for implementing features such as object interaction (Du et al., 2018; Panya et al., 2023; Spittle et al., 2023; Rehman et al., 2025). In sum, these factors limit immersive HMD VR use in design reviews to visualization only, instead of real-time design iteration of the architectural proposal viewed in the virtual environment.

These limitations, however, are not unique to immersive HMD VR. They reflect broader challenges within the Collaborative Virtual Environment (CVE) field, where interactive features, such as object interaction and multi-user features, are viewed as essential for realizing key collaborative criteria. Specifically, CVE literature emphasizes shared context, awareness of others, negotiation and communication, and having access to flexible and multiple viewpoints (Snowdon et al., 2001). In this way, CVE principles help frame end-user involvement in immersive environments as an active Co-Design process, rather than limited to a passive or purely informative form of involvement.

## 2.5 Collaborative Virtual Environments

Collaborative Virtual Environments (CVEs) are defined as computer-based, distributed virtual spaces in which people can meet and interact with others, with agents, or with virtual objects (Churchill et al., 2001). From early definitions (Churchill et al., 2001), collaboration has been central to CVE systems, extending beyond individual visualization to support synchronous interaction among multiple users working toward a shared task. CVEs have therefore been proposed as virtual environments for facilitating early-stage collaboration between designers, end-users, and other stakeholders, particularly when spatial and functional coordination is critical (Churchill et al., 2001; Snowdon et al., 2001). Immersive systems based on head-mounted displays (HMD VR) can be understood as current CVEs that combine embodied immersion with interactive features supporting collaboration. Similar to earlier CVE systems, immersive HMD VR can support coordination between users with different roles and expertise. By presenting the design through a shared visual representation, CVE systems such as immersive HMD VR help reduce differences in how participants interpret the design and reason about spatial and functional aspects of the environment. From a cognitive fit perspective, immersive collaborative environments may support individual understanding of design proposals by presenting information in a format that aligns more closely with how building

occupants typically understand space when considering how they will use it. Such alignment can facilitate initial interpretation of spatial information on an individual level, thereby providing more favorable conditions for discussing design implications and identifying issues during collaborative review (van der Land et al., 2013). These forms of collaborative support reflect established criteria for collaboration in CVE systems (Roupé et al., 2016, 2020).

Early theoretical work on CVEs has specified these criteria by describing the forms of interaction and representation required for collaborative work in virtual environments (Churchill et al., 2001). These include shared context (e.g., users interacting with the same virtual environment or object when reviewing specific design elements), awareness of others (e.g., perceiving others' presence and activity through avatars or non-verbal cues), negotiation and communication (e.g., using speech, gestures, or shared object manipulation to discuss and resolve design issues), and access to flexible and multiple viewpoints (e.g., switching between 2D plans and immersive perspectives depending on task demands) (Churchill et al., 2001). Related to these criteria is the distinction between what researchers refer to as action space and reflection space, both considered characteristics of CVE systems (Arias et al., 2000; Fischer et al., 2005). Action space refers to the part of a CVE system's interface that supports collaborative activity, where users jointly and incrementally construct a shared understanding of the design problem, while reflection space refers to the part of the interface that supports individual exploration and validation, allowing users to examine the consequences of design decisions made in the action space. Together, these spaces support collaborative design by enabling users to alternate between shared design activity and individual assessment of design outcomes (Roupé et al., 2020).

In CVEs used for architectural design, interaction and representation mechanisms have different relevance depending on the task (e.g., informative walkthrough versus design review) and the type of end-user involved. For instance, a simple distance-measure feature may be a poor indicator of visibility or work-practice implications for building occupants in a complex interior environment, while the same measurement tool may be valuable for facility planners or stakeholders with similar backgrounds when assessing whether distances between structural and non-structural elements comply with accessibility requirements for wheelchair users. This task- and stakeholder-dependent relevance of interactive mechanisms remains largely unexplored in immersive HMD VR and the CVE literature more broadly. Only in recent years have advances in hardware (e.g., tracking precision, display fidelity, and real-time processing capability), and VR software (e.g., more stable rendering performance, synchronized multi-user environments), made interactive features such as multi-user and multi-scale readily available for immersive HMD VR (Ibayashi et al., 2015; Truong et al., 2021).

These developments improve the conditions for evaluating how CVE systems, such as immersive HMD VR, can fulfil established CVE criteria and support building design review for end-users. They also make it possible to explore how end-users with different backgrounds interpret and evaluate the same virtual space from distinct perspectives. Specifically, relevant knowledge needed to solve the task is distributed across participants and must be brought together through shared interaction with the content represented in the virtual space and communication around it (Salomon, 1997; Arias et al., 2000; Fischer et al., 2005). This is particularly relevant in design review sessions. In this thesis, immersive HMD VR is examined as a CVE in cases where it was configured with the features needed to support collaborative review, namely multi-user with awareness of other users, a shared virtual space, and

synchronous interaction with shared design objects (as specified per case in Section 3.2). Where such features are present, immersive HMD VR can support higher levels of end-user involvement, including Co-Design.

Achieving this requires understanding how individual participants cognitively engage with and are able to perform their task in a virtual environment, as collaboration depends on participants being able to contribute on the basis of their own, individual, understanding of the task at hand. In this respect, cognitive load becomes critical at the level of individual engagement. During design review, participants must construct and refine a mental representation of the proposed environment in order to assess its spatial and functional implications. Constructing such a representation requires cognitive effort and depends on how clearly spatial relationships, scale, and functional elements are perceived within the virtual environment. The conditions under which these individual mental representations are formed therefore influence how effectively participants can contribute to collaborative evaluation and shared understanding (van der Land, 2013).

Despite the strong theoretical foundations of CVEs and the increasing technical maturity of immersive systems, the relationship between individual cognitive engagement, task performance, and collaborative outcomes has rarely been examined in real-world architectural design review settings. Early CVE research in the 1990s shifted focus from hardware and software challenges toward users' tasks; however, study participants were largely novices, enabling controlled laboratory experiments with undergraduate students rather than skilled domain professionals (Arias et al., 2000). This reliance on student participants has persisted well into the 2010s and is reflected more broadly in reviews of immersive VR research in the built environment (Han and Leite, 2021; Johansson and Roupé, 2024). To this point, recent studies highlight the need for empirical investigations involving larger and more diverse participant groups, particularly expert practitioners, to provide more reliable evidence on the use of immersive VR in real design practice (Sepasgozar, 2020; Paes et al., 2021; Sornoza-Parrales et al., 2025).

These reviews also indicate that studies are predominantly small-scale and exploratory, with a main focus on proof-of-concept testing rather than evaluation in real-world project settings (Prabhakaran et al., 2022a; Sornoza-Parrales et al., 2025). For example, Kim et al. (2013) classified 150 journal articles published between 2005 and 2011 and found that only 36 studies (26%) addressed collaborative use of VR systems, with only two involving immersive head-mounted display (HMD) technology. Fewer than 9.3% of the reviewed studies combined usability evaluation (e.g., user experience and perceived ease of use) with effectiveness measures (e.g., accuracy of spatial judgments, error detection), and only 7.3% involved industrial practitioners and tested systems in real projects. Based on the distribution of studies reviewed by Kim et al. (2013), this corresponds to an average of approximately 4.6 quantitative effectiveness studies and 2.7 comparative studies (immersive VR systems compared to other representational formats) per year during the 2005–2011 period. As a result, there remains uncertainty regarding whether immersive VR systems lead to measurable improvements in user performance in construction-related applications such as design review. This uncertainty is largely due to the limited availability of quantitative and comparative evidence across representational formats and user groups (Paes et al., 2017). More recent reviews indicate that these limitations persist despite advances in hard- and software linked to immersive HMD VR systems. For example, Yu et al., (2022) show that academic research on immersive virtual

environments for design collaboration has not kept pace with technological development. While visualization itself is a central component of design review, much of the existing research stops at evaluating perceptual qualities of the virtual environment, with comparatively fewer studies examining how users actually perform, communicate, and evaluate design proposals during collaborative review tasks. Similarly, Derouech et al., (2024) show in their CVE literature review, including HMD VR systems, how recent studies have explored social dynamics, interaction design, and user experience. Still, much of this work emphasizes user experience and interaction quality and is rarely linked to systematic quantitative measures of task performance or cognitive demands during design review. Therefore, this indicates that empirical evidence remains limited regarding how current immersive HMD VR systems support end-users in cognitively demanding design review tasks under real-world conditions.

The scarcity of quantitative, real-world studies also raises concerns about the ecological validity of existing research on immersive HMD VR for end-user involvement during design review. Design review practice varies across project settings and relies heavily on domain knowledge, yet many studies involving student participants fail to reflect the practical limitations and unequal roles that shape real-world projects. For example, in healthcare facility design, opportunities for healthcare professionals to participate directly in design review are often limited, as managers or representatives typically speak on behalf of entire units (Stichler, 2016; Jouppila, 2025). Moreover, the long lifespan of healthcare buildings means that staff may encounter only one or two such opportunities during their careers (Thompson et al., 2012; Clark, 2014). These conditions increase the risk of miscommunication between designers and end-users, since they often use different terms and have different experience interpreting architectural representations (Cesario, 2009; Reno et al., 2014; Bazzaro et al., 2018). As a result, limited end-user input during design review can undermine the project team's shared understanding of the building design, increasing uncertainty and ambiguity in decision-making (Hey et al., 2007). To keep the design process moving forward, designers often rely on assumptions (Koskela, 2000), which, if incorrect, may lead to costly rework later in the project lifecycle (Gomes and Tzortzopoulos, 2018). Immersive virtual environments can facilitate the articulation and alignment of stakeholder perspectives during design review, thereby enabling the identification of design issues that might otherwise be overlooked (Kim et al., 2016; Yu et al., 2022, 2024)

The three theoretical fields used in this thesis, Cognitive Fit Theory, CVE collaboration criteria, and end-user involvement frameworks, operate at different levels but work together rather than in parallel. Cognitive fit operates at the individual level and concerns how representational format aligns with the user's task and domain expertise. CVE collaboration criteria and end-user involvement frameworks operate at the collective level and concern how individuals act together within a shared representation. The argument made in this thesis is that the individual level conditions the collective level. When the representational format aligns with the task and the user's expertise, cognitive resources are freed from interpreting the representation itself and become available for contributing to shared review (van der Land et al., 2013). When the format is misaligned, cognitive resources are spent on interpreting the representation, and what an individual can contribute to collaboration is constrained, regardless of how the session is organized. Individual cognitive fit is therefore treated as a necessary, though not sufficient, precondition for more effective collaborative review and for the higher levels of end-user involvement described in the participatory-design literature. This framing also implies that no single representation is universally appropriate, and that the question of what fits is not

reducible to a binary contrast between immersive VR and 2D drawings. Rather, what fits depends on the configuration of user, task, and project condition. A building occupant evaluating workflow and visibility may benefit more from immersive HMD VR, while a facility planner checking accessibility compliance against a layout may benefit more from conventional 2D drawings, and many real review situations involve both user groups and both task types within the same session (Caixeta et al., 2019; Carthey, 2021). Immersive VR is therefore used in this thesis not as a representational format or as a participatory tool in isolation, but as a representational configuration whose cognitive consequences shape what end-users can contribute to collaborative review. Through that contribution, the configuration also shapes the level of involvement that becomes possible in a given project setting.

Against the above framing, prior research reveals a gap between the theoretical and technical potential of CVEs, including immersive HMD VR systems, and the empirical evidence needed to assess their effectiveness in real-world architectural design review settings. Although immersive visualization is often described as advantageous for end-users, uncertainty remains regarding how immersive VR compares to traditional representational formats in supporting task performance. A recurring challenge is the lack of objective and comparable evaluation metrics, particularly when effectiveness is examined in terms of cognitive demands and user performance (Paes and Irizarry, 2018). As a result, many existing studies rely on qualitative or exploratory approaches and primarily report usability-oriented outcomes (e.g., perceived ease of use, satisfaction, or presence), while providing limited quantitative evidence on how representational format, task demands, and professional expertise jointly shape design review outcomes within CVE-supported environments (Kim et al., 2013; Paes et al., 2017). Recent work therefore highlights the importance of comparative studies conducted in real projects with domain expert end-users, using interactive immersive systems that reflect contemporary CVE criteria (Paes et al., 2017; Sepasgozar, 2020; Sornoza-Parrales et al., 2025). In response, this thesis investigates how immersive virtual environments, including multi-user and other interactive features, support end-user involvement during design review. It further examines how cognitive fit between representational format, task demands, and professional expertise shapes individual task performance, which is necessary for effective collaboration and Co-Design.



## 3 Research methodology

### 3.1 Research approach

This thesis deals with how immersive virtual environments are used to support end-user involvement during building design review in real-world building projects. To investigate this phenomenon, the research adopts a mixed-methods research approach combining qualitative and quantitative data. This is an embedded mixed-methods design (Creswell and Creswell, 2017): qualitative data is primary across Papers 1–3, with a quantitative component embedded in Paper 4 to make one specific format contrast (2D vs. immersive HMD VR) directly comparable under matched conditions. At the thesis level, the qualitative and quantitative findings are also compared against each other through methodological triangulation in the cross-case synthesis (Section 3.6), so that conclusions are supported by more than one type of evidence

Both the qualitative and quantitative work sit within a single multiple case study research design (Yin, 2018), which provides the structure for examining immersive design review across several real-world building projects. Within this design, qualitative observations, interaction analyses, and quantitative measures of cognitive load and task performance were used, described in detail in Section 3.3 (data collection) and Section 3.4 (data analysis). In this thesis, a case refers to immersive design review situations in which end-users evaluate specific spatial environments within ongoing building projects (e.g., ICU units, emergency wards, or classrooms). Case study research is well suited for investigating contemporary phenomena within real projects where multiple sources of evidence are required (Yin, 2018).

The empirical material consists of 11 building projects (9 healthcare and 2 elementary school), 13 cases, and 63 design review sessions. The breakdown is given in Section 3.2 and Table 1. In addition, Paper 4 includes quantitative analysis of cognitive load (NASA-RTLX) and issue identification performance, enabling comparison of design review conducted using immersive virtual environments and conventional 2D drawings. Combining qualitative observations with quantitative performance measures provides a more comprehensive understanding of how immersive virtual environments influence both participation in design review and the identification of design issues. This combination follows the embedded design described above. In other words, qualitative observations explain how design review unfolded in context, while the quantitative measures in Paper 4 make the format contrast directly comparable.

The research follows an abductive research approach, where theoretical perspectives and empirical observations were developed in parallel and informed each other throughout the research. Rather than moving linearly between theory and data, the research evolved through an iterative process in which insights from empirical design review sessions influenced theoretical framing, while theoretical perspectives helped guide subsequent data collection and analysis. This iterative interplay between theory and empirical material corresponds to what Dubois and Gadde (2002) describe as systematic combining, where the research direction gradually develops as the phenomenon under study becomes more clearly defined. Figure 1 illustrates how the three fields of research, empirical material, and methodological choices relate and jointly interplay with the research phenomenon, and together informed the development of the thesis.

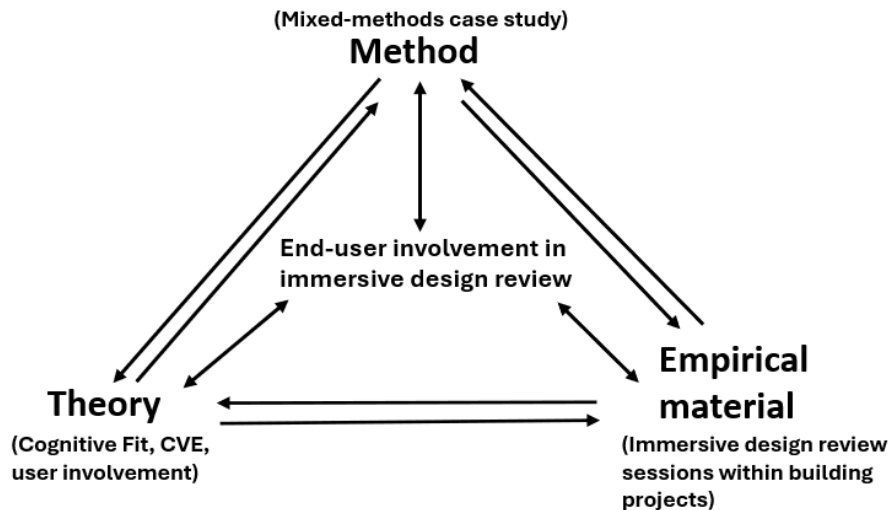


Fig. 1: Relationships between theory, empirical material, and methodological approach in the thesis research design. Adapted from: (Dubois and Gibbert, 2010).

The figure also highlights the role of theory in the research design. The three theoretical fields used in this thesis, cognitive fit, collaborative virtual environment (CVE) research, and end-user involvement frameworks, were selected because they address different aspects of immersive design review. Cognitive fit helps explain how spatial representations influence understanding and task performance, while CVE and end-user involvement research provide perspectives on collaboration and participation during design review. Together, these perspectives informed how immersive design review situations were examined and interpreted in relation to end-user involvement. The figure illustrates how theoretical perspectives, empirical material, and methodological choices were considered together and informed the development of the study.

### 3.2 Multiple case study research

This thesis examines end-user involvement in immersive design review as a single overarching phenomenon, studied across multiple building projects and empirical investigations. To describe the empirical material consistently, the following terms are used throughout the chapter: a building project is the real-world setting that contains one or more cases; a case is a design review situation in which end-users evaluated a specific spatial environment (e.g., an ICU bedspace, emergency ward, or classroom) using immersive virtual environments; a design review session is the empirical event in which a case was studied (a workshop, observed project meeting, or scheduled VR session); and a study is the research investigation reported in each appended paper. Across the four appended papers, the thesis draws on 11 building projects (9 healthcare and 2 elementary schools) and 13 cases (8 in Paper 1, 1 in Paper 2, 1 in Paper 3, and 3 in Paper 4), examined through 63 design review sessions.

The remainder of this chapter first describes the healthcare and school cases (Sections 3.2.1 and 3.2.2), then the data collection (3.3), data analysis (3.4), research process (3.5), cross-case synthesis (3.6), and reflections on research quality (3.7).

The empirical work presented in the four included papers draws on immersive design review activities conducted within several healthcare and school building projects. These building

types were selected because building design directly affects how occupants work, interact, and use space in their daily activities. Such projects typically involve multiple stakeholder groups, specialized functional requirements, and ongoing design negotiations, making them suitable settings for studying end-user involvement in immersive design review. The intention is not to suggest that the findings generalize across all building types, but rather to examine immersive design review situations where user involvement is particularly consequential for decision-making (Ulrich et al., 2008; Woolner, 2010).

These projects involved architects, facility planners, client representatives, and building occupants such as healthcare staff and teachers. In this thesis, cases were defined as specific spatial environments examined during immersive design review within the participating building projects, such as ICU units, emergency wards, or classrooms. The selection of cases was therefore determined by the design review situations made available within the participating projects rather than by predefined sampling, since access to design review processes was not specified at the start of the PhD project and depended on what participating projects could make available. The cases span different project phases, design challenges, and levels of user involvement, allowing exploration of how immersive design review operates under varying practical conditions. Figure 2 provides representative examples of the building projects included in the thesis. The empirical material includes healthcare facility projects (Papers 1 and 4) and school projects (Papers 2 and 3), some of which (Cases E and F in Paper 1; all three cases in Paper 4) involved immersive multi-user design review. While some analyses (the quantitative comparisons in Paper 4) focus on specific subsets of cases (specifically Paper 4's Cases A–C) depending on available data, such as the quantitative comparisons in Paper 4, the cases collectively represent real applications of immersive design review across different building types. These stakeholder groups are not treated as a homogeneous category in this thesis. They differ in domain knowledge of the work practice the building supports and in prior experience with design review, and Section 3.6.1 operationalizes these differences explicitly.



*Fig. 2. Representative immersive VR environments used during design review in healthcare (upper row) and school projects (lower row).*

The conducted multiple case study in this thesis supports analytical rather than statistical generalization (Yin, 2018). Accordingly, the study aims to develop insights that may inform similar situations where immersive virtual environments are used for design review, particularly in building types with intensive operational requirements, such as healthcare and educational facilities, where building design directly affects occupants' work practices. Across the cases included in this thesis, data collection took place within ongoing healthcare and educational building projects where research access was available. Because these cases reflect specific project situations rather than statistically representative samples, statistical analyses (Paper 4) help clarify patterns within the studied cases rather than support population-level generalization. Comparing findings across different projects, stakeholder groups, and representational formats also enables methodological triangulation, where converging qualitative observations, interaction analyses, and quantitative performance measures strengthen the credibility of conclusions regarding cognitive load, task performance, and collaborative design review.

### **3.2.1 Healthcare building projects**

The healthcare cases included in this thesis were examined within several ongoing healthcare building projects, although some of these projects have since been completed. Immersive virtual environments were introduced as part of design review activities involving architects, healthcare staff, facility planners, and client representatives. Healthcare building projects are characterized by complex functional requirements where spatial layout, equipment configuration, and workflow directly influence clinical practice, communication, and patient safety (Joseph and Rashid, 2007; Ulrich et al., 2008). This makes end-user involvement particularly relevant during design review, as there are few opportunities for end-users, such as building occupants, to express their wants and needs regarding the design proposal (Jouppila, 2025).

Table 1 summarizes the healthcare cases included in the thesis, outlining project type, design phase, purpose of VR use, and available interactive features. The table provides a descriptive overview of the empirical material rather than presenting case findings. In some projects, multiple related environments were examined within the same building project. These are distinguished in Table 1 using labels such as C1 and C2, which indicate different spatial environments examined within the same project (e.g., separate ICU rooms, or classrooms in different parts of the building). Each healthcare case represents a design review situation in which immersive virtual environments were used to evaluate specific spatial environments within an ongoing healthcare building project.

**Table 1.** Overview of healthcare cases included in the thesis, indicating the purpose of VR use, design phase, interactive features, and number of VR sessions.

Case (within project)	Purpose for using VR	Project phase, interactive features and number of VR sessions	Paper
<b>Case A.</b> The ICU unit for a whole hospital floor	<ul style="list-style-type: none"> <li>Explore how alternative visual- and information mediums could provide better understanding for future workplace and validate design requirements</li> </ul>	<b>Technical design phase</b> <ul style="list-style-type: none"> <li>Exploration</li> <li>Single-user</li> <li>4 VR-sessions</li> </ul>	<b>Paper 1</b>
<b>Case B1-B2.</b> The psychiatric ward, including patient rooms, administrative area and dining area	<ul style="list-style-type: none"> <li>Inform healthcare staff of the design of the new facility and provide healthcare staff with an accurate insight into their future workplace</li> </ul>	<b>Concept design &amp; technical design phase</b> <ul style="list-style-type: none"> <li>Exploration</li> <li>Single-user</li> <li>2 VR-sessions</li> </ul>	<b>Paper 1</b>
<b>Case C1-C2.</b> (various facilities) Various types of operations and common areas independent of a particular operation	<ul style="list-style-type: none"> <li>Inform and explore how alternative visual- and information mediums could address certain design issues more accurately (e.g., sightline from ICU control room, logistical flow)</li> </ul>	<b>Concept design, spatial coordination, and technical design phase.</b> <ul style="list-style-type: none"> <li>Exploration</li> <li>Single-user</li> <li>30 VR-sessions</li> </ul>	<b>Paper 1</b>
<b>Case D.</b> ICU unit and hyperbaric chamber	<ul style="list-style-type: none"> <li>Explore an alternative visual- and information medium to validate set spatial requirements in final design review before construction document were handed over</li> </ul>	<b>Technical design phase</b> <ul style="list-style-type: none"> <li>Exploration</li> <li>Single-user</li> <li>8 VR-sessions</li> </ul>	<b>Paper 1</b>
<b>Case E. (ViCoDE)</b> Unit of obstetrics and gynecology - Robot assisted surgical room	<ul style="list-style-type: none"> <li>Explore an alternative visual- and information medium that can address design issue related to fitting new surgical room in existing space</li> </ul>	<b>Concept design phase</b> <ul style="list-style-type: none"> <li>Exploration</li> <li>Multi-user</li> <li>Object interaction</li> <li>2 ViCoDE-sessions</li> </ul>	<b>Paper 1</b>
<b>Case F.</b> A single radiology room with adjacent corridor and common area	<ul style="list-style-type: none"> <li>Explore an alternative tool that can address design issue related to fitting new radiology operation room in existing space</li> </ul>	<b>Technical design phase</b> <ul style="list-style-type: none"> <li>Exploration</li> <li>Multi-user</li> <li>Object interaction</li> <li>3 VR-sessions</li> </ul>	<b>Paper 1</b>
<b>Case P4-A.</b> Emergency ward including reception, triage room, orthopedic emergency unit	<ul style="list-style-type: none"> <li>Address overcrowding, limited patient capacity, and outdated layouts affecting staff workflow and patient safety.</li> </ul>	<b>Preparation and brief</b> <ul style="list-style-type: none"> <li>Exploration</li> <li>Multi-user</li> <li>Object interaction</li> <li>1 VR-session</li> </ul>	<b>Paper 4</b>
<b>Case P4-B.</b> ICU units and ICU medication room	<ul style="list-style-type: none"> <li>Address corridor congestion, insufficient bedspace layouts, and obstructed sightlines affecting workflow and patient supervision.</li> </ul>	<b>Preparation and brief</b> <ul style="list-style-type: none"> <li>Exploration</li> <li>Multi-user</li> <li>Object interaction</li> <li>1 VR-session</li> </ul>	<b>Paper 4</b>
<b>Case P4-C.</b> Emergency ward including workstation and monitor room	<ul style="list-style-type: none"> <li>Replace an outdated facility with limited equipment capacity and undersized spaces that did not meet clinical standards.</li> </ul>	<b>Preparation and brief</b> <ul style="list-style-type: none"> <li>Exploration</li> <li>Multi-user</li> <li>Object interaction</li> <li>1 VR-session</li> </ul>	<b>Paper 4</b>

The healthcare cases listed in Table 1 (Cases A-F in Paper 1 and Cases P4-A-P4-C in Paper 4) contribute to the analyses presented in Paper 1 and Paper 4, while the school building cases (Elementary school project in Papers 2 and 3) presented later contribute to Paper 2 and Paper 3. Across the healthcare cases, immersive virtual environments were used to support design review in different project phases, ranging from early concept development to later technical design stages, as illustrated in Figure 3. The projects varied in scope, including both new construction and renovation of existing buildings. These variations provided opportunities to examine how immersive virtual environments were used under different project conditions while maintaining a focus on end-user involvement during design review.

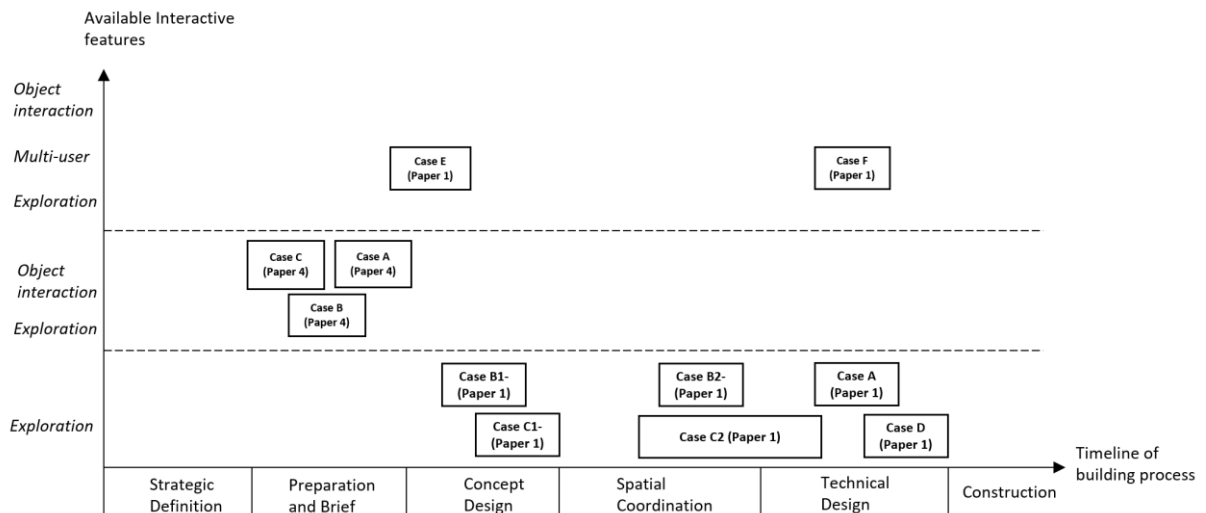


Fig. 3. Overview of healthcare cases within the studied building projects (Table 1), showing the project phases in which the cases were examined and the interactive features available in the immersive environments.

Figure 3 provides an overview of the healthcare cases in relation to project phases and available interactive features in the immersive environments. In this thesis, interactivity refers to the types of interactive features available to users during design review, including exploration of the virtual environment, object interaction, and multi-user collaboration. Exploration refers to users' ability to freely navigate the virtual environment to examine spatial arrangements, identify potential design issues, and develop an understanding of the proposed spatial environment. Object interaction refers to selecting and manipulating spatial elements (e.g., fixed and movable furnishings or equipment), including adjusting their position or orientation to evaluate alternative configurations. The multi-user feature allows multiple participants to be present simultaneously in the same virtual environment, supporting a shared frame of reference and discussion of design proposals. Together, these interactive features can influence how end-users interpret design proposals and engage in design review.

### 3.2.2 School building projects

School building projects were included as cases to examine immersive design review in environments where spatial layout directly influences daily work practices, communication, supervision, and movement between educational activities. Schools involve multiple stakeholder groups, including teachers, school leadership, facility planners, architects, and

client representatives, whose perspectives on space use may differ. End-user involvement during design review is therefore important for identifying spatial requirements related to teaching activities, student supervision, and shared learning environments. In the school cases studied here, this perspective was represented through client representatives involved in the design process, since direct teacher access was limited (see Section 3.3). Compared with healthcare building projects, school projects typically focus less on clinical workflow and safety requirements but still require careful consideration of visibility, spatial flow between classrooms and shared areas, and accommodation of different age groups.

In the school cases, immersive virtual environments were used during design review in several project phases: preparation and brief (Paper 3), concept design (Paper 3), spatial coordination (Paper 3), and technical design (Paper 2). The design review sessions focused on evaluating spatial layout, visibility conditions, furnishing arrangements, and relationships between different learning environments using immersive virtual environments. These cases provided opportunities to examine how immersive design review supported end-user involvement in educational projects where spatial organization directly affects teaching practices.

In the school cases, interactive features were particularly oriented toward supporting shared orientation and discussion of overall building layouts. In Paper 2, this included multi-user collaboration combined with a multi-scale feature allowing participants to shift between full-scale (1:1) and reduced-scale (1:40) representations within the same immersive environment. Similar to Case E in Paper 1, Paper 3 used the CVE system ViCoDE, which supported both immersive user interfaces (immersive HMD VR) and non-immersive interfaces (multitouch table and projected display), enabling participants to engage with the design through different representational formats during review. Together, these school cases provide an additional setting for examining how immersive virtual environments support end-user involvement when stakeholders evaluate both classroom-level spatial conditions and overall building layout relationships. Table 2 summarizes the school project types, design phase, purpose of VR use, available interactive features, and number of VR sessions. Unlike the healthcare cases, the two school cases sit at preparation/brief, concept design, and spatial coordination phases (Paper 3) and at technical design (Paper 2); a separate figure is not provided as the visual would carry only two markers.

**Table 2.** Overview of school building projects included in the thesis, indicating the purpose of VR use, project phase, interactive features, and number of VR sessions.

Case (within project)	Purpose for using VR	Project phase, interactive features and number of VR sessions	Paper
Classrooms, shared learning spaces, connecting hallways and food court	<ul style="list-style-type: none"> <li>VR was introduced when 2D drawings and 3D models were found insufficient for achieving adequate spatial understanding among project participants.</li> </ul>	<b>Technical design phases</b> <ul style="list-style-type: none"> <li>Exploration</li> <li>Multi-user</li> <li>Multi-scale</li> <li>2 VR-sessions</li> </ul>	<b>Paper 2</b>
Classrooms, woodshop, school cloakroom and shared learning spaces	<ul style="list-style-type: none"> <li>Although the project initially relied on 2D drawings, the shift toward VR was driven by the client’s recognition that drawings and rendered images did not provide sufficient spatial understanding.</li> </ul>	<b>Preparation &amp; brief, conceptual design, spatial coordination</b> <ul style="list-style-type: none"> <li>Exploration</li> <li>Multi-user</li> <li>Multi-scale</li> <li>Object interaction</li> <li>3 VR-sessions</li> </ul>	<b>Paper 3</b>

### 3.3 Data collection

Table 3 provides an overview of the empirical data included in the four appended papers of this thesis. The data were collected across several healthcare and school projects through design review sessions, interviews, and workshops involving different stakeholder groups, including building occupants, client representatives, facility planners, and architects. The data are organized according to participant groups (end-users and design team members), type of data collection activity (e.g., design review sessions, workshops, interviews), and project type. In some projects, multiple related environments were examined within the same building project. The overview in Table 3 illustrates how the four appended papers relate to one another and clarifies the project settings underpinning the four appended papers. Detailed descriptions of interview procedures, workshop formats, and design review sessions are provided in the respective papers.

**Table 3.** An overview of the collected data in the four appended papers.

	Participant group	Data collection method	Reviewed environment
Paper 1	3 BIM coordinators, 8 project leaders, 4 facility planners, 4 architects, 13 building occupants	32 semi-structured interviews supported by 2 ViCoDE workshops, several VR workshops (>10), a study visit	Healthcare facility projects that included 2 ICU units, a psychiatric clinic, a hyperbaric chamber, a robot assisted surgical room and a radiology room
Paper 2	An assisting project leader, a project leader, 4 client representatives, a design manager, an interior architect, 2 architects	2 workshops supported by open-ended discussion where participants shared experience of using VR for design review purposes	Classrooms, shared learning spaces, connection hallways and food court
Paper 3	2 client representatives, 2 exterior architects, 1 interior architect	8 semi-structured interviews with 6 exterior architects and 2 client representatives, 3 ViCoDE workshops	Classrooms, woodshop, school cloakroom and shared learning spaces
Paper 4	111 healthcare staff (nurses, assistant nurses, doctors) and 21 non-healthcare staff (facility and functional planners, project leaders)	3 project-team design review sessions, 6 days end-user design review (2D+VR/VR-only), 8 semi-structured interviews with project team members	Different healthcare facility projects including 1 renovation and 1 new build of emergency ward as well as an ICU unit

Across the appended papers, participants were selected to represent relevant stakeholder roles in ongoing building projects, including end-users such as healthcare staff and teachers, as well as architects, planners, and project representatives. In the healthcare projects, end-users primarily consisted of healthcare staff who work directly in the facilities, together with other stakeholders involved in the operational planning of the units, such as facility planners and project representatives. In the school building projects, the operational perspective was instead represented by client representatives involved in the design process rather than teachers as everyday users of the spaces. Selection criteria varied depending on each paper's focus but generally included involvement in the design process, prior experience with design review practices, and access to relevant project material, such as room data sheets or BIM models (e.g., Revit or IFC files) from which VR models could be generated. These stakeholder groups differ in their familiarity with conventional design representations and in their everyday use of the spaces being designed, and are therefore not treated as a single homogeneous user category. Section 3.6.1 specifies how role and expertise are operationalized in the cross-case synthesis:

organizational labels are treated as case-level descriptors, with role used where appropriate as a proxy for domain knowledge and prior experience with 2D-based design review.

Participant selection was also influenced by practical access to stakeholders within the ongoing projects. Specifically, during the school building projects, access to teachers as everyday users of the classroom environments was limited due to availability constraints. Lastly, the inclusion of multiple project types and representational formats (e.g., conventional 2D drawings and immersive VR) allowed the thesis to capture variations in how stakeholders engage with design proposals, supporting both qualitative analysis of user involvement and quantitative assessment of design review performance.

### 3.3.1 Design review setting

The collaborative design review sessions examined in this thesis took place within ongoing building projects and were conducted either as scheduled sessions coordinated with project teams (Papers 2–4) or as observed project meetings (Paper 1). Depending on practical access constraints in each project, sessions were held either on-site within healthcare facilities to enable a larger number of participants without affecting clinical operations, or at the university (Chalmers) where the ViCoDE system was available, with examples of these settings shown in Figure 4. In most cases, immersive virtual environment sessions followed earlier design reviews conducted using conventional representational formats such as 2D drawings or rendered images. These prior materials formed part of the project documentation and served as a reference point for participants' subsequent evaluation of design proposals in VR.



*Fig. 4: Examples of design review settings in healthcare facility projects with healthcare staff (top row) and school building projects with client representatives and architects (bottom row).*

The duration of sessions varied across projects. In Papers 2, 3, and 4, sessions were organized as dedicated workshops lasting several hours, while in Paper 1 existing design review sessions were observed and detailed timing information was not consistently documented. Across the appended papers, design review sessions formed part of ongoing projects while simultaneously providing the empirical basis for this research. This allowed immersive design review to be examined under real project conditions, including constraints related to project schedules and, in the healthcare projects, clinical operations.

### 3.3.2 CVE systems and VR-model preparation

Across the appended papers, immersive virtual environments were mainly implemented using immersive HMD VR systems to support design review in ongoing building projects. These systems typically consisted of VR-ready computers connected to HMDs with handheld controllers (e.g., HTC Vive, Oculus rift, Oculus Quest 3) enabling navigation, spatial exploration, and interaction with virtual environments. Interaction capabilities varied across cases and included object interaction, spatial exploration, and multi-user collaboration, following established classifications of interaction in collaborative virtual environments (Churchill et al., 2001; LaViola et al., 2017).

In addition to standalone immersive VR setups, two cases (Case E in Paper 1 and Paper 3) employed the Virtual Collaborative Design Environment (ViCoDE) system, which integrates immersive HMD VR systems with complementary user-interfaces such as a multitouch table and projected shared views. The multitouch interface provides a top-down facility visualization allowing users to pan, zoom, and manipulate BIM-based components (e.g., furniture and medical equipment) through drag-and-drop interaction. Changes (i.e., moved objects in the VR-model) made on the multitouch table are updated in real-time across connected user-interfaces, enabling synchronous collaborative design review among users.

Virtual environments used in Papers 2–4 were typically generated from Building Information Modelling (BIM) data, including Revit or IFC models, and prepared for immersive review using the BIMXplorer VR viewer (Johansson & Roupé, 2024), as illustrated in Figure 5. Instead of focusing primarily on geometric simplification to improve rendering performance, VR models were prepared to support interaction with both fixed building elements and loose objects such as furniture and medical equipment. This involved removing objects within the review areas from the imported BIM model and reintroducing them as individual *prefabs*—reusable BIM-derived components (Revit families) containing metadata and preview information (Johansson et al., 2023). Prefab organization was informed by project material such as Room Data Sheets (RDS) or equipment databases, including the Swedish national healthcare database PTS (Program for Technical Standard) (PTS, n.d.). This preparation enabled participants to interact with different aspects of the design proposals, including spatial layout, building elements, and movable objects, allowing them to focus on elements most relevant to the design review questions addressed during the session.

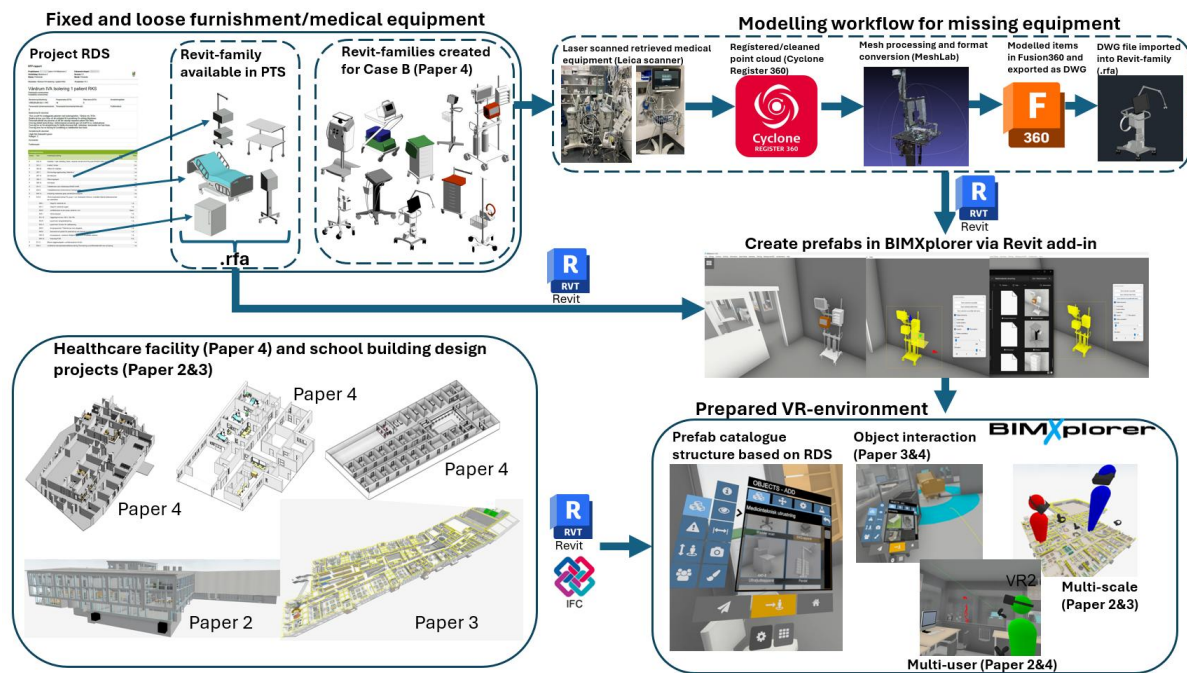


Fig. 5: Workflow for preparing BIM-based architectural models for interactive immersive VR design review across the studied projects. Adapted from Paper 4.

### 3.3.3 Data types collected

Across the four appended papers, multiple types of empirical data were collected from design review sessions to capture both the review processes and participants' experiences of different representational formats. These included observational data from design review sessions, interview material, questionnaire responses, and documentation of identified design issues.

Observational data primarily consisted of recordings and field notes from immersive VR design review sessions and related workshops (Paper 2 and 3). These materials captured participants' interactions with virtual environments, discussions among stakeholders, and reflections emerging during design evaluation activities. In Paper 4, design review sessions involved both conventional 2D drawings and immersive VR environments, enabling comparison of how design issues were identified across representational formats.

Interview data were collected through semi-structured interviews with project stakeholders, including end-users such as healthcare staff, facility planners, client representatives and project leaders, as well as design team members (interior- and exterior architects). The interviews focused on experiences of design review processes, use of representational formats, and perceived value of immersive environments for design review and collaboration.

Quantitative questionnaire data were collected in Paper 4 specifically examining cognitive load and task performance during design review. These included standardized instruments such as the NASA Raw Task Load Index (NASA-RTLX) questionnaire (Hart and Staveland, 1988), alongside counts of identified design issues under different review conditions, namely 2D and immersive HMD VR design review, or VR-only design review.

## 3.4 Data analysis

### 3.4.1 Qualitative analysis

Qualitative analysis was used to understand how immersive virtual environments were applied in design review practice and how different representational formats influenced participants' engagement, collaboration, and identification of design issues across the appended papers. The qualitative data included interview transcripts, observations from design review sessions, workshop discussions, and documentation of identified design issues.

In Paper 1, analysis focused mainly on observational material and interviews to understand how immersive VR was introduced and used in real healthcare facility projects. Papers 2 and 3 examined workshops with architects, client representatives, and end-users, focusing on how participants interacted with the virtual environments and how these interactions supported collaborative design review. In Paper 3 in particular, attention was given to patterns of interaction, including how participants engaged with the CVE system and how this influenced involvement in design discussions.

More systematic qualitative coding was conducted in Paper 4, where design review sessions were documented and identified design issues were categorized to support comparison between representational formats (2D drawings and immersive HMD VR). Interview material from project stakeholders was also analyzed to describe how design review was carried out within ongoing projects.

### 3.4.2 Quantitative analysis

Quantitative analysis was conducted in Paper 4 only. The reason is empirical: it was not until the final year of the PhD project that access to a sufficiently large and comparable end-user sample ( $n = 132$  across three healthcare projects) became available, which made matched-condition comparison feasible. Earlier in the project, the empirical material was qualitatively rich but unevenly distributed across stakeholder groups, which would not have supported a credible quantitative comparison. Quantitative data (NASA-RTLX ratings on an ordinal 20-point scale, and counts of identified design issues) were analyzed using non-parametric tests appropriate for ordinal data and small subgroups: Wilcoxon signed-rank for within-participant 2D-vs-VR comparisons, Mann–Whitney U for between-group comparisons, Kruskal–Wallis with Bonferroni-corrected Dunn's post-hoc for cross-case comparisons, and Spearman's  $\rho$  for correlations between cognitive load, self-rated performance, and objective performance.

Comparisons were made between review conditions involving conventional 2D drawings and immersive VR environments, as well as between participant groups with different professional backgrounds. The number of identified design issues was used as an indicator of task performance during design review.

Statistical comparisons including correlation analysis were done to examine differences between representational formats and participant groups. In Paper 4, qualitative interview data was primarily used to support interpretation of the quantitative results, providing additional insight into participants' experiences of cognitive load, spatial understanding, and perceived advantages or limitations of different representational formats.

## 3.5 Research process

### 3.5.1 Research timeline

Figure 6 illustrates the research process of this PhD project from its start in April 2021 to the completion of the doctoral thesis and the doctoral defense in June 2026. The timeline highlights key milestones that have shaped the development of the research, including conferences, journal publications, and the licentiate seminar. Filled circles indicate journal papers included in the thesis, while hollow circles represent conference papers produced during the PhD project, with the CAADRIA and CONVR 2024 papers forming part of the thesis. The lower part of the figure shows the empirical investigations and data collection activities conducted in both school and healthcare building projects. These activities include multiple design review sessions and project phases that form the empirical basis for the appended papers and ongoing research in the thesis.

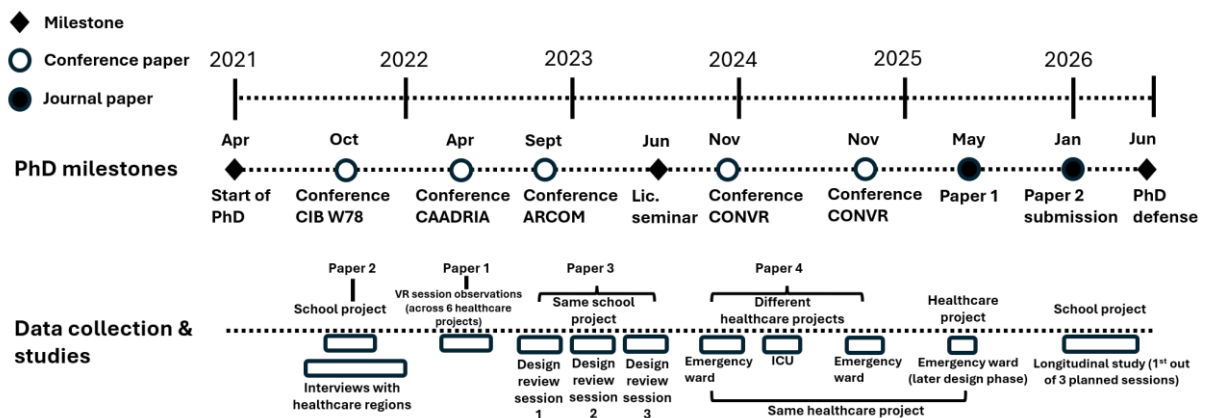


Fig. 6: Research timeline of the PhD project showing key milestones, empirical investigations, and appended papers.

The empirical research presented in this thesis is based on a series of empirical investigations conducted in ongoing building projects within the healthcare and school building sectors. These investigations involved design review sessions in which end-users and other project stakeholders evaluated design proposals using different representational formats, including conventional 2D drawings and immersive virtual reality environments. The investigations were carried out across multiple projects and design phases, allowing the research to examine design review practices across different projects and stages of the design process. The collected empirical material forms the basis for the four appended papers included in the thesis. Some appended papers cover multiple design review sessions within the same project (Paper 3), while others cover design review sessions across different projects (Papers 1 and 4) or across different design phases within the same project (Paper 4). Together, these investigations provide the foundation for exploring how immersive virtual environments support end-user involvement and design review in real-world building projects.

During the early phase of the PhD project, the research focused on reviewing literature on design review practices, end-user involvement, and immersive virtual environments. Part of the empirical material used in Paper 1 builds on data originally collected during my master thesis, which was further developed and analyzed during the PhD project. The COVID-19 pandemic

temporarily affected access to field sites, particularly healthcare facilities, which required adjustments to planned design review sessions. For example, design review sessions were organized at the university with client representatives rather than on-site with building occupants (Paper 3). Also, at the time of the school project cases, access to teachers as everyday users of the classroom environments was limited due to availability constraints. Consequently, the school design reviews involved client representatives and architects participating in the design process rather than teachers as direct users of the spaces. Toward the later stages of the PhD project, access to teachers became available through separate collaborations with schools, enabling subsequent investigations to involve teachers as end-users. As access to project sites was limited during this period, most doctoral courses were completed during the first two years of the PhD project in order to allow later phases of the research to focus on data collection in real-world projects.

In the later stages of the PhD project, additional cases were examined in healthcare projects. These investigations focused on how different representational formats, including conventional 2D drawings and immersive virtual reality environments, influenced end-users' ability to interpret design proposals and identify design issues during design review. Several design review sessions were carried out across different projects and phases of the design process, forming the basis for Papers 3 and 4. These investigations enabled comparisons between representational formats and provided insights into how immersive environments support end-user participation and design review performance in real-world project settings. These investigations, together with the earlier ones described above, are analyzed and discussed in the four appended papers included in this thesis.

### **3.6 Cross-case synthesis and analytical strategy**

The 13 cases reported across the four appended papers were not examined as a single coordinated comparative study. They differ in project type, design phase, participant groups, VR system configuration, available interactive features, and data collection methods. This heterogeneity reflects how immersive VR is used in real-world projects rather than under controlled study conditions. At the same time, it means the cases cannot be compared directly as if they had been examined under matched conditions. Cross-case claims at the kappa level therefore rely on an explicit synthesis strategy that preserves each case's within-paper analysis before any cross-case comparison is made.

The kappa-level synthesis follows Yin's (2018) case-based approach to multiple-case study research. In this approach, each case is first analyzed within its own project context (e.g., its specific participants, design review setting, and method). These within-case analyses are reported in the appended papers themselves. The kappa then takes these within-case findings and develops cross-case patterns across the 13 cases through interpretation, rather than by counting cases as if they were data points. The aim is not to produce a general claim that "VR works" by aggregating across cases. Instead, the synthesis works toward higher-order concepts that the cases together point to (Yin, 2018). In this thesis, that higher-order concept concerns how Cognitive Fit Theory, traditionally treated as an individual-level framework, also shapes collaborative design review. The synthesis proceeds in three steps, summarized in Figure 7.

In the first step, each case's within-case findings, established in the appended papers, are preserved in their original project context before any cross-case comparison is made. The within-case analyses themselves were conducted within each appended paper, on each

individual case, and are not repeated at the kappa level. What the thesis adds is the cross-case mapping in Step 2 and the inference-level sorting in Step 3. Findings were read in relation to each paper's specific project, participants, and methods (left column of Figure 7), rather than being treated as if they were directly comparable to findings from other papers. This keeps each case's contribution in its own context before any cross-case comparison takes place.

In the second step, within-case findings from each paper were mapped onto a set of analytical dimensions so that the cases could be compared despite their differences in project type, phase, and method. The six dimensions came from re-reading the four appended papers and applying two criteria. The first criterion was whether the dimension was documented in each of the four appended papers in enough detail to describe each case on that dimension. The second criterion was whether the dimension was relevant to the thesis's research questions (RQ1–RQ3) and grounded in at least one of the three theoretical fields used in this thesis, namely Cognitive Fit Theory, CVE collaboration criteria, and end-user involvement frameworks. Other factors appeared within individual papers, such as level of detail in the VR model, degree of photorealism, project size, and specific HMD hardware, but were not used to compare cases because they were not documented consistently across all four appended papers. These factors remain part of the within-case findings preserved in Step 1.

The dimensions, shown in the center column of Figure 7, are: (i) representation format (e.g., 2D drawings, immersive HMD VR, projector screen, multitouch table); (ii) interactive features; (iii) end-user role and expertise; (iv) type of design review task (e.g., spatial functionality, workflow, equipment layout, building-code compliance); (v) project type and setting (brief, concept, spatial coordination, technical design phases; healthcare versus educational); and (vi) observed design review outcomes (design issues identified, cognitive load, decision-making roles, collaboration patterns). The first five dimensions describe how each design review was set up. The sixth describes what was observed during it. Table 3 (Section 3.3) describes the empirical material underlying each appended paper. Table 4 records the analytical mapping used in the synthesis. The mapping is not meant to combine the four papers into a single comparison. Rather, it makes clear where the cases can be compared and where they differ, which in turn determines what types of cross-case claim each paper can support in Step 3.

In the third and final step, cross-case claims from the Step 2 mapping are sorted into three inference levels, ranked from strongest support at the top to weakest at the bottom (right side of Figure 7). Each claim is based on a primary paper whose study design directly supports it. Some claims also draw on secondary papers, which observed something consistent with the claim even though their main study focus was different. How well a claim holds up at any level depends on what role each dimension plays in supporting it. Figure 7 shows three such roles, used throughout the synthesis. A dimension is manipulated or varied (M) when it differs across the cases being compared, giving the claim the difference it is built on. It is held constant (C) when it stays the same across the comparison, ruling out alternative explanations for the difference. It is the outcome (O) when it is what gets observed or measured, where the claim is tested.

Case naming follows each appended paper's convention, which reflects how each paper structured its empirical material. Where a paper studied multiple project sites, cases are letter-coded (Paper 1: A through F across six healthcare projects, with B1/B2 and C1/C2 marking distinct VR uses within the same project; Paper 4: A, B, and C across three healthcare projects, referred to as P4-A through P4-C in this thesis to distinguish them from Paper 1's cases). Where

a paper studied a single project site, the case is referred to by setting (Paper 2 and Paper 3). The unit of analysis is the case, defined in Section 3.2 as a design review situation in which end-users evaluated a specific spatial environment using immersive virtual environments. The four appended papers together examine 13 such cases, which form the basis for the cross-case synthesis.

# Cross-case synthesis across appended papers

Adapted from Yin's (2018) case-based approach to multiple-case study research

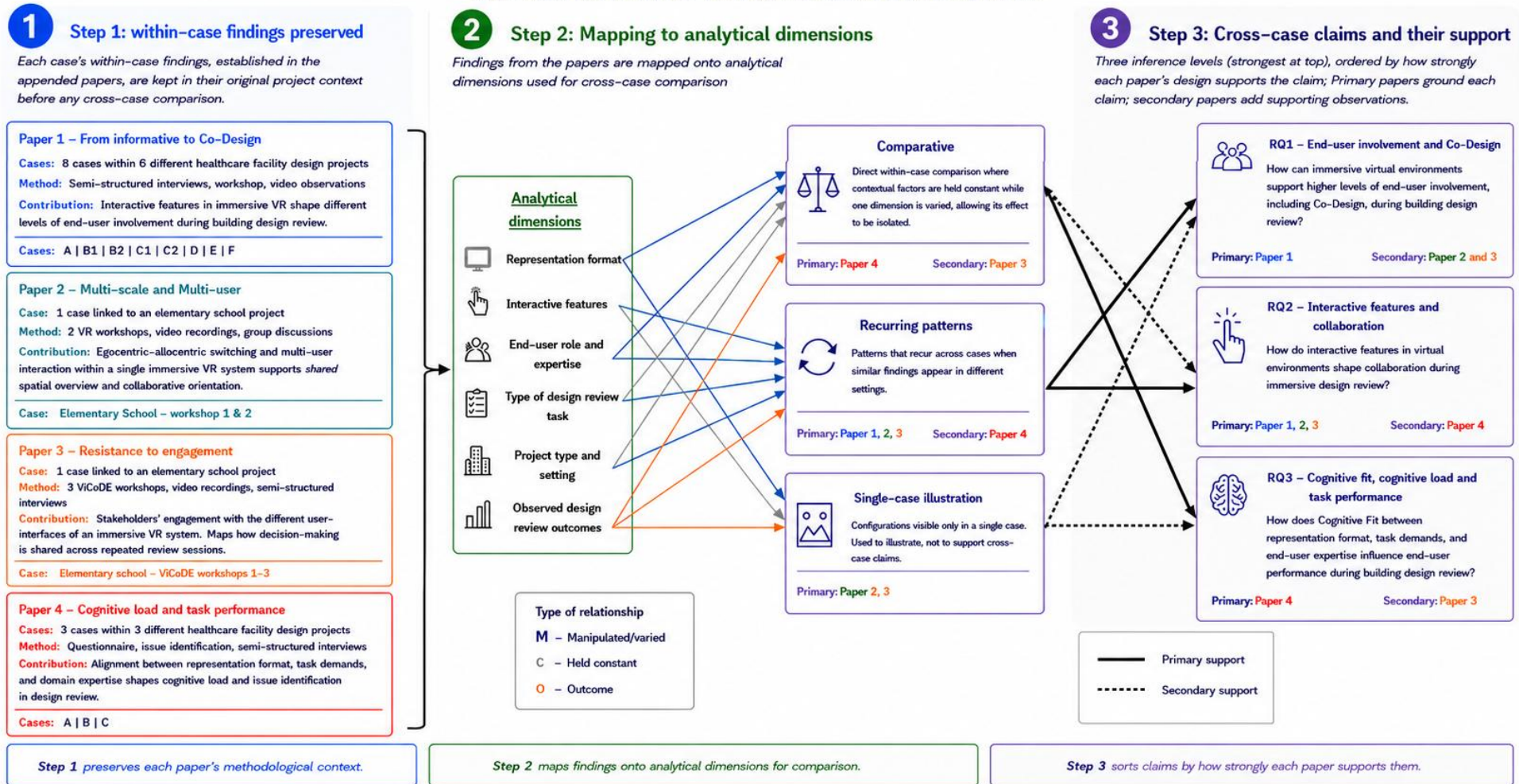


Fig. 7: Three-step cross-case synthesis across the four appended papers, adapted from Yin's (2018) case-based approach to multiple-case study research. Step 1 preserves each paper's within-case findings in their original project context. Step 2 maps these findings onto six analytical dimensions used for cross-case comparison. Step 3 sorts cross-case claims into three inference levels, ordered by methodological strength.

Comparative claims are supported when one dimension is varied within matched cases while the other dimensions are held constant, so the effect of that dimension can be observed on its own (Figure 7). In this thesis, only Paper 4 meets these conditions. Within each of the three healthcare cases (A, B, C), representation format is the manipulated dimension. The same participants reviewed the same design proposal first in 2D and then in immersive HMD VR. Type of design review task and the available interactive features are held constant within each within-subject comparison. For any given participant, the design proposal, the review brief, and the VR system configuration did not change between the 2D and the VR review. NASA-RTLX cognitive load and the number of design issues identified against a project-team reference list are the outcomes. End-user role and expertise (healthcare versus non-healthcare staff) is treated as a between-subjects moderator on the format effect. Role is used as a proxy for domain knowledge and prior 2D-review experience, not as a cognitive profile. Comparative claims about cognitive load and task performance therefore have Paper 4 as their primary support. Paper 3 contributes secondary support. Across three review sessions on a single school project, it documents how the same architects and client representatives engaged differently with 2D drawings and the multi-interface VR system. This is consistent with a format effect, but the study was not designed as a within-subject 2D-versus-VR comparison.

Recurring patterns are supported when the same pattern appears across cases that differ in setting, participants, and method, so that the heterogeneity of the cases itself becomes the basis for the inference (Yin, 2018) (Figure 7). This is weaker than direct comparison but stronger than single-case observation. Across the four papers, claims about how interactive features shape collaboration during immersive design review belong here. Interactive features are the manipulated dimension, varying in configuration across the cases. End-user role and expertise, type of design review task, and project type and setting vary across the set, and the pattern is claimed because it survives this variation. Observed collaboration during design review is the outcome. Papers 1, 2, and 3 jointly provide primary support as three independent cases. Paper 1 observes the pattern across eight cases in six healthcare projects with systematically varying feature configurations. Paper 2 and Paper 3 are two distinct elementary school projects in Gothenburg, both involving the municipality but otherwise independent in their participants, VR system, and study design. Paper 4 contributes secondary support. Its three healthcare projects show collaboration patterns consistent with the claim, but the study was designed around within-subject comparisons of representation format rather than cross-case replication of feature configurations.

Single-case illustrations are made when a configuration or within-case dynamic is observed in only one case and is used to illustrate a possibility rather than to support a general claim (Figure 7). The egocentric–allocentric multi-scale configuration of Paper 2 and the cross-session engagement dynamics observed in Paper 3 are used illustratively in this way (Table 4). The discussion chapter draws on both to describe how each shaped the observed outcomes within its own case. It also uses them to motivate further study of which stakeholder roles benefit from which combinations of interactive features and representational format during design review, rather than to argue that the configurations studied here work in general. At this level there is no cross-case comparison and no cross-case replication, so only the outcome role applies. The three-tier structure carries into the discussion chapter, where each cross-case claim is attributed to its primary and secondary papers in line with Figure 7.

### 3.6.1 Operationalization of analytical dimensions

Four dimensions of the synthesis require explicit operationalization, namely representation format, interactive features, end-user role and expertise, and observed design review outcomes. Each has been used inconsistently in the literature, defined or measured differently across the appended papers (e.g., what counts as design review performance differs between papers), or is specific to this thesis. The remaining dimensions in Figure 7 (type of design review task and project type and setting) are used to describe each paper's case rather than to anchor cross-case claims, and are summarized for each paper in Table 4.

Representation format refers to how the design is shown during review (e.g., 2D drawings, immersive HMD VR). This is separate from interactive features, which describe how users engage with the design and are covered in the following paragraphs. Four representation formats appear across the appended papers. These are 2D drawings, immersive HMD VR, the projector screen mirroring an HMD user's view, and the multitouch top-view table. Within these, immersive HMD VR is treated as a single category at the level of the synthesis, even though the specific HMD hardware varies across the appended papers (listed in Section 3.3.2). Hardware-level differences in field of view, resolution, and tethering were not measured systematically and are not used to support cross-case claims.

Two cases require clarification. In Paper 2, the multi-scale toggle between full-scale and miniature views is treated as an interactive feature, not as a separate representation format. Switching between these scales changes how the user navigates the same VR model, but the format itself stays the same. In Paper 1 Case E and Paper 3, the ViCoDE configuration combined HMD VR, the projector screen, and the multitouch table in a single session. The synthesis treats this combined setup as a single ViCoDE configuration rather than as three separate representation formats. Paper 3 documents within-ViCoDE dynamics, including which stakeholders engaged with which interface during a session. These dynamics are captured under interactive features and observed design review outcomes rather than under representation format.

Interactive features are operationalized as three sub-dimensions that distinguish how users interact with the technology and user interface, with the representation content, and with other users. Interaction with the user interface covers how users move through and reframe the virtual environment, including exploration in LaViola et al.'s (2017) sense of free navigation without an explicit movement goal, and view-switching such as the multi-scale toggle between full-scale and miniature views observed in Paper 2. The related travel subclasses of wayfinding, search, and maneuvering (LaViola et al., 2017) are not analyzed, because the empirical material across the appended papers does not consistently distinguish them. Interaction with the representation content covers object selection and manipulation, including adjusting the position and rotation of design elements while preserving their shape. Interaction with other users covers the multi-user feature in immersive HMD VR, drawing on Churchill et al.'s (2001) definition of collaborative virtual environments. The multi-user feature means multiple users are in the same virtual model at the same time. Whether collaboration occurs between those users is recorded as an observed design review outcome and is described per paper in Table 4.

The appended papers vary in which features are available and in how those features are used during design review. Multi-scale view-switching is observed only in Paper 2 and is therefore treated as a single-case illustration in Figure 7 rather than as a basis for cross-case claims. Object interaction and multi-user appear across Papers 1, 3, and 4 but in different configurations (Table

4). Object interaction is implemented via a multitouch table in Paper 1 (Case E) and Paper 3, and via HMD controllers in Paper 1 (Case F) and Paper 4. Task-based scenarios are how the three interactive features (object interaction, multi-user, and exploration) get put to use during a review session in ways that shape the design review. A task-based scenario is a structured work-practice activity carried out within the review, such as simulating a clinical workflow or testing equipment placement against a procedure. Task-based scenarios are observed in Paper 1 (Cases E and F), Paper 3, and Paper 4 (Cases P4-A–P4-C). Cross-case claims about feature impact are anchored to task-based scenarios. Where a session shows feature availability but no task-based scenario, the synthesis records the availability but does not claim that the features shaped the review.

End-user role and expertise are operationalized as case-level descriptors of who participated in each design review session (healthcare staff, facility planner, client representative, architect), not as variables we use to explain how participants performed. The synthesis does not treat these labels as cognitive profiles. It does not assume, for example, that healthcare staff are inherently less able to interpret 2D drawings than facility planners or architects. Where the data supports it, role is used to indicate two things about each user. The first is domain knowledge of the activity that the building supports (e.g., clinical work in healthcare facilities or teaching in schools). The second is prior experience with 2D-based design review. Together, these two factors shape each user's mental model of the workplace. Paper 4 records each participant's prior design-review experience separately from their professional role. This means Paper 4 can show whether a result is driven by role or by experience, where the other papers cannot. The appended papers did not administer standardized measures of individual spatial ability or cognitive style, nor did they operationalize the more detailed user-characterization frameworks available in the HCI literature, including individual mental-model frameworks (Norman, 1983). Drawing literacy was approximated only through participants' self-reported prior experience with 2D-based design review, captured in Paper 4. Mental models, as reviewed in Chapter 2, are domain-specific representations of the workplace shaped by everyday work practice. They are not individual cognitive profiles. In Chapter 5, cognitive fit is therefore applied to participants' domain knowledge of the work practice and their prior experience with 2D-based design review, not to cognitive profiles inferred from their professional role.

Observed design review outcomes are operationalized as the measures used to record what happened during a design review session. The appended papers document different outcome measures depending on their study design. Paper 1 records levels of end-user involvement (informative, consultative, participatory design, Co-Design) and the design issues identified during sessions. Papers 2 and 3 record collaboration patterns, including which stakeholders engaged with which user-interface and how decision-making shifted across sessions. Paper 4 records cognitive load using the NASA Raw Task Load Index (NASA-RTLX) (Hart and Staveland, 1988) and task performance as the number of design issues identified during a review session, validated against a project-team reference list. Cross-case claims draw on different outcome measures depending on the level of inference. Comparative claims about cognitive load and task performance rely on Paper 4. Recurring-pattern claims about collaboration rely on Papers 1, 2, and 3. Single-case illustrations draw on within-case engagement dynamics in Papers 2 and 3.







Issue identification was chosen as a task-performance measure in Paper 4 for two reasons. It is countable across participants and conditions, and it can be cross-checked against a project-team

reference list of issues considered relevant for the design phase. It is, however, a partial measure. It captures whether issues were detected but not their severity, design impact, or whether the resulting design changes improved operational outcomes after construction. Claims about task performance in the synthesis should be read with this limit in mind.

Step 3 of the synthesis sorts cross-case claims into inference levels (Figure 7). Within this step, each dimension plays one of three roles in supporting a cross-case claim. These roles are manipulated or varied (M), held constant (C), and outcome (O). For comparative claims, M is the dimension that is intentionally changed across the cases being compared, while everything else stays the same. This is what Paper 4 does within each healthcare project, where the same participants review the same design proposal first in 2D and then in immersive HMD VR. C is a dimension that stays the same across the compared cases, which rules out alternative explanations for any observed difference. O is what the comparison measures, such as cognitive load or the number of design issues identified in Paper 4.

For recurring patterns, M is a dimension that already varies across the supporting cases, because those cases are different from each other. This pattern is claimed because it appears despite this variation. C is not used at this level of inference, because no dimension stays strictly the same across heterogeneous cases. For single-case illustrations, only the outcome (O) is marked in Figure 7. M and C do not apply, because no comparison or replication takes place. Table 4 shows, for each appended paper, which dimensions correspond to which role in supporting which level of claim, with bracketed tags [M], [C], and [O] in each cell indicating the role that dimension plays in that paper's primary cross-case contribution. Design issues identified, listed under Observed design review outcomes for Papers 1 and 4, is treated in the synthesis as a partial performance indicator (Section 3.6.1).

**Table 4.** Rows show analytical dimensions; columns show how each paper contributes to that dimension. Bold text marks the main point in each cell.

Analytical dimension	Paper 1	Paper 2	Paper 3	Paper 4
<b>Representation format</b> 	<ul style="list-style-type: none"> <li>• [M] <b>2D drawings and immersive HMD VR</b> ;in some cases (Paper 1, case E; Paper 3) also projector screen and multitouch table (ViCoDE)</li> </ul>	<ul style="list-style-type: none"> <li>• [M] <b>Immersive HMD VR</b> with combined 1:1 full-scale and 1:40 miniature views</li> </ul>	<ul style="list-style-type: none"> <li>• [M] <b>Multi-interface ViCoDE:</b> HMD VR, multitouch table, projector screen</li> </ul>	<ul style="list-style-type: none"> <li>• [M] <b>2D drawings versus immersive HMD VR</b> within the same projects</li> </ul>
<b>Interactive features</b> 	<ul style="list-style-type: none"> <li>• [M] <b>Variable across the eight cases:</b> from exploration only to exploration + multi-user + object interaction</li> </ul>	<ul style="list-style-type: none"> <li>•[M] <b>Exploration, multi-user, multi-scale</b> (egocentric ↔ allocentric switching)</li> </ul>	<ul style="list-style-type: none"> <li>• [M] <b>Exploration, multi-user, object interaction</b> (via multitouch table)</li> </ul>	<ul style="list-style-type: none"> <li>• [C] <b>Exploration, object interaction, multi-user</b> (within project teams)</li> </ul>
<b>End-user role and expertise</b> 	<ul style="list-style-type: none"> <li>• [M] <b>Healthcare staff, architects, facility planners, project leaders</b> across 6 projects</li> </ul>	<ul style="list-style-type: none"> <li>•[M] <b>Architects and client representatives</b></li> </ul>	<ul style="list-style-type: none"> <li>• [M] <b>Architects and client representatives</b> ( same participants across 3 sessions)</li> </ul>	<ul style="list-style-type: none"> <li>• [M] <b>Healthcare staff</b> (n = 111) and <b>non-healthcare staff</b> (n = 21); prior design-review experience reported separately from role</li> </ul>
<b>Type of design review task</b> 	<ul style="list-style-type: none"> <li>• [M] <b>Brief, concept</b>, spatial coordination, and technical design tasks</li> </ul>	<ul style="list-style-type: none"> <li>• [M] <b>Spatial overview, flow</b>, room relationships in an educational facility</li> </ul>	<ul style="list-style-type: none"> <li>• [M] <b>Layout iteration</b>, spatial coordination, building-code review</li> </ul>	<ul style="list-style-type: none"> <li>• [C] <b>Workflow, equipment layout, sightlines, room size, building-code compliance</b> in equipment-intensive healthcare spaces</li> </ul>
<b>Project type and setting</b> 	<ul style="list-style-type: none"> <li>• [M] <b>6 healthcare facility projects</b>, multiple design phases</li> </ul>	<ul style="list-style-type: none"> <li>• [M] <b>One elementary school project</b>, 2 workshops</li> </ul>	<ul style="list-style-type: none"> <li>• [M] <b>One elementary school project</b>, 3 ViCoDE workshops</li> </ul>	<ul style="list-style-type: none"> <li>• [C] <b>3 healthcare facility projects:</b> 2 renovations (Cases P4-A, P4-B) and 1 new build (Case P4-C)</li> </ul>
<b>Observed design review outcomes</b> 	<ul style="list-style-type: none"> <li>• [O] <b>Levels of end-user involvement</b> (informative → consultative → participatory → Co-Design); design issues identified</li> </ul>	<ul style="list-style-type: none"> <li>• [O] <b>Egocentric-allocentric switching</b>; collaborative spatial orientation; design issues identified at multiple scales</li> </ul>	<ul style="list-style-type: none"> <li>• [O] <b>Shifts in stakeholder engagement and decision-making roles</b> across repeated sessions; interaction-pattern analysis</li> </ul>	<ul style="list-style-type: none"> <li>• [O] <b>NASA-RTLX cognitive load</b>; design issues identified by category (flow, sightlines, room size, equipment layout, flexibility, technical requirements)</li> </ul>

### 3.6.2 Contaminating differences and plausible rival interpretations

The cases in this thesis differ in several ways. They cover different project phases, use different VR system setups, involve participants with different levels of design-review experience, and take place in different building types. Ignoring these case differences would weaken any cross-case claim made in this thesis (Yin, 2018). The synthesis therefore treats the case differences as limits on what each claim can say. For example, Paper 4 shows that immersive HMD VR reduces cognitive load compared to 2D drawings. This finding comes from equipment-intensive healthcare projects. It cannot be assumed to hold in less equipment-intensive settings without further study.

Two of those differences need direct attention. First, prior experience with 2D-based design review differs across the appended papers. Paper 4's healthcare staff had little or no prior experience. Non-healthcare staff in Paper 4 had this experience. So did the architects and client representatives in Papers 1, 2, and 3. Differences in how many issues were identified could be due to experience, not the representation format itself. The synthesis therefore treats Paper 4 as the only primary basis for comparative claims about cognitive load and task performance, because its within-case design keeps project context the same. Second, in Paper 4 Case P4-B, the 2D drawing did not include the medical equipment that the VR model showed. Issues found only in VR in that case could reflect this development gap rather than the representational format itself.

Two rival interpretations also need to be addressed. The first is a novelty effect from first-time VR use. This cannot be ruled out in any of the cases. Paper 3's three sessions with the same participants and Paper 4's within-subject comparison both reduce the chance that novelty alone explains what was found. The second is self-selection. In Paper 4, healthcare staff signed up for time slots themselves. Those who signed up may differ from those who did not, in ways that could affect engagement and reported workload. These are the two most likely rivals to the comparative claims and the only ones addressed here (Yin, 2018).

## 3.7 Reflections on research quality

The cases included in this thesis were conducted within ongoing building projects rather than controlled laboratory settings. This provided access to professional stakeholders, real project material, and authentic design review situations, supporting ecological validity. At the same time, working in real-world project settings introduced practical constraints, including limited availability of participants, design proposals at varying stages of development, and the need to schedule sessions around ongoing professional and clinical activities.

To assess the quality of the case study research presented in this thesis, four criteria from Yin (2018) are used: construct validity, internal validity, external validity, and reliability. Construct validity is supported by the operationalization of the key constructs in Section 3.6.1, and by the use of multiple sources of evidence (observations, screen recordings, interviews, NASA-RTLX ratings, and counts of design issues identified against a project-team reference list). Internal validity is addressed through pattern-matching across cases (Section 3.6) and by naming the most plausible rival interpretations, novelty effect and self-selection, rather than treating them as a generic disclaimer. External validity rests on analytical, not statistical, generalization. The inference levels in Figure 7 make the boundary conditions of each cross-case claim visible. Reliability is supported by detailed reporting of data collection and analysis procedures in each appended paper, including intercoder agreement on issue coding in Paper 4.

In several cases, design review took place during early project phases when architectural models were not yet fully furnished or detailed. This was particularly the case in the three healthcare projects in Paper 4, where the VR models were prepared by adding loose furniture and medical equipment that did not yet appear in the architects' 2D drawings at the time of review. The added items were not chosen arbitrarily, they were sourced from the project's Room Data Sheets and from the Swedish national healthcare database PTS, and some items in Case P4-B were laser-scanned and modelled because they were missing from the database. Without this preparation, healthcare staff could not have evaluated the rooms in relation to their actual work practice, since the spaces would otherwise have been empty. This preparation is named here as a study condition rather than treated as neutral background. It means the VR model carried more content than the 2D drawings did at the time of review, and design issues identified only in VR could in principle reflect this content gap rather than the representational format itself, particularly in Case P4-B, where the gap was largest. The synthesis therefore treats this as a boundary on the comparative claim in Paper 4. Reviewing the design at early phases was nonetheless a deliberate choice, since this is when end-user input has the greatest potential to shape the design before structural decisions are locked in.

Participant experience with design review tools and immersive VR varied across the appended papers. In real-world settings, multiple factors may influence design review performance, including prior familiarity with drawings or VR, professional domain knowledge, and the level of detail available in the design representations. These factors are difficult to isolate systematically in project-based studies, and potential novelty effects associated with VR use cannot therefore be fully excluded.

Finally, although the included projects represent both healthcare and school settings, the findings remain grounded in specific real-world cases. End-user expertise is often closely tied to particular building types and work practices, which may influence how design proposals are interpreted and which issues are identified. The intention is therefore not to suggest generalization across all building types, but rather to examine immersive design review in situations where user involvement is particularly consequential for decision-making in building design.

### **Ethical considerations**

The research was conducted in accordance with principles of research integrity, transparency, and respect for participants. All participants were informed about the purpose of the research and how the collected data would be used before participating in design review sessions, interviews, or questionnaire-based data collection. Participation was voluntary, and participants could withdraw from the study at any time.

When design review sessions were recorded for research purposes, participants were informed beforehand. Personal identifiers were not included in the analysis or reporting of results, and findings are presented at an aggregated level to prevent identification of individual participants or organizations. Data storage and management followed applicable research ethics and data protection guidelines.

### **Use of AI**

The period during which this thesis was developed coincided with rapid advancements in artificial intelligence technologies, particularly large language models. These developments created new opportunities to support research workflows while maintaining methodological

rigor. In this thesis, AI tools such as ChatGPT and Copilot were used in a limited and transparent manner to support specific aspects of the writing process. AI-assisted language tools were employed to improve the clarity, coherence, and academic tone of the English writing, including refining sentence structure and ensuring stylistic consistency across chapters. In addition, AI assistance was used to improve the visual layout and pedagogical clarity of Figure 7 (cross-case synthesis), while the analytical content of the figure remains the author's own work. All conceptual content, analytical reasoning, and scientific conclusions presented in this thesis remain the author's own work.



## 4 Results and summary of appended papers

### 4.1 Overview of how the papers are related

Figure 8 shows how the four papers (P1-P4) relate to the research phenomenon of this thesis: *understanding how immersive virtual environments can support end-user involvement and Co-Design during building design review*. Each paper addresses a different aspect of immersive design review. Paper 1 examines how immersive virtual environments may support different levels of end-user involvement. Paper 2 and Paper 3 focus on collaborative design review in immersive environments and examine how interactive features influence stakeholder interaction and participation. Paper 4 investigates how representational format (conventional 2D drawings and immersive HMD VR) affects cognitive load and task performance during design review. Together, the papers contribute complementary perspectives on how immersive environments support end-user participation and design review in real-world building projects.

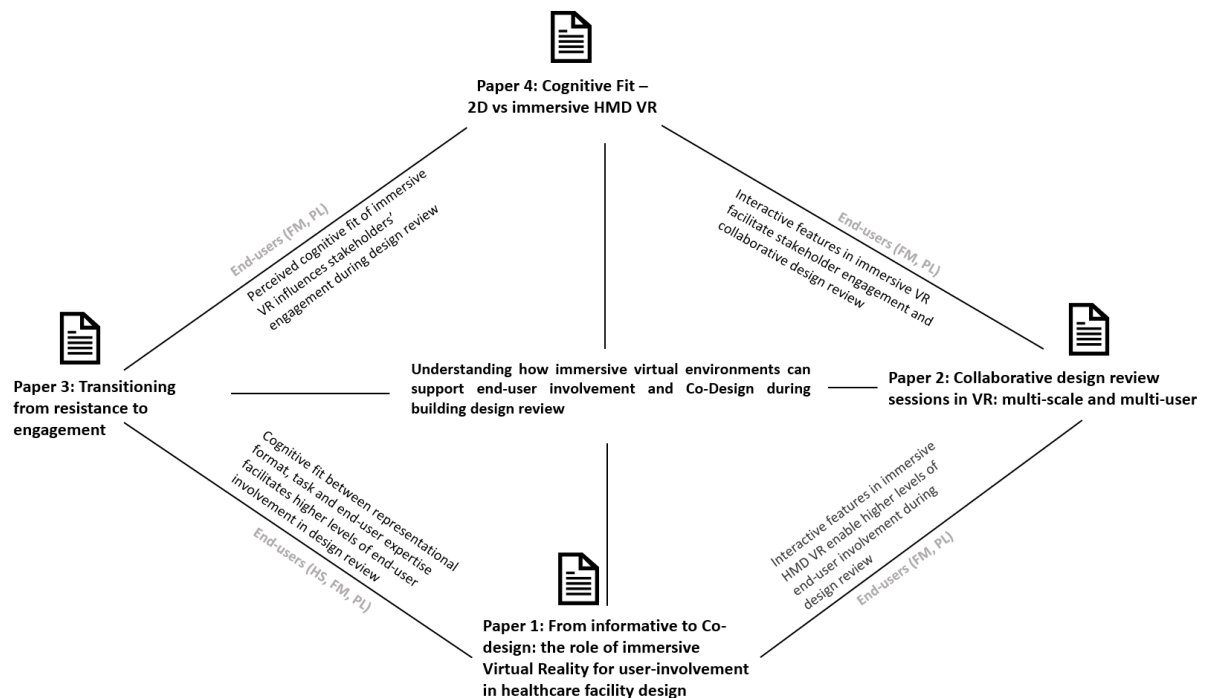


Fig 8: Overview of how papers 1–4 relate to the research phenomenon of the thesis.

Table 5 presents an overview of how the four appended papers relate to the three research questions guiding the thesis. Paper 1 provides the primary contribution to RQ1, examining how immersive virtual environments influence levels of end-user involvement, ranging from informative participation to more collaborative forms of involvement and Co-Design. Papers 1, 2, and 3 jointly provide the primary contribution to RQ2, investigating how interactive features in immersive virtual environments support collaborative design review and stakeholder interaction.

Paper 4 provides the primary contribution to RQ3 by examining how representational format, specifically conventional 2D drawings and immersive HMD VR, influences cognitive load and task performance during design review. While each paper addresses a specific research question, several papers also provide secondary contributions to other questions. In sum, the four papers

provide complementary insights into end-user involvement, collaborative interaction in immersive environments, and the cognitive processes involved in interpreting design proposals.

**Table 5.** Relationship between the appended papers and the thesis research questions. Filled circles denote primary contributions, open circles secondary contributions, and dashes no direct contribution.

Research question	Paper 1	Paper 2	Paper 3	Paper 4
<b>RQ1:</b> <i>How can immersive virtual environments support higher levels of end-user involvement, including Co-Design, during building design review?</i>	● Primary	○ Secondary	○ Secondary	-
<b>RQ2:</b> <i>How do interactive features in virtual environments shape collaboration during immersive design review?</i>	● Primary	● Primary	● Primary	○ Secondary
<b>RQ3:</b> <i>How does cognitive fit between representational format, task demands, and end-user expertise influence end-user performance and involvement during design review?</i>	-	-	○ Secondary	● Primary

## 4.2 Summary of Appended Paper I

### From informative to Co-Design: the role of immersive Virtual Reality for user-involvement in healthcare facility design

Sateei, S., Roupé, M., and Johansson, M. (2025)

Published in: Journal of Information Technology in Construction (ITcon), May 2025.

#### 4.2.1 Background and aim

Previous studies have shown that immersive VR can support end-users' spatial understanding during design review. However, less attention has been paid to how specific interactive features in VR, such as object interaction and multi-user, influence different forms of collaborative practices and level of end-user involvement. Moreover, the integration of immersive VR as a representational format within established collaborative practices, such as participatory design and Co-Design, remains underexplored. The aim of this paper was therefore to gain an understanding of how different interactive features in immersive VR facilitate different levels of end-user involvement and collaborative practices throughout the design process.

#### 4.2.2 Methods

The study is based on six real-world healthcare projects conducted in Sweden and the United States. The cases formed part of ongoing healthcare facility projects and included both new build and renovation of existing healthcare facilities. Empirical data were collected through semi-structured interviews with design team members (e.g., architects and BIM coordinators) and end-users (e.g., healthcare staff and facility planners). In addition, video observations were conducted during VR sessions used both for design review and for informative purposes, where end-user feedback was not formally incorporated into the design process.

### 4.2.3 Results

The results show that the level of end-user involvement during design review is closely related to the interactive features available in the VR environment. When VR supported object interaction and multi-user interaction, end-users were able to engage in task-based scenarios that allowed them to evaluate how design layouts affected their daily work practices. In contrast, VR environments limited to free exploration primarily supported increased spatial understanding and identification of design issues.

Overall, the findings demonstrate that immersive VR can facilitate different collaborative practices depending on available interactive features, ranging from informative and consultative use to participatory design and Co-Design, where end-users actively contribute to the development of design proposals.

### 4.2.4 Contribution to thesis

This paper contributes to the thesis by establishing a conceptual foundation for understanding end-user involvement in immersive VR-supported design review. Most notably, it introduces a classification of end-user involvement that links levels of collaboration, informative, consultative, participatory design, and Co-Design, to the interactive features available in the virtual environment (Fig. 9).

The findings show that interactive features such as object interaction, multi-user and freely exploring the virtual environment are enablers of higher levels of end-user involvement. The paper therefore provides a structured way of understanding how immersive HMD VR can shift design review practices from information delivery toward Co-Design among end-users.

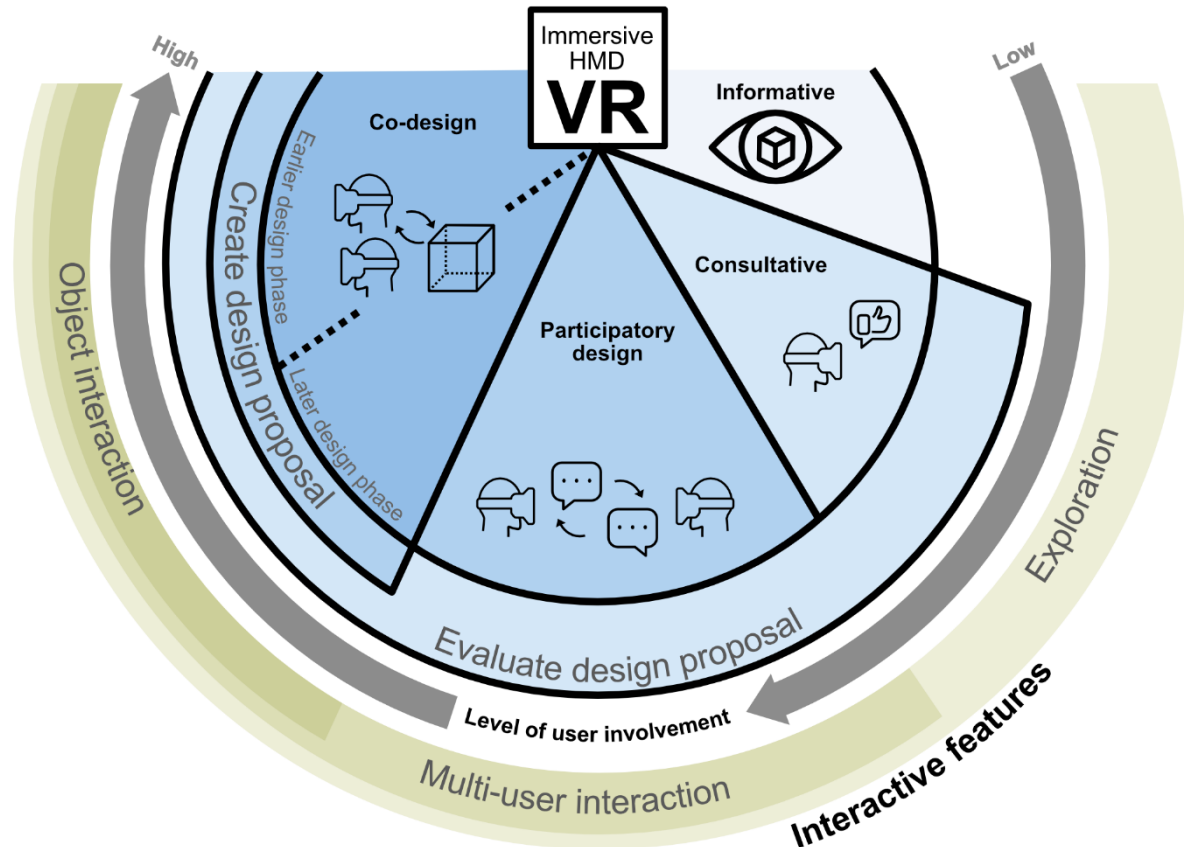


Fig. 9: Classification of immersive HMD VR used in different collaborative practices.

## 4.3 Summary of Appended Paper II

### **Collaborative Design Review Sessions In Virtual Reality: Multi-Scale And Multi-User**

*Sateei, S., Roupé, M., and Johansson, M. (2022)*

Presented at: 27<sup>th</sup> International Conference of the Association for Computer Aided Architectural Design Research in Asia (CAADRIA) 2022. Vol. 1, p.29-38, April 2022.

#### **4.3.1 Background and aim**

While immersive VR has been shown to support spatial understanding during design review, previous research has also highlighted limitations related to orientation, overview, and collaboration, particularly in large and complex building projects. In practice, design review often requires stakeholders to move between detailed, first-person experiences of space and more abstract, overview-based representations in order to reason about functional relationships, workflows, and spatial configurations. However, fewer studies have explored how immersive VR can support such shifts in scale and perspective within the same collaborative setting and representational format. As such, the aim of this paper was to investigate how multi-scale and multi-user functionality in immersive VR can support collaborative design review, with particular focus on spatial understanding, orientation, and cross-disciplinary collaboration in a real-world project.

#### **4.3.2 Methods**

The paper is based on a qualitative case study of two immersive VR workshops conducted during the detailed design phase of a real-world elementary school project. The participants included architects and client representatives responsible for different aspects of the design process. Immersive VR was used as the primary design review medium during both workshops.

Empirical data were collected through video-recorded observations of the VR workshops, complemented by group discussions and reflections with the participants. The VR system supported multi-user collaboration and allowed participants to switch between a full-scale, first-person VR experience and a miniature, bird's-eye 1:40 scale representation of the building within the same virtual environment.

#### **4.3.3 Results**

The results show that the ability to switch between different scales within the immersive VR environment played a central role in supporting collaborative design review. The full-scale, first-person perspective enabled participants to experience spaces from an end-user perspective and identify design issues related to functionality and workflow. In contrast, the miniature representation provided an overview that supported orientation, navigation, and understanding of spatial relationships across the building. The combination of multi-scale representations facilitated collaborative discussion among participants with different roles and expertise. By jointly navigating and referencing the virtual environment at different scales, participants were able to align their understanding of the design, identify potential issues, and discuss alternative solutions more effectively than would have been possible using a single representational format.

#### **4.3.4 Contribution to thesis**

This paper contributes to the thesis by demonstrating how specific interactive features in immersive VR, namely multi-user and support for multi-scale representation, enable collaborative design review practices. It shows that immersive VR can function as a shared

workspace in which stakeholders collectively reason about design decisions by moving between overview and detailed perspectives (Figure 10). Moreover, observations from the second workshop show that adding loose and fixed equipment to the virtual environment helped stakeholders better understand the operational setting in which design issues emerged.

In relation to the overall thesis aim, the paper shows how the levels of end-user involvement introduced in Paper 1 are enacted through specific interaction and representation mechanisms in immersive VR. By demonstrating how representational formats typically associated with 2D drawings (i.e., overview and multi-scale perspectives) are integrated with full-scale immersive experience, the paper illustrates how active participation during design review is supported. As such, it connects the conceptual framing of end-user involvement in Paper 1 with later studies that explore stakeholder engagement and cognitive aspects, as well as design issues found in both conventional 2D drawings and immersive virtual environments (Paper 4).



*Fig. 10: Miniature model (1:40 scale) showcasing the building in its entirety as well as sectioning of the various floors reviewed by the client representatives.*

## 4.4 Summary of Appended Paper III

### Transitioning from 2D to VR in design review – Resistance to Engagement

*Sateei, S., Roupé, M., and Johansson, M. (2023)*

Presented at: 23<sup>rd</sup> International Conference on Construction Applications of Virtual Reality, CONVR 2023. Vol. 23, p. 85-96, November 2023.

#### 4.4.1 Background and aim

Although immersive VR has been shown to support spatial understanding and collaborative design review, its adoption in real-world projects remains uncertain, particularly among architects. Previous research has largely emphasized the benefits of immersive VR, while fewer studies have examined why certain stakeholders remain resistant to its use and how such resistance may change over time. Moreover, there is limited empirical knowledge of how immersive and non-immersive VR user-interfaces influence interaction, roles, and decision-making during repeated design review sessions.

The aim of this paper was therefore twofold: (1) to understand architects' and client representatives' resistance and receptiveness toward different user-interfaces part of a VR-

system during design review, and (2) to examine how interaction and collaboration evolve when such a VR-system with different user-interfaces is used across multiple design review sessions in a real-world project.

#### **4.4.2 Methods**

The study followed a qualitative case-study approach based on three design review workshops conducted during different phases of a real-world elementary school project. The same client representatives and architects participated in all three workshops. The VR system used (ViCoDE) supported both immersive (HMD VR) and non-immersive user-interfaces (multitouch table and projector screen), allowing participants to interact with the design proposal in different ways.

Empirical data were collected through video recordings of the workshops and semi-structured interviews with architects and client representatives who participated in the sessions, complemented by additional interviews with architects and clients from related projects. The analysis focused on interaction patterns, use of different user-interfaces, and changes in participants' roles and attitudes toward VR across the three workshops.

#### **4.4.3 Results**

The results show a contrast between architects' and client representatives' engagement with the different VR user-interfaces. Client representatives were receptive to both immersive and non-immersive VR from the first workshop and actively used the HMD VR and multitouch table to identify and resolve design issues through task-based scenarios. This enabled them to assess spatial relationships, furnishment, and functional layouts in ways they found difficult when using 2D drawings alone.

In contrast, architects were initially resistant to using HMD VR for design review and primarily engaged with the virtual environment through non-immersive interfaces such as the projector screen and multitouch table. Over the three workshops, architects' engagement increased, particularly through growing use of the multitouch table for object interaction and validating their sketched ideas for immediate feedback. This shift was reflected by changes in interaction patterns and decision-making, where client representatives initially led design review activities and architects gradually re-engaged, especially when addressing building code requirements and regulatory constraints.

Overall, the findings show that engagement with different VR user-interfaces varies across stakeholders, and that the choice of user-interface is closely tied to professional roles, familiarity with representational formats, and perceived relevance to specific design tasks (e.g., supporting spatial understanding versus ensuring compliance with building codes).

#### **4.4.4 Contribution to thesis**

This paper contributes to the thesis by showing that stakeholder engagement with immersive VR during design review is shaped by the interplay between user roles, representational formats, and available interactive features. The findings demonstrate that a preference for non-immersive user-interfaces does not necessarily reflect a rejection of immersive VR as a whole, as evidenced by the increased use of the multitouch table. Rather, it reflects which types of design review questions are addressed through user-interfaces that align with stakeholders' familiar work practices. For example, non-immersive interfaces such as the multitouch table—closely aligned with established design practices like sketching—were primarily used by

architects, while HMD-based VR supported embodied spatial experiences that were more frequently used by client representatives when evaluating classrooms and spatial layouts.

In relation to the overall thesis aim, this paper shows that immersive virtual environments can support end-user involvement and Co-Design particularly when stakeholders are able to engage with the VR system in ways that align with their prior experience and familiarity with traditional design representations and tools. By highlighting how engagement between stakeholders and choice of user-interface varies across repeated VR sessions, the paper shows how specific user-interfaces support joint reflection and discussion. In particular, the multitouch user-interface enabled architects and client representatives to jointly reflect on and discuss design issues by using available object interaction and testing alternative solutions in the shared virtual environment. Specifically, architects are making changes on the multitouch table via object interaction, which client representatives could experience via immersive HMD VR and provide immediate feedback. Apart from immediate validation of changes to the design made via the multitouch-table, the findings further indicate that immersive HMD VR allowed design issues that had previously remained unnoticed to be identified and resolved, enabling client representatives to take a more active role in identifying and discussing design concerns (Fig. 11). In contrast, design issues related to building code compliance were more often addressed through non-immersive user-interfaces, which aligned more closely with established design review practices (conventional 2D drawings). In this way, the paper clarifies the conditions under which different, immersive and non-immersive, user-interfaces of a VR-system become relevant for collaborative design review. It also connects earlier papers that focus on interactive features and collaborative practices with the final paper, which provides a cognitive explanation of why immersive and non-immersive representational formats support end-users differently during design review.

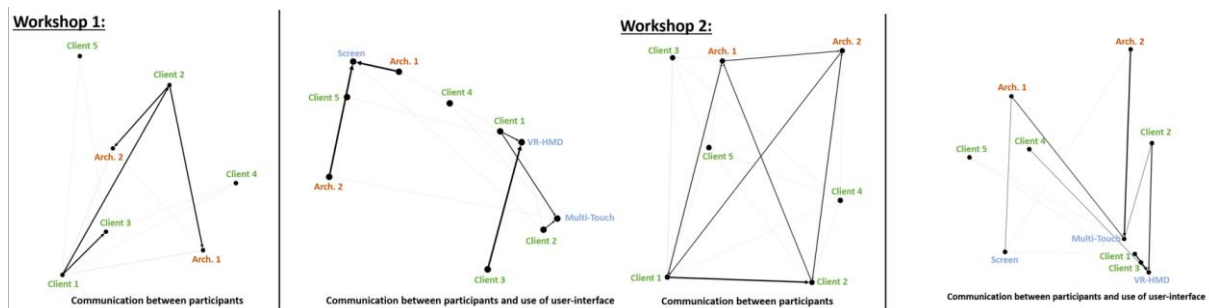


Fig. 11: Interaction analysis illustrating how communication patterns and use of immersive and non-immersive VR user-interfaces differed between stakeholders across two design review sessions.

## 4.5 Summary of Appended Paper IV

### How Representation Format Affects End-User Design Review: Cognitive Load and Task Performance in 2D drawings and immersive HMD Virtual Reality

Sateei, S., Gustafsson, M., Roupé, M., and Johansson, M.

Under review in Journal of Virtual Reality, submitted January 2026.

#### 4.5.1 Background and aim

Design review of building design often relies on traditional representational formats such as conventional 2D drawings, which can be demanding for end-users to interpret because they

require mental reconstruction of three-dimensional space from abstract and fragmented representations (e.g., plans, sections and elevations). This is particularly challenging in healthcare facility design, where healthcare staffs' ability to evaluate flow, room size, sightlines, and equipment-related work tasks is essential for identifying design issues early. While immersive HMD VR has been shown to support spatial understanding, fewer studies have examined how differences in representational format relate to variations in cognitive load and task performance in real-world projects involving domain experts.

The aim of this paper was therefore to examine how representational format (2D drawings and immersive HMD VR) affects end-users' cognitive load and task performance during design review in three ongoing healthcare facility projects, and to interpret these effects through Cognitive Fit Theory—i.e., the alignment between representational format, task demands, and end-user expertise.

#### **4.5.2 Methods**

The study was conducted across three real-world healthcare projects involving both renovation and new build. Participants included healthcare staff, facility planners, project leaders, and technical consultants. Design review sessions were carried out using both conventional 2D drawings and immersive VR, with some participants completing both conditions and others participating only in immersive VR.

Empirical data were collected using a mixed-methods approach. Quantitative analysis was made possible by measuring cognitive load using the NASA Raw Task Load Index (NASA-RTLX), while task performance was assessed through the number and type of design issues identified during design review. The quantitative analysis was complemented by semi-structured interviews with project team members (head nurses, physicians, facility planners, and project leaders) from each project to help interpret the quantitative results. Moreover, coding of the issues identified was done to identify patterns in types of issues identified during design review, resulting in six different design issue categories: medical equipment layout, flow, sightline, room size, flexibility and technical requirements.

#### **4.5.3 Results**

The results show that immersive HMD VR provided a better cognitive fit than conventional 2D drawings for healthcare staff during design review of healthcare facilities. Healthcare staff experienced significantly lower cognitive load and identified a higher number of task-relevant design issues in immersive VR, particularly those related to workflow, spatial layout, sightlines, and equipment placement. In contrast, non-healthcare stakeholders—despite reporting lower cognitive load during 2D design review—identified fewer issues related to everyday work practices and use of space (e.g., sightlines, room size, flow), and instead primarily identified issues linked to requirements and compliance. This suggests that cognitive fit depends not only on representational format but also on domain-specific expertise (facility planning/work practice in healthcare facilities) and task demands (e.g., evaluating spatial qualities of a space versus building code compliance). In addition, healthcare staff's self-assessed performance showed a strong positive correlation with task performance in immersive VR, indicating that immersive review supported more reliable judgments of spatial functionality than 2D drawings.

The results further show that different representational formats supported different types of design reasoning. Immersive HMD VR primarily facilitated identification of design issues that depend on embodied and perceptual assessment, such as blocked visibility, undersized rooms

when furnished, and conflicts in equipment layout. In contrast, 2D drawings were more effective for identifying circulation logic, adjacency conflicts, and issues related to regulatory requirements.

Comparisons between review conditions revealed that healthcare staff identified significantly more design issues when reviewing 2D drawings followed by immersive VR than when using VR alone, achieving an overall increase of 46% in issue detection. At the same time, the VR-only condition resulted in the lowest median cognitive load, suggesting that direct immersion can reduce mental effort by eliminating the need to translate between representational formats (Fig. 12). Finally, differences between renovation and new-build projects highlighted the role of environmental familiarity, as mental demand during 2D review was highest when no existing physical reference was available.

#### 4.5.4 Contribution to thesis

This paper contributes to the thesis by providing a cognitive explanation for why immersive and non-immersive representational formats support end-users differently during design review. By applying Cognitive Fit Theory, the paper shows that immersive HMD VR reduces cognitive effort and supports higher task performance for healthcare staff when design review tasks depend on embodied, perceptual assessment of space, such as evaluating workflow, sightlines, room size, and equipment layout. In contrast, conventional 2D drawings provide a sufficient cognitive fit for tasks focused on regulatory requirements, building code compliance, and spatial flow, particularly for end-users with professional experience in interpreting such representations. The results further show that combining 2D drawings with immersive VR supported the highest overall identification of design issues (46% more than VR-only), indicating that different representational formats can complement each other during design review.

In relation to the overall thesis aim, the paper explains how immersive virtual environments can support end-user involvement and, in particular, Co-Design by lowering the cognitive demands associated with interpreting and validating design proposals. It complements earlier papers that focus on interaction and engagement by showing that the relevance of interactive features and representational formats is shaped by cognitive factors related to task demands and domain expertise. In this way, the paper brings together interaction, engagement, and cognition, and clarifies when and why immersive VR becomes a meaningful support for end-user involvement during design review.

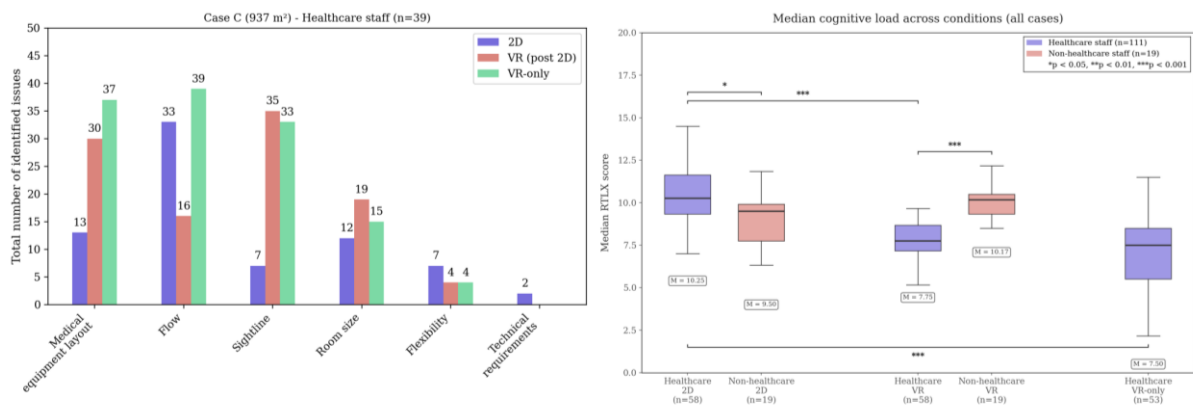


Fig. 12: Comparison of immersive VR and conventional 2D drawings showing how representational format affects design issue identification (left) and cognitive load during design review (right).



## 5 Discussion

This chapter discusses the findings in relation to the research questions introduced in Chapter 1. The discussion is organized around the three analytical themes underlying the research questions. Section 5.1 discusses end-user involvement during immersive design review, Section 5.2 addresses collaboration through interactive features in immersive environments, and Section 5.3 considers the cognitive conditions influencing design review performance.

### 5.1 End-user involvement and Co-Design in immersive design review

Across the appended papers, immersive HMD VR is associated with more active end-user involvement, but the basis for this association varies by paper and should be read accordingly. Paper 1's classification of involvement levels and Paper 4's within-subjects comparison provide the strongest support, while Papers 2 and 3 contribute recurring observations of collaboration patterns within their specific cases. In Paper 4, healthcare staff identified more design issues and reported lower cognitive load in the immersive HMD VR condition than in the 2D drawing condition, while non-healthcare staff in Paper 4 did not show a comparable reduction in cognitive load. The reduction observed for healthcare staff enabled them to contribute operational knowledge within limited participation time by drawing on their work-practice experience in the virtual environment. In Paper 4, the non-healthcare participants (facility planners, project leaders and functional planners), despite prior experience with drawing-based design review, identified additional design issues during immersive sessions that had not emerged in earlier 2D-based reviews. Paper 2, in its elementary school case, records similar in-VR identification of design issues that had not surfaced in earlier 2D-based review; Paper 3, in its separate elementary school case, records similar dynamics qualitatively (client representatives identifying issues independently of architects). Read with Paper 1's healthcare projects, Papers 2 and 3 show that participants find issues in VR that 2D missed across elementary school projects and earlier design phases too.

From a building occupant perspective, end-users often have detailed knowledge of their work practice but limited experience interpreting conventional 2D drawings (Buchanan et al., 2022; Shi et al., 2020; Foroughi Sabzevar et al., 2025). In Paper 4, 2D review was associated with significantly higher cognitive load for healthcare staff, as participants had to decode abstract symbols in plans and sections and mentally reconstruct fragmented information into a coherent three-dimensional understanding of the proposed space (Kosslyn, 1994; Schnabel & Kvan, 2003; Foroughi Sabzevar et al., 2025). In contrast, embodied interaction in immersive VR, where participants can move through the environment in ways that resemble everyday spatial experience, reduces the need for such mental translation. Paper 4 measured this reduction directly, and Paper 1 records consistent qualitative observations across its six healthcare projects of participants assessing the design through embodied movement rather than abstract interpretation. This helps explain why healthcare staff in Paper 4 identified more work-practice-related design issues in immersive review than in 2D review, since cognitive resources could be directed toward functional evaluation rather than toward interpreting the representation format itself. Paper 1 reports the same pattern qualitatively across its six healthcare projects.

Beyond identifying more issues, by lowering the effort required to understand the proposal, immersive review allowed end-users to articulate work-practice-related concerns and identify spatial constraints more readily, with Paper 4 providing the quantitative comparison and Papers 1, 2, and 3 contributing observations from their respective project contexts. In this sense, reduced cognitive effort may help strengthen the baseline conditions for end-user involvement, because participants can focus directly on evaluating the proposed space rather than first spending effort translating drawings into a spatial understanding. This can help narrow the gap between the intention to involve end-users and their actual ability to contribute useful input during design review (Eriksson, 2013; Soikkeli et al., 2023; Christiansson et al., 2011). Under such conditions, end-user involvement may be more likely to extend beyond purely informative input toward higher levels of participation (PD and Co-Design) (Paper 1). Across Paper 4's three healthcare cases (quantitatively), Paper 1's six healthcare projects, and the two elementary school cases in Papers 2 and 3, immersive review consistently revealed overlooked design issues. This suggests that even initial informative use can offer a starting point for project teams to more intentionally pursue higher levels of end-user involvement as the design process develops (Paper 1).

However, the practical challenge is that building occupants such as healthcare staff often have limited time to participate in design review due to demanding work schedules and restricted organizational support (Pirinen, 2016; Støre-Valen, 2021; van Houwelingen et al., 2023). With healthcare staff identifying more work-practice-related design issues in immersive VR than in 2D review (Paper 4), immersive sessions may help end-users such as building occupants provide more concrete input within the limited time available for participation. This is particularly important in healthcare facilities and schools, where design decisions directly affect daily workflow and coordination under strict functional requirements (Azzopardi-Muscat et al., 2020; Soliman-Junior et al., 2021), and where staff may encounter only one or two opportunities to influence design over an entire career (Thompson et al., 2012; Clark, 2014). For this reason, even when involvement remains consultative, immersive review may increase the likelihood that end-user feedback is incorporated into later design iterations. Immersive HMD VR can help occupants identify operational design problems, such as circulation bottlenecks or visibility limitations, that might otherwise depend on the design team's interpretation or be filtered through representatives. Paper 1's six healthcare projects and Paper 4's three healthcare cases document occupants identifying these kinds of issues directly during VR-supported review; Papers 2 and 3 record similar identification by representatives in their two elementary school cases.

Interactive features are particularly important because they allow end-users not only to identify issues that may be overlooked in traditional representational formats, but also to communicate operational needs directly within the shared virtual design proposal. Features such as multi-user collaboration and object interaction provide a shared spatial reference during review sessions (Churchill et al., 2001; Hey et al., 2007), allowing end-users to surface operational needs directly within the proposal rather than having them interpreted by the design team or relayed through representatives. Paper 1's Cases E and F (with object interaction available) document healthcare staff revising design proposals directly during review, and Paper 4 documents similar Co-Design moments in its three healthcare cases. In Paper 4, this supported healthcare staff in simulating future work practices and identifying workflow-related constraints, particularly in Case P4-C (new-build) where staff had no existing reference to draw on. The availability of such interactive features may also reduce misunderstandings that arise when designers and

building occupants use different professional terms and focus on different spatial aspects of the proposal (Cesario, 2009; Reno et al., 2014). In this sense, the classification developed in Paper 1 provides a structured way to describe different levels of end-user involvement, ranging from commenting on predefined solutions to more active participation in exploring and shaping design alternatives. This is relevant not only for building occupants but also for non-clinical participants. Paper 4 documents facility planners, project leaders, and functional planners identifying more technical-requirements issues such as accessibility constraints in 2D, and Papers 2 and 3 record client representatives and architects raising regulatory and project-requirement questions in their two elementary school cases.

When end-users are able to contribute through interactive design review, as in Paper 1's Cases E and F, Paper 3's ViCoDE workshops, and Paper 4's three healthcare cases (all with object interaction available), design discussions may progress more efficiently than in sequential review cycles where issues are identified only after drawings are interpreted and revised (Koskela, 2000; Gomes & Tzortzopoulos, 2018). Interactive immersive review can therefore support the development of design solutions that better reflect both operational experience and project constraints, since multiple stakeholder perspectives are present during the session (Paper 1's Cases E and F; Paper 4's three healthcare cases). This may help reduce the reliance on assumptions that often characterizes drawing-based communication (Henderson, 1998; Sunesson et al., 2008). At the same time, immersive review can reduce designers' dependence on indirect end-user feedback for understanding operational needs, while also reducing occupants' dependence on the design team to translate drawings into a spatial understanding of their future workplace. Paper 4 documents this reduction directly for healthcare staff in its three healthcare cases, and Paper 1 records consistent qualitative observations across its six healthcare projects. Together, this suggests that immersive design review can support more direct mutual understanding between end-users and designers. Paper 4 and Paper 1's healthcare projects record key operational needs being identified directly by end-users, reducing the risk that such needs are left to indirect interpretation (Hey et al., 2007; Cesario, 2009; Reno et al., 2014).

Overall, higher levels of end-user involvement with immersive HMD VR depend not only on immersive visualization (which, in Paper 4, reduced cognitive load for healthcare staff across its three healthcare cases), but also on interactive features that support joint exploration and the development of feasible layout adjustments across stakeholder roles (Paper 1's Cases E and F; Paper 3's ViCoDE workshops; Paper 4's three healthcare cases). Operational concerns linked to work practice (Paper 1's six healthcare projects; Paper 4's three healthcare cases) and project requirements such as accessibility (Paper 4) can then be addressed within shared design review sessions, supporting higher levels of end-user involvement when design decisions remain negotiable (Yu et al., 2022) and relevant stakeholders are able to participate (Pirinen, 2016; Støre-Valen, 2021; van Houwelingen et al., 2023). Across the appended papers, the strongest support for this comes from Paper 1's involvement classification and from Paper 4's comparative data; Papers 2 and 3 contribute consistent within-case observations of collaboration patterns rather than comparative evidence.

## 5.2 Interactive features and collaboration in immersive design review

When multi-user features are available, immersive design review can support collaboration through shared spatial understanding (Paper 1's Cases E and F; Paper 2's elementary school case; Paper 3's elementary school case; Paper 4's three healthcare cases). When both multi-user and object interaction are available, stakeholders can evaluate the functional implications of design choices by modifying the architectural proposal jointly in the virtual environment (Paper 1's Cases E and F; Paper 3's ViCoDE workshops; Paper 4's three healthcare cases). Beyond earlier research's emphasis on immersive visualization supporting end-users' spatial interpretation (Nikolić & Whyte, 2021; Paes et al., 2017), the findings from sessions where task-based scenarios were observed (Paper 1's Cases E and F, Paper 3's ViCoDE workshops, and Paper 4's three healthcare cases) suggest that interactive features support not only building occupants but also architects, client representatives, and facility planners in exploring and negotiating the functional implications of design choices. In this way, interactive features can influence whether immersive design review is used mainly to support individual observation of pre-defined design proposals or also to discuss and test alternative design solutions together (Paper 1).

Design review sessions often bring together stakeholders with different responsibilities (Paper 4), such as building occupants focused on work-practice needs and project representatives concerned with functional and regulatory requirements (Daniels et al., 2019). Collaboration therefore depends on whether the immersive review environment allows these different perspectives to be shared and discussed in relation to the same part of the proposed layout (Gomes & Tzortzopoulos, 2018; Horvat et al., 2022). From a CVE perspective, this requires interaction features that establish *shared context* and *awareness of others*, enabling participants to focus on the same design aspects during review, such as room size, sightlines, or equipment placement (Churchill et al., 2001; Snowdon et al., 2001). As the findings show (Paper 2's elementary school case, centrally; Paper 3's separate elementary school case, with similar observations), the multi-user feature provided stakeholders with a shared frame of reference (Johansson & Roupé, 2022), by allowing them to explore the virtual environment simultaneously and communicate design concerns as they became apparent during review (Truong et al., 2021). This shared frame of reference allowed participants to direct each other's attention to specific locations in the model through bodily cues such as pointing and shared orientation (Johansson & Roupé, 2024), making design concerns easier to discuss and negotiate as part of the same spatial configuration (Paper 2's elementary school case). Rather than having to explain spatial concerns from different individual viewpoints, multi-user review enables stakeholders to reference the same spatial detail in real-time, which can reduce misunderstandings (Sfandyarifard & Tzortzopoulos, 2011), and support quicker agreement on necessary adjustments and compromises across different stakeholder priorities (Truong et al., 2021; Johansson & Roupé, 2024).

In addition to shared context and awareness of others, CVE collaboration criteria emphasize the importance of supporting flexible and multiple viewpoints (Churchill et al., 2001). This means that participants may require different representations of the same proposal depending on whether they are evaluating room-level usability (e.g., staff movement and equipment placement) or considering broader layout concerns such as circulation and adjacency. As the findings show (Paper 2), the multi-scale feature allowed client representatives to alternate between full-scale immersion and an overview in the form of a 1:40 scale representation of the layout. This provided stakeholders with opportunities to examine the design from an embodied, egocentric 1:1 perspective, where questions about how staff would move, perform tasks, and use the space could be discussed in relation to the experienced room configuration (Nikolić & Whyte, 2021). It also enabled an overview, allocentric perspective, where broader spatial relationships such as circulation and adjacency could be considered (Paes et al., 2017; Paper 2). Such shifts between viewpoints reflect Churchill et al.'s (2001) argument that collaborative tasks often require multiple representations that support different participants' subtasks, allowing stakeholders to raise different types of review concerns, as seen in Paper 4 (e.g., workflow-related usability issues versus layout-level organizational questions). In Paper 2, multi-scale interaction supported CVE conditions for collaboration by providing viewpoints that helped stakeholders address both room-level usability concerns and broader layout-level questions within the same review session. Because this configuration was observed only in Paper 2, it is treated here as an illustration of how multi-scale viewpoints can be used in a CVE, rather than as a cross-case claim. In Paper 4, an overview perspective was available through conventional 2D drawings, where circulation and flow-related issues could be identified from an allocentric representation. Paper 2 illustrates how making such an overview perspective available within the immersive environment may help integrate embodied and plan-like reasoning without switching between separate representational formats. The lower median cognitive load observed in the VR-only condition in Paper 4, compared to the VR session that followed 2D review in the sequential condition, is consistent with the possibility that remaining within a single representational format reduces cognitive effort during review, although this remains a single-study observation.

At the same time, Paper 2's elementary school case and Paper 3's separate elementary school case indicate that providing multiple viewpoints within a CVE system does not ensure that all stakeholder groups interact with the system in the same way. While Paper 2 integrated egocentric and allocentric perspectives within the same immersive environment, Paper 3 examined a CVE system that offered parallel interaction modes through immersive HMD VR, a multitouch table, and shared projection. From a CVE perspective, this reflects Churchill et al.'s (2001) argument that collaborative tasks often require different representations and interaction modes to support different participants' subtasks. In Paper 3, both architects and client representatives initially interacted mainly through the multitouch table rather than immersive exploration, suggesting that early use was guided by familiar plan-like practices (e.g., use of conventional 2D drawings) rather than immersive navigation alone (Daniels et al., 2019; Horvat et al., 2022). Over repeated design review sessions in Paper 3, client representatives increasingly shifted toward immersive HMD exploration. Although the participants in Paper 3 were client representatives rather than building occupants, this shift parallels separate observations in Paper 1's six healthcare projects and Paper 4's three healthcare cases, where healthcare staff used immersive HMD VR to evaluate operational implications of design proposals at full scale. Across sessions, the multitouch interface also supported architects in

rapidly proposing, testing, and discussing layout adjustments through object interaction, illustrating how different interaction modes within the CVE system aligned with different stakeholder subtasks during collaborative review (Paper 3) (Churchill et al., 2001; Roupé et al., 2020). Multi-interface CVE systems can therefore support collaborative design review by combining embodied assessment in immersive HMD VR with more plan-like, table-based interaction modes. This suggests that collaboration may be strengthened when immersive review is complemented by interaction formats that different stakeholders can adopt, rather than relying on immersive HMD interaction alone, as observed in Paper 1's Case E and Paper 3's ViCoDE workshops.

Alongside differences in how stakeholders use interaction features across different user-interfaces, findings in Paper 1's Cases E and F and Paper 4's three healthcare cases also suggest that collaboration depends on whether interaction allows building occupants' work-practice knowledge to be made explicit within the proposal. Immersive design review therefore becomes collaborative not only through shared viewing, but through interaction that allows stakeholders, particularly building occupants, to externalize work-practice knowledge within the design proposal. CVE research similarly emphasizes that shared understanding develops when participants can respond to and build upon such externalized knowledge in a shared representation, rather than relying only on verbal interpretation (Arias et al., 2000; Fischer et al., 2005). In Paper 1's Cases E and F and across Paper 4's three healthcare cases, this was reflected in how healthcare staff could point out and enact work-practice issues in relation to the virtual room configuration, for example by testing equipment placement and spatial constraints instead of only describing concerns verbally. Arias et al. (2000) describe collaborative design activity as alternating between reflection, in which stakeholders interpret design implications, and action, in which alternative solutions are explored through direct changes to the representation. Object interaction supported the shift between reflection and action by enabling "what-if" exploration of layout adjustments with immediate spatial feedback, making design implications visible in real time rather than dependent on assumptions or retrospective explanation and interpretation (Paper 1's Cases E and F) (Fischer et al., 2005; Wolfartsberger, 2019). Shared feedback of this kind also provides better conditions for negotiation and communication of trade-offs during review, as emphasized in CVE collaboration criteria (Churchill et al., 2001). Making reflection and action available within the same representational format (Paper 4) is also practically important, since design review is often constrained to a small number of time-limited sessions. Interactive features that allow stakeholders to explore alternatives during the session could therefore reduce reliance on feedback being documented for later interpretation and incorporation (Pirinen, 2016; Støre-Valen, 2021). Under these conditions, object interaction was the feature that most clearly allowed stakeholders to actively propose, test, and adjust design solutions within the proposal, rather than solely issue identification (Paper 1's Cases E and F; Paper 3's ViCoDE workshops).

### **5.3 Cognitive fit and end-user expertise**

Task performance and end-user involvement during design review are shaped not only by immersive visualization or interactive features, but also by whether the representational format supports the cognitive demands of the task and the expertise of those involved. From a cognitive fit perspective, immersive HMD VR and conventional 2D drawings may provide different issue-identification support depending on whether stakeholders are assessing full-scale usability concerns, such as workflow, clearance, and sightlines (Paper 1's six healthcare projects;

Paper 4's three healthcare cases), or broader layout constraints, such as circulation and adjacency (Paper 3's elementary school case; Paper 4's three healthcare cases) (Vessey, 1991). Moreover, cognitive fit also depends on involving stakeholders whose domain experience allows them to recognize work-practice-related issues in the architectural proposal. This aligns with the idea that stakeholders who encounter the consequences of design decisions in everyday practice, “owners of the problem”, contribute tacit knowledge and perspectives that other participants may not access through representation format alone (Arias et al., 2000; Fischer et al., 2005) (Paper 1's six healthcare projects; Paper 4's three healthcare cases). Cognitive Fit Theory therefore helps explain why different representational formats support different forms of end-user contribution and subtasks (e.g., usability assessment versus requirement-oriented layout evaluation) to varying degrees during design review.

This alignment between representational format and end-user expertise was particularly visible in Paper 4. Healthcare staff identified more design issues with immersive HMD VR than with conventional 2D drawings, while also reporting lower cognitive load. Such differences are consistent with earlier observations that immersive environments can reduce cognitive demands for end-users who lack training in plan-based representations, since room usability can be evaluated through full-scale experience rather than mental reconstruction (Nikolić & Whyte, 2021; Paes et al., 2017). In Paper 4, this contrast became apparent because review of 2D drawings required participants to mentally reconstruct fragmented plans and sections into a coherent spatial understanding, whereas immersive VR allowed spatial concerns to be assessed more directly in relation to the experienced room configuration (Kosslyn, 1994; Schnabel & Kvan, 2003; Foroughi Sabzevar et al., 2025). Viewed through a cognitive fit lens, immersive environments provided better conditions for building occupants to draw on their detailed work-practice knowledge, since less effort was spent interpreting the representational format itself. For example, distinguishing between medical equipment in 2D drawings can be difficult (Wingler et al., 2019), making it harder for healthcare staff to simulate task scenarios linked to everyday work (Paper 4). In immersive VR, by contrast, building occupants were able to assess the proposal from an egocentric frame of reference rather than from the fixed, allocentric viewpoint of drawings (Paper 1's six healthcare projects; Paper 4's three healthcare cases), experiencing the space in a way that more closely resembles how workplaces are experienced during daily tasks (Filimon, 2015). These conditions help explain why several design issues across the studied projects became visible only once the environment could be experienced at full scale through immersive VR (Paper 1's six healthcare projects; Paper 4's three healthcare cases). Issue identification via immersive HMD VR occurred even though multiple design review sessions had taken place beforehand using conventional representations (Paper 4's renovation Cases P4-A and P4-B, with seven and four prior 2D sessions respectively; with similar observations recorded across Paper 1's six healthcare projects), suggesting that 2D drawings provided a weaker cognitive fit for work-practice-oriented review.

At the same time, non-building-occupant stakeholders in Paper 4 also identified more issues such as hidden sightlines and constrained room size through immersive HMD VR than with conventional 2D drawings. This suggests that certain spatial usability issues, such as hidden sightlines, constrained room size, or limited clearance around equipment, can be recognized through immersive full-scale experience even by stakeholders without detailed work-practice expertise (Filimon, 2015; Nikolić & Whyte, 2021). In these cases, immersive VR may reduce interpretive effort enough for a broader range of end-users to identify concerns that would be difficult to infer from allocentric drawings alone (Foroughi Sabzevar et al., 2025, Shi et al.,

2020). Moreover, building occupants often contribute work-practice-relevant issues that other stakeholders may overlook, since they encounter the operational consequences of design decisions directly (with empirical support across Paper 4's three healthcare cases) (Lu et al., 2022; Shultz & Jha, 2021). This creates a starting point from which other end-users, such as those prioritizing requirement compliance or long-term facility constraints, can build and negotiate subsequent design solutions, as illustrated in Paper 4's Cases P4-B and P4-C, where healthcare staff revisions (such as revised medical equipment layouts) were incorporated into the architect's subsequent design proposals. In sum, Paper 1's six healthcare projects and Paper 4's three healthcare cases demonstrate how immersive HMD VR can strengthen cognitive fit for building occupants by supporting mental representations shaped by everyday spatial experience, enabling more effective identification of work-practice-related design issues during review.

However, the findings also indicate that representational formats supporting building occupants' experiential reasoning do not necessarily provide the same cognitive fit for other professional groups or design subtasks. Paper 3 shows that architects and client representatives initially relied more on plan-like interaction through the multitouch table than on immersive HMD exploration. Paper 2 records the same preference for allocentric overview through a different mechanism in its separate elementary school case, where the miniature 1:40 view within HMD VR was used more than expected. The same pattern across two different setups suggests that for these stakeholders, plan-like representations reflect what their design tasks typically require, rather than what any one representational format happens to offer. In Paper 3, these participants had extensive prior experience with 2D-based design review, and their early interaction patterns aligned with that experience rather than with immersive navigation (Daniels et al., 2019; Horvat et al., 2022). Rather than indicating resistance to immersive VR, the interaction analysis patterns in Paper 3, where stakeholders first engaged through plan-like representations before gradually adopting immersive exploration, can be understood in terms of cognitive fit. Tasks such as proposing layout adjustments, coordinating spatial relationships, and iterating design solutions were predominantly engaged through representations resembling conventional 2D drawings and sketch-based workflows, which align with professional design practices (Vessey, 1991) (Paper 3). This pattern may help explain why stakeholders whose tasks rely on allocentric representations, such as regulatory assessment or layout coordination, did not experience the same cognitive load reduction in immersive HMD VR as building occupants (Paper 4). Stakeholders with limited prior 2D-based design review experience but detailed work-practice knowledge, such as the healthcare staff in Paper 1's six healthcare projects and Paper 4's three healthcare cases, were more likely to rely on egocentric, full-scale spatial experience when evaluating workflow, visibility, and operational conditions.

With these differences in spatial reasoning strategies, representations that allow stakeholders to shift between egocentric and allocentric frames of reference become particularly important. Paper 2 demonstrated that multi-scale interaction enabled stakeholders to alternate between full-scale embodied experience and overview layout perspectives within the same review session. Across the three independent case studies (Papers 1, 2, and 3), with corroboration from Paper 4, the dimension that varied with cognitive fit was not professional role itself but the combination of domain knowledge of the work practice and prior experience with 2D-based design review. In Paper 4, participants whose review concerns centered on workflow, clearance, and visibility, primarily building occupants in these projects, drew more on full-scale, embodied evaluation (Filimon, 2015), while participants whose concerns centered on circulation,

functional relationships, and requirement compliance — primarily client representatives and facility planners — drew more on overview representations (Paes et al., 2017). These observed differences are consistent with variations in mental models of the workplace shaped by everyday practice, rather than with cognitive profiles inferred from professional role. Interactive features such as object interaction and multi-scale viewpoints further supported these differences by allowing stakeholders to externalize their reasoning within the shared representation (Arias et al., 2000, Fischer et al., 2005). In Paper 1's Cases E and F, building occupants could demonstrate work-practice concerns directly through changes to the virtual proposal, making tacit operational knowledge visible to other participants. Similarly, multi-scale interaction in Paper 2 allowed non-building-occupant stakeholders to articulate layout- and requirement-related considerations through overview representations. Rather than aligning mental models directly, such interaction appears to support mutual understanding by making different perspectives explicit and available for discussion (Arias et al., 2000; Fischer et al., 2005). This interpretation is consistent with CVE collaboration criteria emphasizing shared context and negotiation, where complementary representations allow operational work-practice concerns and broader organizational or regulatory priorities to be related within the same review session (Paper 1) (Churchill et al., 2001). Combining immersive and overview representations can therefore support different forms of end-user contribution during design review (Paper 4), since stakeholders bring different expertise, responsibilities, and review priorities that cannot be addressed through a single representational format alone (Arias et al., 2000; Gomes & Tzortzopoulos, 2018).

Because different stakeholder priorities cannot always be addressed through a single representation, intended end-user involvement does not always translate into actual contribution during design review. Across the three independent case studies (Papers 1, 2, and 3), with corroboration from Paper 4, involvement appeared to depend on whether participants could work with the representation without first having to interpret it extensively. Specifically, in Paper 4, building occupants identified more work-practice-related issues once the design could be experienced at full scale in immersive HMD VR than during earlier drawing-based sessions, suggesting that higher representational complexity and the associated cognitive load can constrain stakeholders' ability to identify design issues, as also observed in design-review research (Gustafsson et al., 2025; Umair et al., 2022).

At the same time, there is no universal “optimal level” of cognitive load during design review. Workload ratings are inherently relative and difficult to define across different tasks and conditions (Hart, 2006), and Cognitive Load Theory similarly emphasizes that effective performance depends on how cognitive demand aligns with task characteristics (e.g., evaluation of design review questions linked to work practice, requirement compliance) rather than on minimizing load alone (Sweller et al., 2019). For this reason, interpreting design review performance benefits from combining subjective workload assessments with objective performance indicators (Paas et al., 2003, Shi et al., 2020), since lower reported cognitive load does not automatically imply better task outcomes, and higher load may reflect engagement with complex spatial or operational questions rather than reduced performance (Paper 4). Findings from Paper 4 further illustrate that the relationship between cognitive load and design review performance varies depending on the review conditions. Immersive HMD VR alone was associated with the lowest cognitive load among building occupants, which may support rapid

end-user involvement in time-constrained review sessions or when engaging larger groups within a department. However, when immersive HMD VR was preceded by review in conventional 2D drawings, which support allocentric frames of reference, a broader range of design issues was identified (46% more in total) and review sessions appeared more accessible to non-building-occupant stakeholders, given the increase in flow- and sightline-related issues they identified. Together, these findings suggest that end-user involvement during design review depends less on minimizing cognitive load alone than on providing representational formats that allow stakeholders to apply their domain knowledge directly in evaluating spatial, operational, and requirement-related aspects of the building design.

These observations indicate that variations in involvement and performance are closely tied to how well representational formats support stakeholders' cognitive processes. The findings suggest that reduced end-user participation during design review does not necessarily reflect lack of expertise or difficulty understanding the design proposal itself, but may instead result from misalignment between the representational format, the review task, and stakeholders' professional experience (Nikolić & Whyte, 2021; Vessey, 1991). Individual task performance during design review appears closely tied to how easily stakeholders can interpret and work with the representation, which in turn influences their ability to participate actively in design discussions (Paper 4). End-users such as building occupants are therefore more likely to engage as active contributors to the design process rather than as passive recipients, with immersive HMD VR helping shift their involvement from symbolic to more active participation (Christiansson et al., 2011; Nazeer et al., 2024). By enabling a better cognitive fit for building occupants, allowing them to apply their domain knowledge more directly, immersive HMD VR may create more favorable conditions for design review negotiation (Churchill et al., 2001). At the same time, immersive HMD VR may help end-users better understand why certain design requests cannot be implemented (Paper 4), reducing their reliance on design team members or representatives to interpret and justify design decisions on their behalf (Stichler, 2016; Jouppila, 2025). In practice, improving involvement therefore appears to depend less on introducing immersive technology alone than on ensuring that representations allow different end-user groups to apply their domain knowledge directly during review (Papers 1, 2, and 3, supported by Paper 4).

## 6 Conclusions

This thesis examined how immersive virtual environments can be used in practice to support end-user involvement and Co-Design during building design review. Drawing on four empirical studies conducted across several ongoing healthcare and school projects involving diverse end-user groups, the findings show that immersive virtual environments can strengthen design review by enabling end-users to experience proposed environments at full scale, evaluate how design proposals affect daily operational work practices, and identify design issues related to room layout, visibility, spatial flow, and equipment placement at earlier stages of the design process. The findings further indicate that immersive environments were most effective for identifying design issues during design review when combined with conventional 2D drawings and interactive features rather than used as a standalone representational format.

A key contribution of the thesis concerns how representational formats influence end-user involvement during building design review across different project phases. The findings indicate that immersive representations reduce the need for building occupants to reconstruct spatial layouts from abstract drawings, allowing them instead to apply their professional work-practice experience to evaluate how design proposals would affect daily operations. In the other empirical studies, immersive and interactive representations similarly enabled end-users to shift between overview and full-scale perspectives when evaluating spatial layouts, discuss and iteratively assess alternative design solutions, and articulate operational concerns more actively during collaborative design review sessions. Together, these findings suggest that representational alignment can support more active participation and facilitate movement from lower levels of end-user involvement toward participatory design and Co-Design. At the same time, immersive visualization does not in itself ensure higher levels of end-user involvement. Rather, the degree of involvement depends on how interactive features, and representational formats align with the cognitive demands of the review task (e.g., evaluating room layout, workflow, and visibility) and with stakeholders' domain expertise (e.g., building code compliance, work practice experience). Taken together, this suggests that different representational formats and interactive features can support a better cognitive fit between end-users' domain expertise, the spatial evaluation tasks involved, and their level of involvement in design review. Beyond individual cognitive alignment, these dynamics also shape the collaborative conditions of immersive design review. In this way, the findings extend research on Collaborative Virtual Environments by demonstrating how established collaboration criteria, such as shared context, awareness of others, and negotiation within a common representation, operate within real-world projects rather than controlled experimental settings.

The thesis also contributes to cognitive fit research by extending its focus from individual task performance to collaborative design review settings. While Cognitive Fit Theory has traditionally examined how alignment between representational format, task demands, and user expertise affects information processing efficiency, the findings here indicate that such alignment also shapes the conditions under which active end-user involvement can occur. When representational formats require extensive mental reconstruction before operational knowledge can be applied, participation risks remaining symbolic even when formal opportunities for involvement are provided. Where building occupants are better able to articulate how design proposals affect their work practices, other end-user groups responsible for planning and coordination gain clearer insight into operational priorities. A similar constraint applies to non-

operational end-users, such as facility planners. When representational formats make it difficult to maintain an overview of the layout or understand how design decisions affect different parts of the project, their planning and coordination expertise may not be fully applied. By contrast, representations that reduce the cognitive effort required to interpret the design enable stakeholders to evaluate proposals using their domain expertise more readily, thereby supporting more active contribution to design discussions. In collaborative review settings, cognitive fit is therefore not a single property of a representational format but a relationship that varies across participants within the same session: a format that aligns well with one stakeholder group's domain knowledge and prior representational experience may impose higher cognitive demands on another, so design review benefits from offering complementary representational formats that allow different participants to apply their respective expertise within the same session. In this way, the thesis demonstrates that cognitive fit not only influences individual understanding but also affects whether intended levels of end-user involvement can be realized in collaborative design processes.

From a practical standpoint, the findings suggest that immersive design review is particularly useful for identifying operational design issues during design review when used alongside conventional 2D drawings or other overview-based representational formats rather than as the sole representational format. Across the studied projects, immersive review frequently revealed operational design issues, including workflow constraints, sightline limitations, spatial usability concerns, and equipment placement challenges, including projects where several rounds of conventional drawing-based reviews had already been conducted. Combining immersive full-scale experience with overview views of the layout supports participation from end-user groups with different expertise, enabling both direct spatial understanding of the environment and evaluation of layouts, regulatory requirements, and project constraints. Interactive features such as multi-user environments, object interaction, and multi-scale perspectives allow operational concerns to be expressed directly within the design representation rather than relying solely on verbal explanation or subsequent interpretation by other participants. In this respect, immersive visualization appears to support cognitive alignment for spatial evaluation tasks, while interactive features further reinforce alignment by enabling end-users to explore, manipulate, and negotiate design proposals in ways consistent with their domain expertise and review objectives. Such interaction within immersive environments supports more direct communication between operational and planning perspectives and helps align design decisions more closely with end-user priorities.

More broadly, the thesis contributes empirical insights from real-world design review sessions, extending prior research that has often relied on controlled experimental settings, student participants, or simplified design review tasks. By examining immersive virtual environments within ongoing building projects involving professional end-user groups and combining qualitative observations with quantitative measures of cognitive load and task performance, the research provides further understanding of how immersive virtual environments operate within practical project conditions. The findings indicate that immersive environments can support earlier identification of operational design issues, improve shared understanding among participants, and create more favorable conditions for active end-user involvement in building design processes.

At the same time, the findings should be interpreted in relation to the specific projects studied, primarily healthcare and school projects where spatial design directly affects operational work

practices. Design review sessions are inherently shaped by project conditions, including project phase, stakeholder roles, organizational constraints, available project material, and organizational capacity. These project-related factors suggest that immersive virtual environments should be viewed not as universal solutions but as representational formats whose effectiveness depends on alignment with project needs, stakeholder expertise, and intended levels of involvement. When such alignment is achieved, immersive representations can support more active end-user involvement during design review and create favorable conditions for Co-Design. Ultimately, this highlights how alignment between representational format and end-users' cognitive interpretation of design proposals can support more active participation in design review and thereby create favorable conditions for Co-Design in building design.



## 7 Future research

Building on the findings of this thesis, several avenues for future research can be identified, which are discussed below.

### **Longitudinal studies of immersive design review**

While this thesis demonstrates how immersive virtual environments influence cognitive load and issue identification during individual design review sessions, design review typically occurs through multiple sessions across different phases of the design process. It therefore remains unclear how repeated exposure to immersive and conventional representational formats affects cognitive load, issue identification performance, and time spent evaluating design proposals. As design proposals become more detailed over time, the cognitive demands associated with interpreting spatial information may also change. An additional open question concerns whether observed performance changes reflect increasing familiarity with representational formats or growing familiarity with the specific spatial layouts under review. Longitudinal studies could examine how these factors evolve across successive review sessions and how observed task performance changes over time.

### **End-user expertise variation and cognitive fit**

Future research could extend the thesis' cognitive fit contribution by exploring end-user expertise beyond professional roles. Rather than only comparing different end-user groups, studies could analyze within-group variation in work-practice experience, ability to interpret allocentric and egocentric representations, and experience spanning both operational and planning roles. An open question is whether cognitive fit during design review varies with work-practice experience or mainly reflects differences between end-user role groups. This issue is particularly relevant for end-users who have moved from operational roles into planning or representative positions, where prior work-practice experience may not fully match the types of design issues they are now expected to evaluate during design review. It also remains unclear how much work-practice experience is required before immersive design review reliably supports identification of domain-specific design issues in operationally demanding building types such as healthcare and educational facilities.

### **Integration of conversational AI in immersive design environments**

Immersive design review often requires participants to relate spatial evaluation to dispersed project documentation, including project requirements, design guidelines, regulatory constraints, and prior project decisions. Accessing such material during design review in current practice may increase cognitive load and require attention to shift away from spatial evaluation, particularly for end-users responsible for coordinating operational needs with project constraints. This raises questions about how access to project information within immersive environments might support design review without interfering with spatial interpretation. Future research could examine how conversational AI integrated into immersive environments influences cognitive load, interpretation of design proposals, and the evaluation of design solutions. However, it is not yet established whether such support facilitates shared understanding during participatory design review involving both end-users and design team members.



## References

- Agrawala, M., Beers, A. C., McDowall, I., Fröhlich, B., Bolas, M., & Hanrahan, P. (1997). The two-user Responsive Workbench: Support for collaboration through individual views of a shared space. *Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques*, 327–332. <https://doi.org/10.1145/258734.258875>
- Aguilar-Moya, R., R. Diamanti, and D. Melero-Fuentes. 2025. Teaching Methods, Learning and Development: A 15-Year Research Perspective by Educational Stages. *Education Sciences* 15: 1213.
- Alghamdi, A., M. Sulaiman, A. Alghamdi, M. Alhosan, M. Mastali, and J. Zhang. 2017. Building Accessibility Code Compliance Verification Using Game Simulations in Virtual Reality. 262–270.
- Andrews, C., J. Day, P. Agee, R. Wener, Q. Jin, and J. Senick. 2023. Methods to Obtain the Occupant Perspective. *Occupant-Centric Simulation-Aided Building Design*, Routledge.
- Arias, E., H. Eden, G. Fischer, A. Gorman, and E. Scharff. 2000. Transcending the individual human mind—creating shared understanding through collaborative design. *ACM Transactions on Computer-Human Interaction* 7: 84–113.
- Arnstein, S. R. 1969. A ladder of citizen participation. *Journal of the American Institute of planners* 35.
- Arthur Jr., W., W. Bennett Jr., P. L. Stanush, and T. L. McNelly. 1998. Factors That Influence Skill Decay and Retention: A Quantitative Review and Analysis. *Human Performance* 11: 57–101.
- Åsgård, T., L. Jørgensen, and H. Breistrand Bringsvor. 2024. Closing the gap between good intentions and realized potential of end-user involvement. *IOP Conference Series: Earth and Environmental Science* 1389: 012041.
- Azzopardi-Muscat, N., A. Brambilla, F. Caracci, and S. Capolongo. 2020. Synergies in Design and Health. The role of architects and urban health planners in tackling key contemporary public health challenges. *Acta Bio Medica : Atenei Parmensis* 91: 9–20.
- Bazzaro, F., M. Charrier, S. Chevriau, T. Rouxel, and J.-C. Sagot. 2018. Impact of Architectural Representation on Users' Feelings: From 2d Plans to Virtual Models and Physical Prototypes. *Journal of Architectural and Planning Research* 35: 244–257.
- Berg, M. C. van den, T. Hartmann, and R. S. de Graaf. 2017. Supporting design reviews with pre-meeting virtual reality environments. *Journal of information technology in construction* 22: 305–321.
- Bergvall-Kåreborn, B., and A. Ståhlbrost. 2008. Participatory design: one step back or two steps forward? *Proceedings of the Tenth Anniversary Conference on Participatory Design 2008, PDC '08*, 102–111. Indiana University, USA.

- Bjørn, P., M. Wulff, M. S. Petráeus, and N. H. Møller. 2021. Immersive Cooperative Work Environments (CWE): Designing Human-Building Interaction in Virtual Reality. *Computer Supported Cooperative Work (CSCW)* 30: 351–391.
- Brittin, J., D. Sorensen, M. Trowbridge, K. K. Lee, D. Breithecker, L. Frerichs, and T. Huang. 2015. Physical Activity Design Guidelines for School Architecture. *PLOS ONE* 10: e0132597.
- Buchanan, E., G. Loporcaro, and S. Lukosch. 2022. On the Effectiveness of Conveying BIM Metadata in VR Design Reviews for Healthcare Architecture. 2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), 806–807.
- Buchanan, E., G. Loporcaro, and S. Lukosch. 2023. On the Effectiveness of Using Virtual Reality to View BIM Metadata in Architectural Design Reviews for Healthcare. *Multimodal Technologies and Interaction* 7: 60.
- Byci Jakupi, A., and A. Xhambazi. 2024. Participatory design as an instrument in designing functionally and technically complex buildings. *Architectural Engineering and Design Management* 20: 1280–1300.
- Byers, T., W. Imms, and E. Hartnell-Young. 2018. Evaluating teacher and student spatial transition from a traditional classroom to an innovative learning environment. *Studies in Educational Evaluation* 58: 156–166.
- Caixeta, M. C. B. F., and M. M. Fabricio. 2021. Physical-digital model for co-design in healthcare buildings. *Journal of Building Engineering* 34: 101900.
- Caixeta, M. C. B. F., P. Tzortzopoulos, and M. M. Fabricio. 2019. User Involvement in Building Design: a State-of-the-Art Review. *Pós. Revista Do Programa De Pós-Graduação Em Arquitetura E Urbanismo Da FAUUSP* 26: 1–23.
- Capolongo, S., M. Gola, A. Brambilla, A. Morganti, E. I. Mosca, and P. Barach. 2020. COVID-19 and Healthcare Facilities: a Decalogue of Design Strategies for Resilient Hospitals. *Acta Bio Medica : Atenei Parmensis* 91: 50–60.
- Carpentier, N. 2016. Beyond the Ladder of Participation: An Analytical Toolkit for the Critical Analysis of Participatory Media Processes. *Javnost - The Public* 23: 70–88.
- Carroli, L., J. Willis, and J. Franz. 2025. Aspirations and the design of vertical schools. *Discover Education* 4: 399.
- Carthey, J. 2021. Participatory Design, Project Clients, and Healthcare User Groups. *HERD: Health Environments Research & Design Journal* 14: 96–108.
- Carthey, J. F. 2013. Australasian Health Facility Guidelines: results of a user survey. *Facilities* 31: 574–590.
- Castronovo, F., D. Nikolic, Y. Liu, and J. I. Messner. 2013. An evaluation of immersive virtual reality systems for design reviews: International Conference on Construction Applications of Virtual Reality. 22–29.

- Cesario, S. K. 2009. Designing Health Care Environments: Part I. Basic Concepts, Principles, and Issues Related to Evidence-Based Design. *The Journal of Continuing Education in Nursing* 40: 280–288.
- Choguill, M. B. G. 1996. A ladder of community participation for underdeveloped countries. *Habitat International* 20: 431–444.
- Chrastil, E. R., and W. H. Warren. 2013. Active and passive spatial learning in human navigation: acquisition of survey knowledge. *Journal of Experimental Psychology. Learning, Memory, and Cognition* 39: 1520–1537.
- Christiansson, P., K. Svidt, K. B. Pedersen, and U. Dybro. 2011. User participation in the building process. *Journal of Information Technology in Construction (ITcon)* 16: 309–334.
- Churchill, E. F., and D. Snowdon. 1998. Collaborative virtual environments: An introductory review of issues and systems. *Virtual Reality* 3: 3–15.
- Churchill, E. F., D. N. Snowdon, and A. J. Munro. 2001. Collaborative Virtual Environments: Digital Places and Spaces for Interaction. Springer Science & Business Media.
- Clark, E. 2014. Bedside to blueprints: the role of nurses in hospital design. *HERD* 7: 100–107.
- Coburn, J. Q., Freeman, I., & Salmon, J. L. (2017). A Review of the Capabilities of Current Low-Cost Virtual Reality Technology and Its Potential to Enhance the Design Process. *Journal of Computing and Information Science in Engineering*, 17(3), 031013. <https://doi.org/10.1115/1.4036921>
- Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications.
- Cummings, J. J., and J. N. Bailenson. 2016. How Immersive Is Enough? A Meta-Analysis of the Effect of Immersive Technology on User Presence. *Media Psychology* 19: 272–309.
- Dadi, G. B., P. M. Goodrum, T. R. B. Taylor, and C. M. Carswell. 2014. Cognitive Workload Demands Using 2D and 3D Spatial Engineering Information Formats. *Journal of Construction Engineering and Management* 140: 04014001.
- Damodaran, L. 1996. User involvement in the systems design process—a practical guide for users. *Behaviour & Information Technology* 15: 363–377.
- Dane, G., S. Evers, P. van den Berg, A. Klippel, T. Verduijn, J. O. Wallgrün, and T. Arentze. 2024. Experiencing the future: Evaluating a new framework for the participatory co-design of healthy public spaces using immersive virtual reality. *Computers, Environment and Urban Systems* 114: 102194.
- Daniels, H., H. M. Tse, A. Stables, and S. Cox. 2019. Design as a social practice: the experience of new-build schools. *Cambridge Journal of Education* 49: 215–233.
- Das Chakladar, D., and P. P. Roy. 2024. Cognitive workload estimation using physiological measures: a review. *Cognitive Neurodynamics* 18: 1445–1465.
- Davidsson. 1998. Spinning the wheel of empowerment. *Planning*: 14–15.

- Derouech, O., H. Hrimech, M. Lachgar, and M. Hanine. 2024. A Literature Review of Collaborative Virtual Environments: Impacts, Design Principles, and Challenges. *Journal of Information Technology Education: Research* 23: 011.
- Du, J., Z. Zou, Y. Shi, and D. Zhao. 2018. Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making. *Automation in Construction* 85: 51–64.
- Dubois, A., and L.-E. Gadde. 2002. Systematic combining: an abductive approach to case research. *Journal of Business Research* 55: 553–560.
- Dubois, A., and M. Gibbert. 2010. From complexity to transparency: managing the interplay between theory, method and empirical phenomena in IMM case studies. *Industrial Marketing Management* 39: 129–136.
- Dulgeroglu, Y. F. 1977. The role of user participation in design decisions. Website <https://repository.gatech.edu/entities/publication/74e03e9a-e2e2-46f7-843a-e030e97c584d> [accessed 4 December 2025].
- Ehab, A., G. Burnett, and T. Heath. 2023. Enhancing Public Engagement in Architectural Design: A Comparative Analysis of Advanced Virtual Reality Approaches in Building Information Modeling and Gamification Techniques. *Buildings* 13: 1262.
- Elf, M., P. Fröst, G. Lindahl, and H. Wijk. 2015. Shared decision making in designing new healthcare environments—time to begin improving quality. *BMC Health Services Research* 15: 114.
- Elf, M., R. Lipson-Smith, M. Kylén, J. P. Saa, J. Sturge, E. Miedema, S. Nordin, et al. 2024. A Systematic Review of Research Gaps in the Built Environment of Inpatient Healthcare Settings. *HERD: Health Environments Research & Design Journal* 17: 372–394.
- Eriksson, J. 2013. Architects and users in collaborative design. Department of Architecture, Chalmers tekniska högskola, Göteborg.
- Eriksson, J., W. Glad, and M. Johansson. 2015. User involvement in Swedish residential building projects: a stakeholder perspective. *Journal of Housing and the Built Environment* 30: 313–329.
- Filimon, F., 2015. Are All Spatial Reference Frames Egocentric? Reinterpreting Evidence for Allocentric, Object-Centered, or World-Centered Reference Frames. *Frontiers in Human Neuroscience*.
- Fischer, G., E. Giaccardi, H. Eden, M. Sugimoto, and Y. Ye. 2005. Beyond binary choices: Integrating individual and social creativity. *International Journal of Human-Computer Studies* 63: 482–512.
- Fletcher, J. F., J. Everatt, G. Chang, and Y. Subramaniam. 2025. Teacher collaboration and innovative learning spaces in New Zealand. *Teachers and Teaching* 31: 297–312.
- Foroughi Sabzevar, M., M. Gheisari, and J. Lo. 2025. Analyzing the pros and cons of paper-based 2D drawings in construction: a survey of U.S. construction professionals. *International Journal of Construction Management* 25: 428–438.

- Frelin, A., and J. Grannäs. 2021. Designing and Building Robust Innovative Learning Environments. *Buildings* 11: 345.
- Frelin, A., and J. Grannäs. 2022. Teachers' pre-occupancy evaluation of affordances in a multi-zone flexible learning environment – introducing an analytical model. *Pedagogy, Culture & Society* 30: 243–259.
- Gomes, D., and P. Tzortzopoulos. 2018. Building Shared Understanding During Early Design. 473–483.
- Granath, J., Lindahl, Göran, and Rehal, Saddek. 1996. From Empowerment to Enablement - An evolution of new dimensions in participatory design. *Logistik und Arbeit*.
- Grannäs, J., A. Frelin, and T. Östlin. 2025. Unpacking flexibility in innovative learning environments - teachers' experiences in practice. *Educational Studies* 0: 1–17.
- Grannäs, J., and S. M. Stavem. 2021. Transitions through remodelling teaching and learning environments. *Education Inquiry* 12: 266–281.
- Grier, R. A. 2015. How High is High? A Meta-Analysis of NASA-TLX Global Workload Scores. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 59: 1727–1731.
- Gustafsson, M., M. Roupé, M. Johansson, S. Sateei, and O. Disney. 2025. Evaluating Design Review Efficiency and Cognitive Load: 2D vs 3D vs Immersive. In E. Noroozinejad Farsangi, A. H. Rasouli, N. Dawood, and G. Morrison [eds.], *Construction Applications of Virtual Reality, Volume I*, 139–151. Springer Nature, Singapore.
- Haahr, M. T., and H. B. Knak. 2022. Multi-user virtual reality based design review of students construction designs. *The Future of Construction in the Context of Digitalization and Decarbonization: Proceedings of the 22nd International Conference on Construction Applications of Virtual Reality*, 38–49.
- Hahm, J., K. Lee, S.-L. Lim, S.-Y. Kim, H.-T. Kim, and J.-H. Lee. 2007. Effects of active navigation on object recognition in virtual environments. *Cyberpsychology & Behavior: The Impact of the Internet, Multimedia and Virtual Reality on Behavior and Society* 10: 305–308.
- Han, B., and F. Leite. 2021. Measuring the Impact of Immersive Virtual Reality on Construction Design Review Applications: Head-Mounted Display versus Desktop Monitor. *Journal of Construction Engineering and Management* 147: 04021042.
- Hart, S. G. 2006. Nasa-Task Load Index (NASA-TLX); 20 Years Later. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 50: 904–908.
- Hart, S. G., and L. E. Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In P. A. Hancock, and N. Meshkati [eds.], *Advances in Psychology, Human Mental Workload*, 139–183. North-Holland.
- Henderson, K. 1998. On Line and On Paper: Visual Representations, Visual Culture, and Computer Graphics in Design Engineering.

- Hey, J. H. G., C. K. Joyce, and S. L. Beckman. 2007. Framing innovation: negotiating shared frames during early design phases. *Journal of Design Research* 6: 79–99.
- Heydarian, A., J. P. Carneiro, D. Gerber, B. Becerik-Gerber, T. Hayes, and W. Wood. 2015. Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations. *Automation in Construction* 54: 116–126.
- Higuera-Trujillo, J. L., C. Llinares, and E. Macagno. 2021. The Cognitive-Emotional Design and Study of Architectural Space: A Scoping Review of Neuroarchitecture and Its Precursor Approaches. *Sensors* 21: 2193.
- Ho, K. L. D., and Y. C. Lee. 2012. The quality of design participation : intersubjectivity in design practice. *International journal of design* 6: 71–83.
- Horvat, N., Kunnen, S., Štorga, M., Nagarajah, A., & Škec, S. (2022). Immersive virtual reality applications for design reviews: Systematic literature review and classification scheme for functionalities. *AdvancedEngineering Informatics*, 54, 101760. <https://doi.org/10.1016/j.aei.2022.101760>
- van Houwelingen, T., A. C. M. Meeuse, and H. S. M. Kort. 2023. Enabling nurses' engagement in the design of healthcare technology – Core competencies and requirements: A qualitative study. *International Journal of Nursing Studies Advances* 6: 100170.
- Huang, T. T.-K., D. Sorensen, S. Davis, L. Frerichs, J. Brittin, J. Celentano, K. Callahan, and M. J. Trowbridge. 2013. Healthy Eating Design Guidelines for School Architecture. *Preventing Chronic Disease* 10: E27.
- Huang, Y. 2023. Leveraging virtual reality to understand human spatial navigation. *Nature Reviews Psychology* 2: 662–662.
- Ibayashi, H., Y. Sugiura, D. Sakamoto, N. Miyata, M. Tada, T. Okuma, T. Kurata, et al. 2015. Dollhouse VR: a multi-view, multi-user collaborative design workspace with VR technology. SIGGRAPH Asia 2015 Emerging Technologies, SA '15, 1–2. Association for Computing Machinery, New York, NY, USA.
- Im, J.-B., R.-L. Hong, M. Joo, E. Zhang, and J.-H. Kim. 2025. Visual fidelity effects on occupants' performance, mental states, and emotions in mixed reality environments. *Architectural Science Review* 0: 1–21.
- Johansson, M., P. Fröst, E. Brandt, T. Binder, and J. Messeter. 2002. Partner engaged design : new challenges for workplace design.
- Johansson, M., and M. Roupé. 2024. Real-world applications of BIM and immersive VR in construction. *Automation in Construction* 158: 105233.
- Johansson, M., and M. Roupé. 2022. VR in Construction – Multi-User and Multi-Purpose. Proceedings of the 22nd International Conference on Construction Applications of Virtual Reality (CONVR 2022), 248–259.

- Johansson, M., M. Roupé, and M. V. Tallgren. 2023. Collaborative site layout planning using multi-touch table and immersive VR. *CONVR 2023 Proceedings of the 23rd International Conference on Construction Applications of Virtual Reality*, 81–90.
- Joo, M., J.-B. Im, K.-T. Lee, and J.-H. Kim. 2025. Comparative analysis of work performance and physiological response based on office types and indoor space design. *Architectural Engineering and Design Management* 0: 1–17.
- Joseph, A., and M. Rashid. 2007. The architecture of safety: hospital design. *Current Opinion in Critical Care* 13: 714–719.
- Jouppila, T. 2025. Exploring Virtual Reality as a Tool for Co-Design in Healthcare Facilities. Tampere University.
- Jouppila, T. 2022. Staff participation in design with multiple tools: Impact on design and POE results. *HERD: Health Environments Research & Design Journal* 15: 315–330.
- Kim, M. J., X. Wang, P. E. Love, H. Li, and S.-C. Kang. 2013. Virtual reality for the built environment: a critical review of recent advances. *Journal of Information Technology in Construction (ITcon)* 18: 279–305.
- Kim, T. W., S. H. Cha, and Y. Kim. 2016. A framework for evaluating user involvement methods in architectural, engineering, and construction projects. *Architectural Science Review* 59: 136–147.
- Kitamoto, E., and S. Yamada. 2026. Distance Perception and Spatial Impression in Immersive Virtual Spaces: Implications for VR and Architectural Design. *Journal of Biomedical Engineering and Biosciences (JBEB)* 13: 14–24.
- Koskela, L. 2000. An exploration towards a production theory and its application to construction: Dissertation. VTT Technical Research Centre of Finland, Espoo.
- Kosslyn, S. M. 1994. *Image And Brain: The Resolution of the Imagery Debate*. The MIT Press.
- Krukar, J., and C. Schultz. 2025. Ecological validity of architectural cognition: a framework. *Architectural Science Review* 68: 355–362.
- Kujala, S. 2003. User involvement: A review of the benefits and challenges. *Behaviour & Information Technology* 22: 1–16.
- van der Land, S., A. P. Schouten, F. Feldberg, B. van den Hooff, and M. Huysman. 2013. Lost in space? Cognitive fit and cognitive load in 3D virtual environments. *Computers in Human Behavior* 29: 1054–1064.
- Larsen, A. S. A., A. T. Karlsen, B. Andersen, and N. O. E. Olsson. 2021. Exploring collaboration in hospital projects' front-end phase. *International Journal of Project Management* 39: 557–569.
- LaViola Jr., J. J., E. Kruijff, R. P. McMahan, D. Bowman, and I. P. Poupyrev. 2017. *3D User Interfaces: Theory and Practice*. Addison-Wesley Professional.

- Lavrson, J. C., and J. Daalhuizen. 2024. Balancing cognitive load in design work: A conceptual and narrative review: *Design Research Society* 2024.
- Lawson, B. 2013. Design and the Evidence. *Procedia - Social and Behavioral Sciences* 105: 30–37.
- Leggat, S. G. 2008. Hospital Planning: The Risks of Basing the Future on Past Data. *Health Information Management Journal* 37: 6–14.
- Loyola, M. 2019. Use of Virtual Reality in Participatory Design. Sousa, JP, Xavier, JP and Castro Henriques, G (eds.), *Architecture in the Age of the 4th Industrial Revolution - Proceedings of the 37th eCAADe and 23rd SIGraDi Conference - Volume 2*, University of Porto, Porto, Portugal, 11-13 September 2019, pp. 449-454, CUMINCAD.
- Lu, J., C. Fu, T. Zhou, J. Xie, and Y. M. Loo. 2022. A Review of Physical and Digital Mock-Up Applications in Healthcare Building Development. *Buildings* 12: 745.
- Luck, R. 2003. Dialogue in participatory design. *Design Studies* 24: 523–535.
- Luck, R. 2007. Learning to talk to users in participatory design situations. *Design Studies* 28: 217–242.
- Memari, S., T. Kocaturk, M. Lozanovska, F. Andrews, and R. Tucker. 2025. Architect Insights: Implications and Barriers of Future-Proofing Hospitals. *HERD: Health Environments Research & Design Journal*: 19375867251374676.
- Memari, S., T. Kocaturk, M. Lozanovska, F. Andrews, and R. Tucker. 2022. The interdisciplinary conceptualization of future proofing in the context of hospital buildings. *Building Research & Information* 50: 810–826.
- Mourshed, M., and Y. Zhao. 2012. Healthcare providers' perception of design factors related to physical environments in hospitals. *Journal of Environmental Psychology* 32: 362–370.
- Naamati-Schneider, L., and D. Alt. 2024. The Complex and Ever-Changing Environment of Healthcare Systems: Characteristics and Future Challenges. In L. Naamati-Schneider, and D. Alt [eds.], *Technology and Competency-Oriented Learning: Effective Methods for Training the Next Cohort of Healthcare Managers*, 11–23. Springer Nature, Singapore.
- Navaratnam, S., K. Nguyen, K. Selvaranjan, G. Zhang, P. Mendis, and L. Aye. 2022. Designing Post COVID-19 Buildings: Approaches for Achieving Healthy Buildings. *Buildings* 12: 74.
- Nazeer, F. S., I. Kamardeen, and A. Hasan. 2024. Establishment of an end-user engaged building design framework. *Built Environment Project and Asset Management* 15: 106–124.
- Niemi, K. 2021. 'The best guess for the future?' Teachers' adaptation to open and flexible learning environments in Finland. *Education Inquiry* 12: 282–300.

- Nikolić, D., and J. Whyte. 2021. Visualizing a New Sustainable World: Toward the Next Generation of Virtual Reality in the Built Environment. *Buildings* 11: 546.
- Norman, D. A. 1983. Some Observations on Mental Models. *Mental Models*, Psychology Press.
- Olsson, N. O. E., G. K. Hansen, and S. H. Blakstad. 2022. Who are the users? User categorisations and implications on building performance measurement. *International Journal of Public Sector Performance Management* 10: 566–579.
- Paas, F., J. E. Tuovinen, H. Tabbers, and P. W. M. Van Gerven. 2003. Cognitive Load Measurement as a Means to Advance Cognitive Load Theory. *Educational Psychologist* 38: 63–71.
- Paes, D., E. Arantes, and J. Irizarry. 2017. Immersive environment for improving the understanding of architectural 3D models: Comparing user spatial perception between immersive and traditional virtual reality systems. *Automation in Construction* 84: 292–303.
- Paes, D., and J. Irizarry. 2018. A Usability Study of an Immersive Virtual Reality Platform for Building Design Review: Considerations on Human Factors and User Interface. 419–428.
- Paes, D., J. Irizarry, and D. Pujoni. 2021. An evidence of cognitive benefits from immersive design review: Comparing three-dimensional perception and presence between immersive and non-immersive virtual environments. *Automation in Construction* 130: 103849.
- Panya, D. S., T. Kim, and S. Choo. 2023. An interactive design change methodology using a BIM-based Virtual Reality and Augmented Reality. *Journal of Building Engineering* 68: 106030.
- Park, Y., J. Krukar, M. Brösamle, J. Gero, and C. Hölscher. 2026. Interpreting Architectural Drawings: The Role of Gaze and Gestures in Cognitive Offloading. *Applied Cognitive Psychology* 40: e70127.
- Payne, S. R., J. Mackrill, R. Cain, J. Strelitz, and L. Gate. 2015. Developing interior design briefs for health-care and well-being centres through public participation. *Architectural Engineering and Design Management* 11: 264–279.
- Pimentel, K., & Teixeira, K. (1993). Virtual reality - through the new looking glass.
- Pirinen, A. 2016. The Barriers and Enablers of Co-design for Services. *International Journal of Design*. Website <https://www.ijdesign.org/index.php/IJDesign/article/view/2575/750> [accessed 19 November 2025].
- Piroozfar, P., I. Farooqi, A. Judd, S. Boseley, and E. R. P. Farr. 2022. VR-Enabled Participatory Design of Educational Spaces: 12th International Conference on Construction in the 21st Century S. M. Ahmed, S. Azhar, A. D. Saul, and K. L. Mahaffy [eds.], *Proceedings of the 12th International Conference on Construction in the 21st Century (CITC 12)*: 496–502.

- Prabhakaran, A., A.-M. Mahamadu, and L. Mahdjoubi. 2022a. Understanding the challenges of immersive technology use in the architecture and construction industry: A systematic review. *Automation in Construction* 137: 104228.
- Prabhakaran, A., A.-M. Mahamadu, L. Mahdjoubi, and P. Boguslawski. 2022b. BIM-based immersive collaborative environment for furniture, fixture and equipment design. *Automation in Construction* 142: 104489.
- Pruijsten, R., E. Ista, J. Maben, L. van Heel, and M. van Dijk. 2024. Nurses' perceptions of the transition to 100% single-occupancy patient rooms in a university hospital in the Netherlands: an uncontrolled before and after study. *BMC Nursing* 23: 106.
- PTS. Program för Teknisk Standard. Website <https://www.ptsforum.se/> [accessed 11 March 2026].
- Räisänen, C., D. U. Duman, M. V. Tallgren, and J. Eriksson. 2024. Multimodal Interaction in Collaborative Design of a Healthcare Space: A Social Semiotic Approach. *Studies in health technology and informatics* 319: 33–45.
- Rance, G., R. C. Dowell, and D. Tomlin. 2023. The effect of classroom environment on literacy development. *npj Science of Learning* 8: 9.
- Rehman, S. U., K.-E. Hwang, and I. Kim. 2025. Semantic-enriched framework for asynchronous bidirectional BIM data exchange with immersive visualization platform. *Automation in Construction* 178: 106409.
- Reno, K., K. Okland, N. Finis, G. LaMantia, R. Call, K. Cardon, D. Gerber, and J. Zeigler. 2014. Lessons Learned: Clinicians' Post-Occupancy Perspective of Facility Design Involvement. *HERD: Health Environments Research & Design Journal* 7: 127–139.
- Roupé, M., M. Johansson, L. Maftai, R. Lundstedt, and M. Viklund-Tallgren. 2020. Virtual Collaborative Design Environment: Supporting Seamless Integration of Multitouch Table and Immersive VR. *Journal of Construction Engineering and Management* 146: 04020132.
- Roupé, M., M. Johansson, M. Viklund Tallgren, F. Jörnebrant, and A. Tomsa. 2016. Immersive visualisation of Building Information Models: Usage and future possibilities during design and construction.
- Salomon, G. 1997. *Distributed Cognitions: Psychological and Educational Considerations*. Cambridge University Press.
- Sanders, E. B.-N., and P. J. Stappers. 2008. Co-creation and the new landscapes of design. *CoDesign* 4: 5–18.
- Schrader, C., and T. J. Bastiaens. 2012. The influence of virtual presence: Effects on experienced cognitive load and learning outcomes in educational computer games. *Computers in Human Behavior* 28: 648–658.
- Sepasgozar, S. M. E. 2020. Digital Twin and Web-Based Virtual Gaming Technologies for Online Education: A Case of Construction Management and Engineering. *Applied Sciences* 10: 4678.

- Sfandyarifard, E. 2013. An investigation into the consideration of children and young peoples' preferences in children's hospital design.
- Sfandyarifard, E., and P. Tzortzopoulos. 2011. Supporting value generation in children's hospital design through participatory approaches: 19th Annual Conference of the International Group for Lean Construction. *19th Annual Conference of the International Group for Lean Construction 2011, IGLC 2011*: 372–381.
- Shi, Y., J. Du, and D. A. Worthy. 2020. The impact of engineering information formats on learning and execution of construction operations: A virtual reality pipe maintenance experiment. *Automation in Construction* 119: 103367.
- Schnabel, M. A., and T. Kvan. 2003. Spatial Understanding in Immersive Virtual Environments. *International Journal of Architectural Computing* 1: 435–448.
- Shultz, J., and R. Jha. 2021. Using Virtual Reality (VR) Mock-Ups for Evidence-Based Healthcare Facility Design Decisions. *International Journal of Environmental Research and Public Health* 18: 11250.
- Simonsen, J., and T. Robertson eds . 2012. Routledge International Handbook of Participatory Design. Routledge, London.
- Simonsen, T., J. Sturge, and C. Duff. 2022. Healing Architecture in Healthcare: A Scoping Review. *HERD: Health Environments Research & Design Journal* 15: 315–328.
- Slater, M., and M. V. Sanchez-Vives. 2016. Enhancing Our Lives with Immersive Virtual Reality. *Frontiers in Robotics and AI* 3.
- Snowdon, D., E. F. Churchill, and A. J. Munro. 2001. Collaborative Virtual Environments: Digital Spaces and Places for CSCW: An Introduction. In E. F. Churchill, D. N. Snowdon, and A. J. Munro [eds.], *Collaborative Virtual Environments: Digital Places and Spaces for Interaction, Computer Supported Cooperative Work*, 3–17. Springer, London.
- Soikkeli, A., E. Santamäki, O. Hynninen, and S. Äijälä. 2023. Challenges of participatory design in apartment buildings' renovation projects in Finland. *Journal of Housing and the Built Environment* 38: 1889–1905.
- Soliman-Junior, J., P. Tzortzopoulos, J. P. Baldauf, B. Pedo, M. Kagioglou, C. T. Formoso, and J. Humphreys. 2021. Automated compliance checking in healthcare building design. *Automation in Construction* 129: 103822.
- Sornoza-Parrales, D., G. O. Baque Vera, M. L. Parrales Poveda, and T. M. Macías-Parrales. 2025. Evolution and research trends in virtual reality and augmented reality technologies for the architecture, engineering, and construction (AEC) industry: a systematic review and science mapping approach. *Frontiers in Virtual Reality* 6.
- Souza, C. B. de, S. Tucker, Z. Deme-Belafi, A. Reith, and R. T. Hellwig. 2023. Occupants in the Building Design Decision-Making Process. *Occupant-Centric Simulation-Aided Building Design*, Routledge.

- Spittle, B., M. Frutos-Pascual, C. Creed, and I. Williams. 2023. A Review of Interaction Techniques for Immersive Environments. *IEEE Transactions on Visualization and Computer Graphics* 29: 3900–3921.
- Stern, A. L., S. MacRae, M. Gerteis, T. Harrison, E. Fowler, S. Edgman-Levitan, J. Walker, and W. Ruga. 2003. Understanding the Consumer Perspective to Improve Design Quality. *Journal of Architectural and Planning Research* 20: 16–28.
- Stichler, J. F. 2016. Nursing’s Impact on Healthcare Facility Design. *HERD: Health Environments Research & Design Journal* 9: 11–16.
- Støre-Valen, M. 2021. FM and clinical employees’ involvement in the design of eight Norwegian hospital projects. *Facilities* 39: 778–801.
- Sundblad, Y. 2011. UTOPIA: Participatory Design from Scandinavia to the World. In J. Impagliazzo, P. Lundin, and B. Wangler [eds.], *History of Nordic Computing* 3, 176–186. Springer, Berlin, Heidelberg.
- Sunesson, K., Allwood, C. M., Paulin, D., Heldal, I., Roupé, M., Johansson, M., & Westerdahl, B. (2008). Virtual Reality As a New Tool in the City Planning Process. *Tsinghua Science & Technology*, 13(Supplement 1), 255-260. [https://doi.org/10.1016/S1007-0214\(08\)70158-5](https://doi.org/10.1016/S1007-0214(08)70158-5)
- Sweller, J., J. J. G. van Merriënboer, and F. Paas. 2019. Cognitive Architecture and Instructional Design: 20 Years Later. *Educational Psychology Review* 31: 261–292.
- Taghizadeh, K., E. Noorzai, Z. Zaman, M. Amiri, and N. Samaee Rahnee. 2021. Identifying the Most Important Rework Factors in Building Projects and Providing a Solution to Reduce Their Effects. *Journal of The Institution of Engineers (India): Series A* 102: 1027–1043.
- Tampio, K.-P., H. Haapasalo, and F. Ali. 2022. Stakeholder analysis and landscape in a hospital project – elements and implications for value creation. *International Journal of Managing Projects in Business* 15: 48–76.
- Tampio, K.-P., H. Haapasalo, and J. Lehtinen. 2023. The client’s essential stakeholder collaboration activities at the front-end phase of a hospital construction project. *International Journal of Managing Projects in Business* 16: 182–207.
- Tastan, H., M. A. Heyik, and İ. E. Er. 2026. Assessing usability and performance in 3D modeling and design review: a comparison of immersive virtual reality, desktop, and hybrid environments. *Virtual Reality*.
- Thompson, D. R., D. K. Hamilton, C. D. Cadenhead, S. M. Swoboda, S. M. Schwindel, D. C. Anderson, E. V. Schmitz, et al. 2012. Guidelines for intensive care unit design. *Critical Care Medicine* 40: 1586–1600.
- Thyssen, M. H., S. Emmitt, S. Bonke, and A. Kirk-Christoffersen. 2010. Facilitating Client Value Creation in the Conceptual Design Phase of Construction Projects: A Workshop Approach. *Architectural Engineering and Design Management* 6: 18–30.
- Triberti, S., C. Sapone, and G. Riva. 2025. Being there but where? Sense of presence theory for virtual reality applications. *Humanities and Social Sciences Communications* 12: 79.

- Truong, P., K. Hölttä-Otto, P. Becerril, R. Turtiainen, and S. Siltanen. 2021. Multi-User Virtual Reality for Remote Collaboration in Construction Projects: A Case Study with High-Rise Elevator Machine Room Planning. *Electronics* 10: 2806.
- Ulrich, R. S., C. Zimring, X. Zhu, J. DuBose, H.-B. Seo, Y.-S. Choi, X. Quan, and A. Joseph. 2008. A review of the research literature on evidence-based healthcare design. *HERD* 1: 61–125.
- Umair, M., A. Sharafat, D.-E. Lee, and J. Seo. 2022. Impact of Virtual Reality-Based Design Review System on User's Performance and Cognitive Behavior for Building Design Review Tasks. *Applied Sciences* 12: 7249.
- VanHeuvelen, J. S. 2019. Isolation or interaction: healthcare provider experience of design change. *Sociology of Health & Illness* 41: 692–708.
- Vasarainen, M., L. Vetoshkina, and S. Paavola. 2025. From virtual reality to virtual safaris: new form of participatory design in an architectural design project. *CoDesign* 21: 152–169.
- Vessey, I. 1991. Cognitive Fit: A Theory-Based Analysis of the Graphs Versus Tables Literature. *Decision Sciences* 22: 219–240.
- Vessey, I., and D. Galletta. 1991. Cognitive Fit: An Empirical Study of Information Acquisition. *Information Systems Research* 2: 63–84.
- Vlasblom, J. I. D., H. J. M. Pennings, J. van der Pal, and E. A. P. B. Oprins. 2020. Competence retention in safety-critical professions: A systematic literature review. *Educational Research Review* 30: 100330.
- Whyte, J., and D. Nikolić. 2024. Augmented and virtual reality and creativity in the built environment. *Routledge Companion to Creativity and the Built Environment*, Routledge.
- Wingler, D., H. Machry, S. Bayramzadeh, A. Joseph, and D. Allison. 2019. Comparing the Effectiveness of Four Different Design Media in Communicating Desired Performance Outcomes With Clinical End Users. *HERD: Health Environments Research & Design Journal* 12: 87–99.
- Wolfartsberger, J. 2019. Analyzing the potential of Virtual Reality for engineering design review. *Automation in Construction* 104: 27–37.
- Woolner, P. 2010. The Design of Learning Spaces. 1–144.
- Wulz, F. 1986. The concept of participation. *Design Studies* 7: 153–162.
- Yap, J. B. H., H. Abdul-Rahman, and C. Wang. 2016. A Conceptual Framework for Managing Design Changes in Building Construction. *MATEC Web of Conferences* 66: 00021.
- Yin, R. K. 2018. *Case Study Research and Applications: Design and Methods*. SAGE Publications.

- Young, F., and B. Cleveland. 2022. Affordances, Architecture and the Action Possibilities of Learning Environments: A Critical Review of the Literature and Future Directions. *Buildings* 12: 76.
- Yu, R., N. Gu, G. Lee, and A. Khan. 2022. A Systematic Review of Architectural Design Collaboration in Immersive Virtual Environments. *Designs* 6: 93.
- Yu, R., N. Gu, and S. Masoumzadeh. 2024. Exploring the Impact of Digital Technologies on Team Collaborative Design. *Buildings* 14: 3263.
- Zimmerer, C., and S. Matthiesen. 2021. STUDY ON THE IMPACT OF COGNITIVE LOAD ON PERFORMANCE IN ENGINEERING DESIGN. *Proceedings of the Design Society* 1: 2761–2770.

## **Appended Papers**

