

The Virtual Embodied Experience: Virtual Reality as a Medium for Computing, Analysing, and Representing the Cityscape

Enriqueta LLabres-Valls

Bartlett School of Architecture, University College London, UK

Correspondence: Enriqueta LLabres-Valls (e.llabres-valls@ucl.ac.uk)

Submitted: 2 April 2026 **Accepted:** 3 July 2026 **Published:** 14 October 2026

Issue: This article is part of the issue “The Urban Canvas: Spatial Computing in Planning, Analysing, and Representing the Cityscape” edited by Valerio Signorelli (University College London), Andy Hudson-Smith (University College London), and in memory of Heejung Kwon (Yonsei University), fully open access at <https://doi.org/10.17645/up.i484>

Abstract

The increasing availability of urban data has transformed how the built environment is analysed and designed, yet the tools used to represent and interpret that data remain largely abstract and symbolic. Virtual reality (VR) offers the possibility of engaging with spatial data immersively, but its role in architectural and urban research remains predominantly confined to visualisation and simulation. The extent to which VR supports embodied interaction with data, where users experience and interpret information through spatial presence and movement, remains underexplored. This article addresses this gap through a systematic literature review of Scopus and CumInCAD (Cumulative Index of Computer Aided Architectural Design), comparing interdisciplinary and architecture-specific research across three dominant themes: representation and analysis, simulation, and embodied interaction. The findings reveal a conceptually fragmented field: While computational research has advanced VR simulation significantly, embodied approaches remain weakly integrated with data-driven workflows. To address this divide, the article proposes virtual embodied experience (VEE), a framework that positions VR as a cognitive interface through which environmental data are navigated as a spatial condition rather than consulted as an abstract output. The implications of VEE are discussed in relation to emerging professional requirements established by the Architects Registration Board and the Royal Institute of British Architects around climate literacy, lifecycle thinking, and ecological design.

Keywords

built environment; embodied interaction; immersive analytics; spatial computing; virtual reality

1. Introduction

The increasing availability of digital data has transformed how the built environment is analysed, designed, and managed. Advances in sensing technologies, computational modelling, and urban data infrastructures have enabled architects and planners to access unprecedented volumes of information relating to energy consumption, environmental performance, mobility patterns, and ecological systems. Moreover, virtual reality (VR) and spatial computing offer new ways to interact with these data, opening a possibility where architectural practice moves from drawing and modelling toward data-driven and experience-based modes of design.

This transformation is reinforced by evolving professional frameworks, particularly those established by the Architects Registration Board (ARB) and the Royal Institute of British Architects (RIBA). Both institutions now mandate climate literacy, lifecycle thinking, energy performance, and biodiversity awareness as core professional competencies (ARB, 2024; RIBA, 2021). These requirements demand a more direct engagement with complex datasets, integrating them into the design process. However, despite the growing importance of data, the tools used to represent and interpret them remain largely rooted in abstract and symbolic formats, such as drawings, diagrams, and dashboards. While effective for communication, these modes of representation often fail to capture the spatial and experiential dimensions of environmental data, limiting their role in decision-making.

VR enables users to engage with spatial information in an immersive way. However, while VR adoption for visualisation, simulation, and communication within architecture and urban planning is extensive, its role remains largely confined to representation and presentation, with limited integration into analytical and decision-making processes. In particular, the extent to which VR supports embodied interaction with data, where users experience and interpret information through spatial presence and movement, remains underexplored.

This article addresses this gap by examining how VR is currently used in the built environment and to what extent it has progressed from representation toward embodied interaction with data and simulations. It proposes the concept of virtual embodied experience (VEE) as a framework for understanding VR as a cognitive interface through which spatial data can be experienced and interpreted. By situating this concept within broader developments in spatial computing and embodied cognition, the article aims to bridge the divide between computational and experiential approaches to VR.

Methodologically, the study adopts a systematic literature review (Page, Moher, et al., 2021) of Scopus and CumInCAD (Cumulative Index of Computer Aided Architectural Design), enabling a comparison between interdisciplinary and architecture-specific research. The analysis identifies three dominant themes—representation, simulation, and embodied interaction—and evaluates their relative development within the field.

The article is structured as follows: Section 2 establishes the theoretical framework across spatial computing, embodied cognition, and VEE; Section 3 describes the methodology; Section 4 presents results across the three themes; Section 5 discusses the disciplinary divide and positions VEE as a bridging framework; and Section 6 addresses implications for professional practice in relation to ARB and RIBA. Despite VR maturing as

a technological platform, its potential for embodied interaction with data remains underdeveloped. Addressing this limitation is essential for advancing data-driven design practices in the built environment.

2. The Urban Canvas and Embodied Experience

2.1. *Spatial Computing in Architecture*

In spatial computing, digital information is embedded within and interacted with through 3D space. It is the integration of computation with 3D environments, enabling users to interact with digital content as if it were part of the physical world (Greenwold, 2003; Shekhar & Vold, 2020). This approach has paved the way for advances in VR and AR (augmented reality), positioning space itself as the primary interface for computation.

Spatial computing in architecture and urbanism aligns two streams: a shift toward data-driven design and a need for more tacit, embodied interaction with data in the design process. As Batty (2013, 2018, 2024) argues, contemporary urban analysis relies on computational models that simulate and predict urban processes. Digital twins extend this logic further, enabling real-time synchronisation between physical environments and their virtual counterparts (Grieves & Vickers, 2017). However, while these tools have improved our ability to analyse data, their interfaces are often hard to navigate, relying on dashboards, maps, and models (Chen et al., 2017; Miranda et al., 2024). Spatial computing, especially in immersive environments, offers something different: It lets people experience urban data in a more physical way, not just as symbols. This technology can be seen as an “urban canvas,” a digital space where data, simulation, and design come together (Batty & Hudson-Smith, 2005).

2.2. *Embodied Cognition*

The theoretical underpinnings of spatial computing in architecture lie in the concept of embodied cognition, which challenges the view of cognition as purely abstract or computational. Spatial perception is situated in the body and shaped by sensory engagement (Mallgrave, 2013; Merleau-Ponty, 1962). Polanyi (1973) distinguishes between tacit and codified knowledge, where tacit knowledge requires face-to-face contact and embodied experience; a distinction extended into architectural theory by Hale (2017) and Robinson and Pallasmaa (2015). Cognitive scientists argue that human reasoning is grounded in bodily experience and spatial narratives (Varela et al., 1991). Jelić et al. (2016) have proposed that designed environments enact embodied cognitive processes through relational coupling between person and environment.

Architecture is a multisensory and embodied experience (Pallasmaa, 2012). Yet representations of architecture performance datasets remain abstract, creating two separate disciplinary regimes: one concerned with precision and data gathering through sensor simulations and digital twins, and another that deals with the narrative as well as qualitative counterpart of visual representation, scale, and atmosphere. VR systems induce a sense of “being there,” allowing users to perceive and respond to virtual spaces in ways analogous to physical environments (Slater, 2009; Slater & Wilbur, 1997). More recent work on presence and immersion demonstrates the possibility of operationalising embodiment within digital environments through sensors, simulations, and digital twins (Slater, 2018; Slater & Sanchez-Vives, 2016). Traditional representations, plans, sections, and even GIS visualisations abstract spatial experience into symbolic

formats, often failing to capture the social and experiential dimensions of urban space critical to supporting design decision-making (Dembski et al., 2020; C. Zhang et al., 2021).

2.3. VEE

VEE results from the convergence of spatial computing and embodied cognition within immersive environments. Unlike conventional visualisation, which positions the user as an external observer, VEE situates the user within the data space itself, where understanding arises through interaction, movement, and scale rather than observation. Environmental data—temperature gradients, pollution levels, and energy flows—are perceived as experienced spatial conditions, enabling a more situated and intuitive form of interpretation.

This trajectory builds on Negroponte's (1975, 1995) anticipation of computation as an interactive design medium, extended by Batty (2007, 2024) and Kalay (2004) into urban systems capable of simulation and analysis. Recent work in immersive analytics, including Bach et al. (2018), Marriott et al. (2018), and Safikhani et al. (2024), demonstrates that interaction and immersion enhance users' ability to interpret complex datasets, suggesting a progression from representation to simulation to experience. However, immersive analytics has largely focused on abstract datasets; its application to the built environment remains limited. This article extends that trajectory by proposing VEE as a cognitive interface for architectural research and design, through which the urban canvas becomes not merely a visualisation of the city but an experiential medium for engaging with its data.

3. Methodology: Systematic Literature Review

This article employs a systematic literature review (Page, McKenzie, et al., 2021; Page, Moher, et al., 2021) to examine the extent to which developments in VR applications within the built environment have engaged with the emerging concept of VEE. It addresses the following research question:

To what extent are embodied interactions with data and simulations developed in academic research on VR in the built environment?

3.1. Database Selection

Two databases were selected to balance interdisciplinary breadth with domain-specific depth. Scopus provides broad coverage of peer-reviewed literature across computer science, engineering, social sciences, and environmental studies, ensuring coverage of VR research, human–computer interaction, and immersive technologies. CumInCAD complements this with a focused repository of architecture and design computation research, capturing practice-oriented and experimental work not typically indexed in broader databases.

3.2. Search Strategy and Screening

Keywords were organised into three thematic blocks: (a) immersive technologies, (b) urban and architectural contexts, and (c) analytical or representational functions, combined using Boolean operators. A representative

Scopus query is: (“virtual reality” OR VR OR “immersive environment*” OR “spatial computing”) AND (urban OR city OR architecture OR planning) AND (analysis OR simulation OR visualisation OR representation). Searches were limited to 1993–2023 across Engineering, Social Sciences, Arts and Humanities, Environmental Sciences, and Computation. Three targeted searches were conducted for each theme: representation and analysis, simulation, and embodied interaction. The same three themes were applied in CumInCAD using the queries “data analytics,” “simulation,” and “embodied experience.”

Following PRISMA 2020 guidelines (Page, McKenzie, et al., 2021), duplicates were removed, and titles and abstracts were screened against inclusion criteria: peer-reviewed articles and conference papers focused on urban design, architecture, or spatial planning involving spatial data, environmental modelling, or design processes. Studies unrelated to the built environment, including gaming and entertainment applications, medical VR research, hardware-only papers, and non-peer-reviewed sources, were excluded. However, studies using game engines as tools for constructing urban simulation environments were retained where relevant, as these are distinct from gaming applications. From the remaining pool, five key papers per theme per database were selected based on relevance to the research question, citation impact, and methodological fit, yielding 15 core studies across the three themes. The full screening process is illustrated in the PRISMA flowchart (Figure 1).

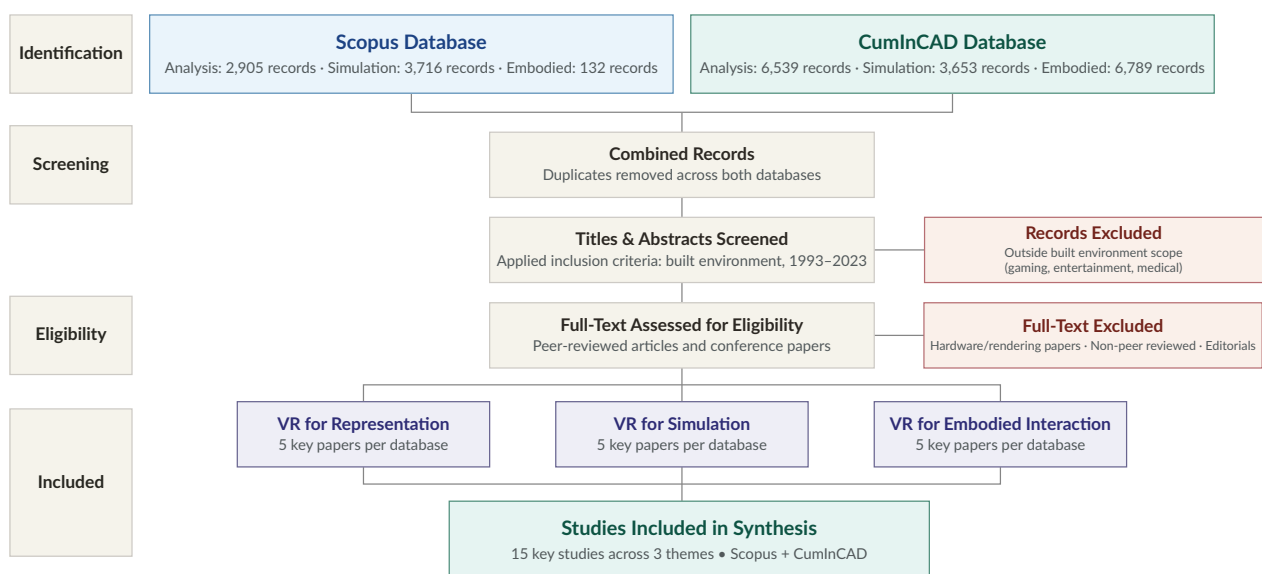


Figure 1. PRISMA 2020 flow diagram: VEE systematic literature review. Source: Adapted from Page, McKenzie, et al. (2021).

4. Results: Three Dominant Research Themes (Scopus + CumInCAD)

The systematic literature review, conducted following PRISMA 2020 guidelines (Page, McKenzie, et al., 2021), identified three dominant research themes in the use of VR within the built environment: (a) representation and analysis, (b) simulation, and (c) embodied interaction. Structured searches in Scopus, complemented by parallel searches in CumInCAD, enabled a comparison between broader interdisciplinary research and architecture-specific discourse.

4.1. VR for Urban Representation (Analysis Search)

The analysis-focused search returned 2,905 documents in Scopus. Much of this work remains at the level of enhanced visualisation rather than rigorous analytical processing. Y. Zhang et al. (2020), in a bibliometric review of 229 Scopus articles, found that VR research predominantly addresses visualisation, design communication, and stakeholder engagement rather than data analysis. Shehadeh et al. (2025) confirm this pattern, demonstrating that Building Information Modelling–Virtual Reality integration in urban development primarily serves design precision and communication, reporting a 62% increase in stakeholder engagement and a 48% improvement in spatial awareness, while data-driven analytical functions remain secondary. Portman et al. (2015) offer an early and widely cited example, concluding that VR's primary contribution lay in enabling users to navigate and visualise spatial proposals rather than interrogate underlying data. The CumInCAD dataset, returning approximately 6,539 results, reinforces this pattern: Most studies emphasise design exploration and visualisation over computational analysis. Across both datasets, VR is predominantly used to communicate design intent and support architectural presentation.

4.2. VR for Simulation (Simulation Search)

The simulation search returned 3,716 documents in Scopus, the largest of the three themes, and approximately 3,653 in CumInCAD. Both datasets show a move away from static representation toward dynamic, data-rich environments, though the character of that movement differs between sources.

Scopus simulation research is primarily technically rigorous. Hu (2025) developed a VR-based system for green building environment design and thermal energy management, demonstrating a 20% improvement in energy consumption prediction accuracy and a 30% reduction in design cycle time. Shawash and Marji (2023) integrated VR into an architectural pedagogy workflow for daylight design, showing VR enabling real-time environmental modelling. In both cases, however, interaction remains mediated through interfaces: Users adjust parameters within dashboards rather than experiencing data as spatial conditions.

CumInCAD presents a contrasting orientation, where simulation tends toward design experimentation. Loyola et al. (2019) deployed a game engine-based VR environment, distinct from gaming or entertainment applications, in a participatory urban design process in Santiago, Chile, enabling community members with no prior digital experience to navigate and evaluate spatial proposals. Similarly, Dembski et al. (2020) developed an interactive VR urban model of Herrenberg, Germany, prioritising citizen engagement over technical performance outputs. This suggests two parallel directions: one grounded in engineering precision, the other in design-led exploration and public engagement.

4.3. VR for Embodied Interaction (Embodied Search)

The embodied search returned only 132 documents in Scopus, markedly fewer than representation and analysis (2,905) or simulation (3,716). This imbalance reflects a genuine limitation of the field rather than a methodological gap: Embodied approaches to VR remain marginal within interdisciplinary research. That the theme was nonetheless identified as a distinct category reflects its conceptual significance, confirmed by CumInCAD, where the equivalent search returned approximately 6,789 results, demonstrating that embodied and experiential approaches are well established within architectural discourse specifically.

Hilmer (2024) and van Leeuwen et al. (2018) demonstrate VR's capacity to capture the qualitative aspects of urban environments, enabling communities to experience and evaluate design scenarios rather than merely observe them. Van Leeuwen et al. (2018) tested VR headsets with 1,302 citizens during a ballot on competing park designs, finding immersive VR equally effective as other display technologies in informing decision-making. However, a critical limitation emerges: Embodied interaction remains weakly integrated with data-driven workflows. The PaKOMM project (Hilmer, 2024) deployed VR and AR tools in a Hamburg participatory design workshop, enabling shared spatial understanding among residents, yet environmental and infrastructural performance data remained outside the immersive experience. This structural separation is representative across the field.

This divide is not between technical and academic research—both streams are academically rigorous—but between two epistemological orientations: a computational orientation, dominant in Scopus, prioritising measurable performance outputs; and a design-experiential orientation, dominant in CumInCAD, prioritising perception, presence, and qualitative spatial understanding (Kvan, 2000; Schnabel, 2009).

4.4. *Synthesis*

The review reveals a critical disciplinary divide. The Scopus dataset highlights research focused on representation and simulation driven by computational concerns, where users remain external observers of data (Hu, 2025; Shehadeh et al., 2025; Y. Zhang et al., 2020). In contrast, CumInCAD reveals a strong engagement with experience, perception, and embodiment, evidenced by the authors' participatory work (Hilmer, 2024; Loyola et al., 2019; van Leeuwen et al., 2018).

Representation, simulation, and embodiment should be understood not as separate categories but as overlapping trajectories. Yet the disciplinary landscape remains too fragmented for this progression to be fully realised. The computational orientation prioritises measurable outputs, while the design-experiential orientation emphasises lived spatial understanding, and integration between the two remains limited. VEE addresses this gap, proposing a framework that integrates data, simulation, and experience, positioning VR as a cognitive interface for the built environment.

5. Discussion: From Representation to VEE

This article examines the extent to which academic research on VR in the built environment has advanced toward embodied interaction with data and simulations. The results reveal a rapidly expanding field, but one that remains conceptually fragmented. VR adoption is widespread for representation and simulation. However, its development as a medium for embodied interaction is uneven. This section interprets these findings, highlighting a divide between computational and experiential approaches, and positioning VEE as a framework to address this gap.

5.1. *Fragmentation Between Computational and Experiential Paradigms*

The comparison between Scopus and CumInCAD reveals a disciplinary divergence in how VR is conceptualised and applied. Y. Zhang et al. (2020) characterise the resulting body of knowledge as vast, diverse, and fragmented. Scopus literature is dominantly technical, with a strong emphasis on simulation,

data integration, and analytical performance. As demonstrated by Hu (2025) and Shehadeh et al. (2025), the primary metrics of success in this stream are efficiency gains and energy prediction accuracy, outcomes measured through quantifiable outputs rather than spatial understanding. In contrast, CumInCAD reflects a design-oriented perspective, foregrounding perception, experience, and interaction (Loyola et al., 2019; van Leeuwen et al., 2018). This divergence is epistemological. The result is a fragmentation into two parallel streams: a computational stream where VR enhances analysis but lacks embodied engagement, and an experiential stream where VR supports interaction but remains weakly integrated with data.

5.2. Representation, Simulation, and the Limits of Interaction

The three dominant themes can be understood as stepping stones, but integration between them is neither linear nor complete. In the analysis-focused literature, exemplified by Portman et al. (2015) and Shehadeh et al. (2025), VR primarily extends traditional visualisation techniques. Data are treated as a visual output rather than an experiential condition. Simulation, as demonstrated by Hu (2025) and Shawash and Marji (2023), introduces greater interaction, enabling users to explore dynamic environmental systems. However, users manipulate parameters rather than engaging with data spatially. In the embodied stream, Ergan et al. (2019) and van Leeuwen et al. (2018) demonstrate VR's capacity to capture situated, physiological responses to spatial conditions. Nevertheless, environmental performance data, energy loads, carbon outputs, and material lifecycles remained external to the immersive experience in each case. The transition from observing data to experiencing them remains incomplete.

5.3. Embodied Interaction as an Underdeveloped Trajectory

The Herrenberg digital twin (Dembski et al., 2020) illustrates the core tension: A game engine-based urban VR model prioritised citizen engagement, while environmental performance data remained confined to external dashboards. Similarly, the PaKOMM workshops (Hilmer, 2024) provided shared spatial understanding through VR, yet disconnected from the analytical data informing those decisions. Embodied interaction is consequently treated as an enhancement rather than a fundamental mode of engaging with data, limiting VR's capacity to support the decisions that matter most in practice: choices about energy use, material selection, carbon reduction, and biodiversity that require both analytical rigour and spatial intuition to evaluate meaningfully.

5.4. VEE as a Framework

VEE is proposed as a cognitive interface through which data can be experienced spatially. Rather than representing or manipulating data, users navigate environmental variables—temperature, pollution, and energy flows—as perceived spatial conditions. VEE extends existing approaches in two directions. It embeds simulation data, of the kind produced by Hu (2025) and Shawash and Marji (2023), within spatial experience, making environmental performance perceptible as a quality of space. It also brings the embodied approaches of Hilmer (2024) and van Leeuwen et al. (2018) into direct contact with data-driven workflows. Ergan et al. (2019) provide an early indication of this convergence, capturing physiological responses to spatial conditions within immersive environments. VEE extends this by proposing that data themselves become part of the immersive experience, enabling a shift from Representation → Simulation → Experience within a unified conceptual model.

5.5. Implications for Research and Practice

The findings carry several implications. First, VR must move beyond its established role as a representational and analytical tool (Portman et al., 2015; Y. Zhang et al., 2020) toward one in which data are experienced rather than merely visualised. Second, greater integration between computational and design-oriented approaches is needed, combining the strengths demonstrated by Hu (2025) and van Leeuwen et al. (2018), respectively. Finally, as architectural practice confronts climate change, energy performance, and urban resilience, tools supporting intuitive, experiential understanding of data will become essential. VEE offers a framework for this, positioning VR as a medium for informed, situated decision-making in the built environment.

6. Implications for Practice: Aligning VEE with ARB/RIBA Agendas

The ARB's *Strategic Statement on Climate Change and Sustainability* establishes that all architects must maintain competence in the skills, knowledge, and behaviours required to address climate change through sustainable architecture (ARB, 2021, 2024). Architects Registration Board's (ARB) continuing professional development (CPD) framework specifies competencies including designing low- and zero-carbon buildings, preserving natural habitats to encourage biodiversity, and applying whole-life carbon analysis. The RIBA 2030 Climate Challenge reinforces these requirements, mandating submission of operational energy, embodied carbon, and water performance data, biodiversity net gain, and post-occupancy evaluation (Hasman, 2022; RIBA, 2021, 2024). Together, these frameworks signal a profession-wide shift toward data-intensive, ecologically conscious practice, one that current representational tools are ill-equipped to support (Dembski et al., 2020; C. Zhang et al., 2021).

VEE offers a direct response. Where ARB requires architects to understand the relationship between buildings and a changing climate, VEE enables those relationships to be experienced spatially, with energy flows, temperature gradients, and carbon loads becoming perceptible conditions within a navigable environment rather than abstract numerical outputs. Lifecycle thinking, central to both frameworks, is similarly served: As demonstrated by Hu (2025) and Shawash and Marji (2023), immersive simulation environments can model material and energy dynamics in real time. VEE extends this by making lifecycle data experienceable, enabling designers to perceive the consequences of design decisions as spatial conditions rather than spreadsheet outputs. Biodiversity requirements, which demand understanding of ecological systems as spatial and dynamic, are addressed through VEE's participatory potential, enabling non-expert stakeholders to engage with ecological data meaningfully, as demonstrated by Loyola et al. (2019) and van Leeuwen et al. (2018).

However, realising this potential requires more than technological development. Current VR applications in practice remain largely siloed, aligned with representation and simulation when data are present, and with embodied experience when atmosphere is the primary concern, but rarely both simultaneously. For VEE to influence ARB and RIBA agendas meaningfully, it must be integrated into professional workflows and design education curricula, positioning immersive environments not as presentation tools but as cognitive interfaces through which architects develop the climate literacy, lifecycle thinking, and ecological awareness that professional frameworks now demand.

7. Conclusion

This article has examined the extent to which academic research on VR in the built environment has progressed from representation toward embodied interaction with data and simulations. Through a systematic literature review of Scopus and CumInCAD, following PRISMA 2020 guidelines (Page, McKenzie, et al., 2021), three dominant research themes were identified: representation and analysis, simulation, and embodied interaction.

The findings reveal a rapidly expanding but conceptually fragmented field. VR is widely adopted for visualisation and simulation, as demonstrated by Hu (2025), Shawash and Marji (2023), Shehadeh et al. (2025), and Y. Zhang et al. (2020), yet these applications position users as external observers of data rather than experiential participants within them. Embodied and participatory approaches, exemplified by Ergan et al. (2019), Hilmer (2024), Loyola et al. (2019), and van Leeuwen et al. (2018), are conceptually well developed within architectural research but remain weakly integrated with data-driven workflows. Data interaction does not necessarily lead to embodied understanding.

This article proposes VEE as a framework to address this divide, positioning immersive environments as cognitive interfaces through which environmental variables such as energy flows, carbon loads, and biodiversity conditions are navigated as spatial conditions rather than consulted as abstract outputs. This reframing has relevance given the professional requirements established by ARB and RIBA around climate literacy, lifecycle thinking, and ecological design, where the capacity to interpret complex data spatially and intuitively is increasingly essential.

As VR technology matures, its potential for embodied interaction with data will only grow. Realising that potential will require both technical innovation and a conceptual shift across research, education, and practice, toward immersive environments understood not as tools of presentation, but as media through which the built environment is analysed, experienced, and ultimately designed.

Conflict of Interests

The author declares no conflict of interests.

LLMs Disclosure

The author used Claude (Anthropic) during the revision and final preparation of the manuscript to check in-text citations against the reference list, format references to the journal's APA guidelines, verify bibliographic details of cited works against publisher records, and copy-edit for grammar and consistency. No content, analysis, or argument was generated by the tool. All suggested changes were reviewed and verified by the author, who takes full responsibility for the content of the article.

References

- Architects Registration Board. (2021). *Strategic statement on climate change and sustainability*.
- Architects Registration Board. (2024). *CPD scheme: Environmental sustainability competencies*.
- Bach, B., Sicat, R., Beyer, J., Cordeil, M., & Pfister, H. (2018). The hologram in my hand: How effective is interactive exploration of 3D visualizations in immersive tangible augmented reality? *IEEE Transactions on Visualization and Computer Graphics*, 24(1), 457–467. <https://doi.org/10.1109/TVCG.2017.2745941>
- Batty, M. (2007). *Planning support systems: Progress, predictions, and speculations on the shape of things to come* (CASA Working Paper No. 122). Centre for Advanced Spatial Analysis, University College London.

- Batty, M. (2013). *The new science of cities*. MIT Press.
- Batty, M. (2018). Digital twins. *Environment and Planning B: Urban Analytics and City Science*, 45(5), 817–820. <https://doi.org/10.1177/2399808318796416>
- Batty, M. (2024). Digital twins in city planning. *Nature Computational Science*, 4(3), 192–199. <https://doi.org/10.1038/s43588-024-00606-7>
- Batty, M., & Hudson-Smith, A. (2005). Urban simulacra: From real to virtual cities, back and beyond. *Architectural Design*, 75(6), 42–47. <https://doi.org/10.1002/ad.170>
- Chen, Z., Wang, Y., Sun, T., Gao, X., Chen, W., Pan, Z., Qu, H., & Wu, Y. (2017). Exploring the design space of immersive urban analytics. *Visual Informatics*, 1(2), 132–142. <https://doi.org/10.1016/j.visinf.2017.11.002>
- Dembski, F., Wössner, U., Letzgus, M., Ruddat, M., & Yamu, C. (2020). Urban digital twins for smart cities and citizens: The case study of Herrenberg, Germany. *Sustainability*, 12(6), Article 2307. <https://doi.org/10.3390/su12062307>
- Ergan, S., Radwan, A., Zou, Z., Tseng, H.-A., & Han, X. (2019). Quantifying human experience in architectural spaces with integrated virtual reality and body sensor networks. *Journal of Computing in Civil Engineering*, 33(2), Article 04018062. [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000812](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000812)
- Greenwold, S. (2003). *Spatial computing* [Unpublished master's thesis]. Massachusetts Institute of Technology.
- Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In F.-J. Kahlen, S. Flumerfelt, & A. Alves (Eds.), *Transdisciplinary perspectives on complex systems: New findings and approaches* (pp. 85–113). Springer. https://doi.org/10.1007/978-3-319-38756-7_4
- Hale, J. (2017). *Merleau-Ponty for architects*. Routledge. <https://doi.org/10.4324/9781315645438>
- Hasman, M. (2022). *RIBA climate guide*. RIBA Publishing.
- Hilmer, L. (2024). Beyond urban challenges—Virtual reality tools in participatory design processes. In *PDC '24: Proceedings of the Participatory Design Conference 2024—Exploratory Papers and Workshops* (Vol. 2, pp. 81–86). Association for Computing Machinery. <https://doi.org/10.1145/3661455.3669874>
- Hu, Y. (2025). Development and research of green building environment design and thermal energy management integrated system based on virtual reality technology. *Energy Informatics*, 8, Article 82. <https://doi.org/10.1186/s42162-025-00544-2>
- Jelić, A., Tieri, G., De Matteis, F., Babiloni, F., & Vecchiato, G. (2016). The enactive approach to architectural experience: A neurophysiological perspective on embodiment, motivation, and affordances. *Frontiers in Psychology*, 7, Article 481. <https://doi.org/10.3389/fpsyg.2016.00481>
- Kalay, Y. E. (2004). *Architecture's new media: Principles, theories, and methods of computer-aided design*. MIT Press.
- Kvan, T. (2000). Collaborative design: What is it? *Automation in Construction*, 9(4), 409–415. [https://doi.org/10.1016/S0926-5805\(99\)00025-4](https://doi.org/10.1016/S0926-5805(99)00025-4)
- Loyola, M., Rossi, B., Montiel, C., & Daiber, M. (2019). Use of virtual reality in participatory design. In J. P. Sousa, G. C. Henriques, & J. P. Xavier (Eds.), *Architecture in the age of the 4th Industrial Revolution: Proceedings of the 37th eCAADe and 23rd SIGraDi Conference* (Vol. 1, pp. 449–454). Blucher. https://doi.org/10.5151/proceedings-ecaadesigradi2019_156
- Mallgrave, H. F. (2013). *Architecture and embodiment: The implications of the new sciences and humanities for design*. Routledge. <https://doi.org/10.4324/9780203071144>
- Marriott, K., Schreiber, F., Dwyer, T., Klein, K., Henry Riche, N., Itoh, T., Stuerzlinger, W., & Thomas, B. H. (Eds.). (2018). *Immersive analytics*. Springer. <https://doi.org/10.1007/978-3-030-01388-2>

- Merleau-Ponty, M. (1962). *Phenomenology of perception*. Routledge.
- Miranda, F., Ortner, T., Moreira, G., Hosseini, M., Vuckovic, M., Biljecki, F., Silva, C. T., Lage, M., & Ferreira, N. (2024). The state of the art in visual analytics for 3D urban data. *Computer Graphics Forum*, 43(3), Article e15112. <https://doi.org/10.1111/cgf.15112>
- Negroponte, N. (1975). *Soft architecture machines*. MIT Press.
- Negroponte, N. (1995). *Being digital*. Knopf.
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., . . . Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, 372, Article n71. <https://doi.org/10.1136/bmj.n71>
- Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., . . . McKenzie, J. E. (2021). PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews. *BMJ*, 372, Article n160. <https://doi.org/10.1136/bmj.n160>
- Pallasmaa, J. (2012). *The eyes of the skin: Architecture and the senses* (3rd ed.). Wiley.
- Polanyi, M. (1973). *Personal knowledge: Towards a post-critical philosophy*. Routledge.
- Portman, M. E., Natapov, A., & Fisher-Gewirtzman, D. (2015). To go where no man has gone before: Virtual reality in architecture, landscape architecture and environmental planning. *Computers, Environment and Urban Systems*, 54, 376–384. <https://doi.org/10.1016/j.compenvurbsys.2015.05.001>
- Robinson, S., & Pallasmaa, J. (Eds.). (2015). *Mind in architecture: Neuroscience, embodiment, and the future of design*. MIT Press.
- Royal Institute of British Architects. (2021). *RIBA 2030 climate challenge*. <https://www.riba.org/media/ykxpwv4p/riba-2030-climate-challenge.pdf>
- Royal Institute of British Architects. (2024). *RIBA CPD core curriculum: Sustainable architecture*.
- Safikhani, S., Arbesser-Rastburg, G., Schreuer, A., Suschek-Berger, J., Edtmayer, H., & Pirker, J. (2024). VR4UrbanDev: An immersive virtual reality experience for energy data visualization. In *VRST '24: Proceedings of the 30th ACM Symposium on Virtual Reality Software and Technology* (Article 69). Association for Computing Machinery. <https://doi.org/10.1145/3641825.3689510>
- Schnabel, M. A. (2009). Framing mixed realities. In X. Wang & M. A. Schnabel (Eds.), *Mixed reality in architecture, design and construction* (pp. 3–11). Springer. https://doi.org/10.1007/978-1-4020-9088-2_1
- Shawash, J., & Marji, N. (2023). Virtual reality in the study of daylight for sustainable architecture. In D. Jones, N. Borekci, V. Clemente, J. Corazzo, N. Lotz, L. M. Nielsen, & L.-A. Noel (Eds.), *Learn X Design 2023: Proceedings of the 7th International Conference for Design Education Researchers*. Design Research Society. <https://doi.org/10.21606/drsld.2024.097>
- Shehadeh, A., Alshboul, O., Taamneh, M. M., Jaradat, A. Q., Alomari, A. H., & Arar, M. (2025). Advanced integration of BIM and VR in the built environment: Enhancing sustainability and resilience in urban development. *Heliyon*, 11(4), Article e42558. <https://doi.org/10.1016/j.heliyon.2025.e42558>
- Shekhar, S., & Vold, P. (2020). *Spatial computing*. MIT Press.
- Slater, M. (2009). Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1535), 3549–3557. <https://doi.org/10.1098/rstb.2009.0138>
- Slater, M. (2018). Immersion and the illusion of presence in virtual reality. *British Journal of Psychology*, 109(3), 431–433. <https://doi.org/10.1111/bjop.12305>

- Slater, M., & Sanchez-Vives, M. V. (2016). Enhancing our lives with immersive virtual reality. *Frontiers in Robotics and AI*, 3, Article 74. <https://doi.org/10.3389/frobt.2016.00074>
- Slater, M., & Wilbur, S. (1997). A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. *Presence: Teleoperators and Virtual Environments*, 6(6), 603–616. <https://doi.org/10.1162/pres.1997.6.6.603>
- van Leeuwen, J. P., Hermans, K., Jylhä, A., Quanjer, A. J., & Nijman, H. (2018). Effectiveness of virtual reality in participatory urban planning: A case study. In *MAB '18: Proceedings of the 4th Media Architecture Biennale Conference* (pp. 128–136). Association for Computing Machinery. <https://doi.org/10.1145/3284389.3284491>
- Varela, F. J., Thompson, E., & Rosch, E. (1991). *The embodied mind: Cognitive science and human experience*. MIT Press. <https://doi.org/10.7551/mitpress/6730.001.0001>
- Zhang, C., Zeng, W., & Liu, L. (2021). UrbanVR: An immersive analytics system for context-aware urban design. *Computers & Graphics*, 99, 128–138. <https://doi.org/10.1016/j.cag.2021.07.006>
- Zhang, Y., Liu, H., Kang, S.-C., & Al-Hussein, M. (2020). Virtual reality applications for the built environment: Research trends and opportunities. *Automation in Construction*, 118, Article 103311. <https://doi.org/10.1016/j.autcon.2020.103311>

About the Author



Enriqueta Llabres-Valls is an architect and urbanist, lecturer at the Bartlett School of Architecture, University College London, and a PhD candidate at the Bartlett Centre for Advanced Spatial Analysis. She co-leads Research Cluster 18 in the MArch Urban Design programme. Her research examines the metaverse and immersive environments as emerging media for architectural and urban practice, with a focus on climate change adaptation and on how the evolution of technology reshapes the way architects design, collaborate, and make decisions. She trained as an architect in Barcelona and holds an MSc in local economic development from the London School of Economics. She co-founded Relational Urbanism in 2009 and LlabresTabony Architects in 2017, received the RIAI award for public space design for the Le Fanu Skate and Play Park, and is a TED fellow.