Urban Planning
2026 • Volume 11 • Article 12687
https://doi.org/10.17645/up.12687

REVIEW

Open Access Journal

Towards Perception-Oriented Digital Participation in Urban Planning: A PRISMA-Guided Scoping Review

Adelina Berkemeier, Holger Hoffmann, and Angelika C. Bullinger

Chair for Ergonomics and Innovation, Chemnitz University of Technology, Germany

Correspondence: Adelina Berkemeier (adelina.berkemeier@mb.tu-chemnitz.de)

Submitted: 29 April 2026 **Accepted:** 13 July 2026 **Published:** 19 August 2026

Issue: This review is part of the issue "Digitalisation and (Un)Sustainability: Assessing Digital Waste and Material Pollution in the City" edited by Letizia Chiappini (University of Twente / NIAS-KNAW), Valeria Ferrari (University of Bologna), and Athanasios Votsis (University of Twente), fully open access at https://doi.org/10.17645/up.i531

Abstract

Citizen participation is increasingly supported by digital tools, yet many existing participation formats prioritise static visualisation and offer limited insight into how pedestrians perceive and evaluate dynamic traffic situations. This is particularly relevant for vehicle speed perception, which shapes perceived safety and crossing decisions. Additionally, a "participation paradox" occurs when citizens engage only after preliminary planning has been conducted, and is hence approachable for the public, but costly to change. To understand how digital participation tools might better account for such experiential components, this study presents a scoping review conducted in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR; $N = 52$), mapping evidence across the thematic categories of technology, urban context, and sustainability. The review identifies a methodological gap between behavioural perception research and current participatory practices. By outlining design considerations, e.g., multisensory integration and technical offsets, the scoping review provides a state of the art for perception-oriented participation, a foundation for valid and inclusive urban design decisions. Findings indicate that while immersive technologies, such as virtual reality (VR) or 360° videos in head-mounted displays (HMDs), offer distinct advantages for methodological safety, preventive testing, and expanded reach, they remain limited to experimental pilot stages with marginal integration into formal planning procedures. These results highlight the potential of immersive tools that bridge the gap between technical planning and human perception. However, a critical discrepancy for the use of immersive technologies is revealed: Vehicle speed is systematically underestimated in virtual environments, fostering riskier crossing decisions compared to reality.

Keywords

digital citizen participation; digital tools; immersive technologies; resource-sensitive planning; traffic safety perception; urban planning

1. Introduction

The design of urban spaces affects the everyday lives of a large share of the population and therefore represents a key societal responsibility (Hofmann et al., 2020). Although urban planning has traditionally been perceived as a technocratic procedure, increasing demands for transparency, social inclusion, and public legitimacy have led to calls for active citizen participation (Chronéer et al., 2019; Pissourios, 2014; von Brackel-Schmidt et al., 2024). At the same time, urban planning remains a complex process shaped by uncertain developments, competing stakeholder interests, and differing perspectives, norms, and values (Loorbach, 2010; Raynor et al., 2017).

Digital transformation enables e-participation, which can be defined as the use of digital citizen participation tools, such as web-based platforms or social media, to involve the public in planning and decision-making processes (Hofmann et al., 2020). This shift can broaden participation across spatial boundaries and engage additional population groups (Hofmann et al., 2020; Kajosaari et al., 2025). While these benefits follow the intent to increase inclusivity, analysis of planning practice often reveals a "participation paradox": Citizens tend to participate less in the early stages of planning, when their potential influence would be greatest. One reason is that the consequences for their daily lives are not yet apparent (Kluge et al., 2025; Wolf et al., 2020). Within the field of planning and participation sciences, researchers have identified motivational factors that shape individuals' intention to participate, including civic responsibility, personal interest, and social influence (Gower et al., 2023; Guler et al., 2024; Szczepańska et al., 2021).

However, there are significant drawbacks to current digital participation formats. Barriers such as restricted access to information, inadequate technological competencies, and the perception that one's involvement has negligible influence can hinder engagement (Biancifiori et al., 2025; Chiappini & Ferrari, 2024; W. Li et al., 2020). Moreover, the increasing use of data-intensive technologies, artificial intelligence (AI), and digital twins amplifies the complexity of digital planning processes (Luo et al., 2025). These technologies facilitate more efficient analysis of citizen feedback. However, their underlying decision-making logic frequently remains opaque and may reinforce technocentric perspectives (Othengrafen et al., 2025). At the same time, the ecological implications of digital technologies are receiving increasing attention. Energy-intensive computations, rapid hardware replacement, and growing data volumes contribute to higher resource consumption and digital waste (Alam, 2024; Almulhim, 2025; Nizamani et al., 2026). Furthermore, highly immersive tools can create new forms of digital exclusion for citizens with limited technical experience or access to digital technologies (Abu Selo et al., 2025; Srivastava et al., 2019). This can be defined as an immersion-equity paradox. Higher levels of immersion improve the quality of citizen feedback. However, they also increase barriers for people with limited digital literacy or hardware resources. This can potentially exacerbate the digital divide (Biancifiori et al., 2025; Dorostkar & Ziari, 2025; Gower et al., 2023; Simonofski et al., 2024; Szczepańska et al., 2021).

To harness the benefits and overcome these drawbacks, there is a need to link the reality of citizens to the formal planning processes. This necessity arises because established formal procedures, such as public consultations and the display of two-dimensional plans in municipal offices, are increasingly criticised for their limited accessibility and declining relevance (Hofmann et al., 2020). While digital participation formats, including web-based platforms, social media, and participatory geographic information systems, facilitate the asynchronous collection of opinions, they often fail to capture the experiential depth of urban spaces

(Hofmann et al., 2020; Jankowski & Nyerges, 2003; Lu et al., 2018). Nevertheless, there is a need for clearer design and evaluation criteria for digital participation processes, as well as for the tools applied across different planning phases (Berigüete et al., 2024).

A promising approach to overcoming the abstraction of conventional planning representations for citizens is the use of immersive technologies such as virtual reality (VR) or 360° videos in head-mounted displays (HMDs). These technologies enable citizens to experience complex traffic situations (Jamei et al., 2017; Maksimenko et al., 2026). This development is particularly relevant for pedestrian-related considerations within urban infrastructure planning (Berkemeier et al., 2025; Schrom-Feiertag et al., 2019). VR can support pedestrians by enabling more realistic assessments of planned infrastructure. The utilisation and acceptance of infrastructure are frequently influenced more by subjective perceptions of safety than by objective safety indicators (Götschi et al., 2018; Winters et al., 2012). Perceptual processes, including speed estimation and distance evaluation, play a crucial role in crossing decisions and, consequently, in traffic safety outcomes (Liu & Tung, 2014; Maruhn et al., 2020). Perception-oriented experiments may be better at capturing real behaviour than monitor-based approaches (W. Zhu et al., 2021). Perception-oriented participation is defined as a participatory process focusing on citizens' cognitive and affective appraisal of urban space. It moves beyond static visualisation to evaluate dynamic experiences such as perceived safety and vehicle speed (Luo et al., 2025).

Immersive tools offer three distinct advantages for participatory planning. Regarding the safety of the method, VR enables controlled and safe testing conditions, allowing participants to evaluate hazardous traffic scenarios without physical risk (Angulo et al., 2023; Burns et al., 2020; Yao et al., 2021). VR facilitates preventive testing by allowing the evaluation of infrastructure prior to its physical implementation. Research conducted by Schrom-Feiertag et al. (2020) demonstrates the efficacy of integrating virtual environments with traffic simulations to evaluate perceived safety and place quality in newly designed street spaces. This approach helps identify infrastructural adaptations prior to real-world implementation, thereby ensuring more efficient resource use and maximising potential benefits. Concurrent studies emphasise that VR should complement rather than replace traditional participation methods. It serves as a visual and experiential tool that enhances perspective-taking and comprehensibility (van der Horst & Peeters, 2021). Further research indicates that inadequate regulation of emerging mobility forms may impose additional challenges for pedestrians, underscoring the significance of perception-oriented evaluation of infrastructural interventions (Arshi et al., 2026).

Despite this potential, the current state of research reveals a threefold gap that prevents immersive tools from being integrated into standard urban planning:

1. Applications of VR and other immersive tools frequently remain in the experimental pilot stage, with only marginal integration into formal planning procedures (Goncalves et al., 2026; Simonofski et al., 2024). Institutional frameworks and participatory mindsets that extend beyond involvement are lacking, thereby limiting meaningful public engagement.
2. Many digital participation tools continue to prioritise visualisation and information provision (Jutraž & Moine, 2016), while the subjective perception of dynamic traffic situations has rarely been systematically examined in participatory contexts.

3. The validity of immersive studies depends on the correspondence of perception and behaviour between real and virtual environments (Bhagavathula et al., 2018). Theoretical foundations and standardised methodologies for integrating digital and immersive tools into participatory planning processes remain limited (J. Li et al., 2021).

To address this overarching gap, the present study examines how perception-related aspects of traffic situations, particularly pedestrians' vehicle speed perception, could be better integrated into digital participation formats in urban and transport planning. To achieve this, the study employs a scoping review conducted in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) to map the current state of evidence. The study aims to identify the methodological gap in current participatory planning approaches and highlight the potential of immersive technologies to better represent and communicate experiential qualities of urban environments. These insights provide a foundation for future research on perception-oriented participation tools, particularly immersive approaches for evaluating pedestrian perception processes in realistic planning scenarios.

2. Methodology

The methodological framework for this research is based on a scoping review in accordance with the PRISMA-ScR guidelines (Tricco et al., 2018). This approach was chosen to map the scope, range, and nature of the available evidence on digital, particularly immersive, participation tools. A formal critical appraisal or risk-of-bias assessment of the individual included studies was not performed, as the primary objective is to map a heterogeneous and rapidly evolving field rather than to critically appraise specific interventions (Tricco et al., 2018). This allows for a comprehensive overview of the current state of research regardless of the methodological quality of individual sources. Figure 1 presents the PRISMA-ScR flow diagram of the literature search and screening process, including the number of records retrieved from each database and the subsequent exclusion steps.

To identify sources relevant to the research questions, keywords were defined across several thematic categories, including citizen participation, immersive technologies, planning contexts, perceptual aspects, and critical perspectives on digitalisation. Synonyms and related terms were combined using Boolean operators to capture a broad range of relevant literature. This resulted in a total of 11 search strings (e.g., "citizen participation" OR "public participation" OR "participatory planning") AND ("virtual reality" OR "VR" OR "360 video" OR "head-mounted display") AND ("urban planning" OR "transport planning" OR "traffic planning"), which were applied across three databases (Scopus, Web of Science, IEEE Xplore Digital Library). A detailed overview of the keyword categories (Table S1) and the complete set of search strings (Table S2) is provided in the Supplementary File.

During the identification phase, studies were screened based on titles, abstracts, and keywords. At this stage, articles published prior to 2015, non-English articles, and studies focusing exclusively on external human–machine interfaces (eHMIs) research, communication between autonomous vehicles (AVs) and pedestrians, algorithm development, driver or passenger perspectives, or purely simulation-based model studies were excluded. In a subsequent step, the duplicates were removed. The literature search, screening, and synthesis were conducted by the lead author, while the search strategy and final synthesis were iteratively reviewed and validated by all co-authors to ensure methodological consistency.

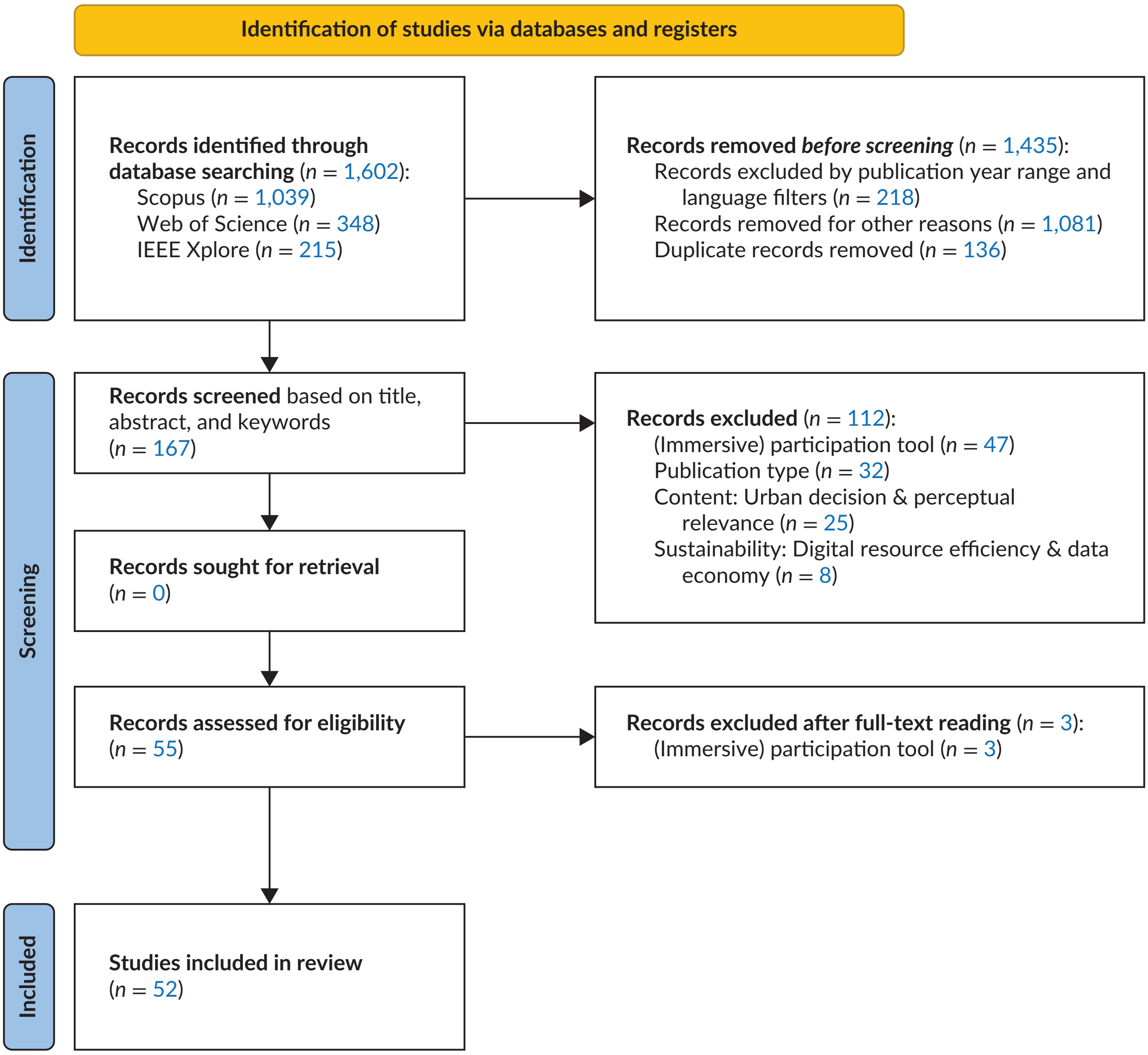

Figure 1. PRISMA-ScR flow diagram for the scoping review process. Source: Adapted from Tricco et al. (2018).

The screening phase was guided by predefined eligibility criteria to ensure the methodological relevance of the selected literature (see Table 1). In accordance with the PRISMA-ScR guidelines (Tricco et al., 2018), the screening and eligibility assessment were conducted in a structured and transparent manner to maintain consistency throughout the review process.

A total of 55 articles were identified as eligible for inclusion in the review. Following full-text screening, three articles were excluded for not meeting the participation tool criterion. Consequently, 52 articles were included.

Following the completion of the screening process, the content-related synthesis of the included studies was conducted using a deductive approach. The predefined criteria presented in Table 1, which had previously been applied during screening, were subsequently used to guide the deductive synthesis. Relevant characteristics were extracted, including the applied tool, sample information, research context, study design, measured variables, and findings.

Table 1. Overview of inclusion criteria.

Criterion focus	Inclusion criteria
Publication type	Primary, peer-reviewed empirical studies (journal articles and full conference papers). Secondary literature (reviews, meta-analyses), and grey literature were excluded to ensure empirical comparability.
Participation tool	Immersive VR and 360° video environments (presented via HMDs or virtual environments) that enable strong real-world embeddedness and spatial interaction beyond passive visualisation.
Content Urban decision context & experiential relevance	Studies situated in urban, spatial, or transport planning involving perception-based measures (e.g., safety or speed perception, time-to-collision, workload) within participatory decision-making processes.
Sustainability Data economy & critical digitalisation perspective	Research reflecting strategies for resource-efficient planning and the generation of targeted, perception-based evidence for decision-making, rather than large-scale data accumulation.

3. Results

The results of the scoping review are synthesised according to the deductive analysis categories defined in Table 1. This mapping approach facilitates a structured characterisation of the extent and nature of the evidence, moving beyond a descriptive summary to identify key conceptual themes and research gaps. The framework specifically links the technological development of immersive participation tools with their application in real urban decision-making contexts and their role in supporting resource-sensitive, evidence-based planning. To support this synthesis, a summary table (Table S3) is provided in the Supplementary File, encompassing the specific hardware utilised, participant demographics, research settings, and study designs, as well as the specific data points, and individual results. The following sections present the data charting results from the 52 included studies across these three core perspectives.

3.1. Participation Tool

The synthesis of the 20 sources identified in the "Participation tool" category highlights a shift from static 2D representations to immersive VR environments that capture human perception and bridge technical planning with experiential understanding. A detailed overview of the specific hardware and software configurations used in the reviewed studies is provided in Table S3 in the Supplementary File. The literature identifies a broad spectrum of technical setups, ranging from fully HMDs and cave automatic virtual environments (CAVEs) to non-immersive, monitor-based desktop VR (De Oliveira et al., 2025; Jamei et al., 2017; Srivastava et al., 2019). The delivery of content serves to differentiate between 360° video recordings and interactive environments constructed using game engines such as Unity or Unreal (Guler et al., 2024; Schewenius & Wallhagen, 2024). The findings indicate that the choice of immersive tools substantially influences the quality and nature of user engagement. HMD-based applications tend to enhance emotional immersion, presence, and empathy by facilitating perspective-taking. In contrast, desktop VR is often associated with improved spatial learning and orientation because it places lower cognitive demands on users and reduces sensory conflicts (Pouke et al., 2019; van Leeuwen, Hermans, Jylhä, et al., 2018). The level of software interactivity further shapes the extent of user participation: 360° environments primarily support information provision and consultation, whereas interactive game-engine-based applications enable participants to manipulate urban elements in real time and assume a more active role in the planning process (Goncalves et al., 2026; Schrom-Feiertag et al., 2020). The technological setup also influences the social dimension of participation: HMDs generally provide individual experiences, while CAVE systems and stationary installations are better suited to synchronous collaboration, stakeholder dialogue, and consensus-building (Dembski et al., 2019; Jamei et al., 2017; Luo et al., 2025). The key findings are summarised in Table 2.

Table 2. Synthesis of immersive participation tools.

Key findings of the subcategories	References
Technological evolution of participation tools	
A shift from static 2D plans and CAD representations towards immersive virtual environments can be observed, with VR used as a diagnostic tool. These tools bridge complex technical planning and citizens' subjective experience, reduce cognitive barriers, and enable intuitive, location- and time-independent participation with higher engagement. Highly immersive HMD-based VR supports emotional engagement, while desktop VR is more suitable for spatial learning and orientation. Immersive tools also enable efficient simulation and evaluation of infrastructure in early planning phases.	(Angulo et al., 2023; Guler et al., 2024; Jutraž & Moine, 2016; J. Li et al., 2021; Schrom-Feiertag et al., 2020; Srivastava et al., 2019; van Leeuwen, Hermans, Quanjer, et al., 2018)
Perception validation	
In virtual environments, vehicle speed is systematically underestimated, leading users to rely more on spatial distance rather than temporal cues such as time-to-collision. This shift results in riskier decision-making behaviour compared to real-world settings. Despite these discrepancies, VR remains a valid tool for analysing human perception and behaviour and offers a safe environment to train estimation abilities, particularly for vulnerable groups, as well as to evaluate the subjective safety of new infrastructures.	(Angulo et al., 2023; Bhagavathula et al., 2018; De Oliveira et al., 2025; Feldstein & Dyszak, 2020; Maruhn et al., 2020; Schrom-Feiertag et al., 2019; Schwarzkopf et al., 2024; Schwebel et al., 2024)
Multisensory integration	
The integration of auditory and olfactory stimuli in immersive environments increases interaction rates and improves the recall of planning details. Auditory information is essential for accurately perceiving dynamic processes such as vehicle acceleration, as purely visual simulations are often insufficient, particularly in the context of electric vehicles. Multisensory simulations also enable perspective-taking, for example by simulating the viewpoint of vulnerable groups, thereby making safety deficits in traffic environments more tangible.	(Meenar & Kitson, 2020; Oberfeld et al., 2024; Schrom-Feiertag et al., 2020)
User-centred barriers	
Physiological and cognitive barriers, such as simulation sickness and increased cognitive load in complex tasks, represent key limitations of immersive tools. Higher symptom levels have been reported among certain user groups, although increased realism can mitigate these effects.	(Abu Selo et al., 2025; Luque et al., 2024)
Methodological aspects	
VR environments also influence decision-making and can lead to more pronounced attitude changes compared to traditional representations. At the same time, they enable the analysis of qualitative risk aspects, such as the violation of personal space.	(Hori et al., 2025; W. Zhu et al., 2021)

In summary, immersive tools integrate subjective safety and perceptual experience into planning processes. These tools extend beyond visualisation, functioning as instruments of empathy and diagnosis in decision-making processes. However, the validity of their application is contingent upon the consideration of perceptual biases, such as speed underestimation, and the integration of multisensory components. Multisensory integration involves the combination of visual, auditory, and sometimes olfactory stimuli to create near-real immersive environments, which has been shown to improve the recall of planning details (Meenar & Kitson, 2020) and reduce perceptual errors (Oberfeld et al., 2024; Wessels & Oberfeld, 2024).

3.2. Content: Urban Decision Context & Experiential Relevance

The category "Content" focuses on the application of tools in urban decision-making and perception contexts. The fundamental question guiding this research is how these tools capture human perception and decision-making in urban spaces and how these processes can be used for planning decisions. The key findings are summarised in Table 3.

Table 3. Synthesis of findings for urban decision context.

Key findings of the subcategories	References
Built environment and planning impact	
Infrastructure parameters such as reduced traffic lanes, warm lighting, and clearly defined pathways decrease stress and increase perceived safety. While vegetation enhances well-being, it may obstruct visibility at crossings and increase stress. VR enables empathy through perspective-taking, transforming citizens from passive observers into active contributors to more inclusive and sustainable urban spaces.	(Arshi et al., 2026; Joo et al., 2023; Kwon et al., 2022; C. Lee et al., 2025; Llinares et al., 2020; Martinez et al., 2024; Oberfeld et al., 2022; Pouke et al., 2019; Shahi et al., 2025; van der Horst & Peeters, 2021)
Dynamic and multisensory perception	
A systematic misperception of vehicle motion exists, as acceleration is often neglected in time-to-collision estimations. Visual information dominates over auditory cues. Electric vehicles are perceived as slower or more distant due to their acoustic signature (intensity-arrival effect). VR environments are suitable for simulating such dynamics, even though speeds may be partially overestimated.	(Krautwurm et al., 2025; Oberfeld et al., 2022; Pugliese et al., 2020; Schneider et al., 2022; Wessels et al., 2022; Wessels & Oberfeld, 2024)
User factors	
Individual characteristics such as age, gender, and visual impairments influence perception, search strategies, and risk assessment.	(Carrigan et al., 2025; Khademi et al., 2024; C. Lee et al., 2025; Shahi et al., 2025)
Situational influences	
External factors, including digital distraction through smartphones and reduced visibility due to environmental conditions such as rain or fog, further affect perception and increase uncertainty. Assistance systems, such as vehicle-based light signals, can support the correction of perceptual errors, provided they do not introduce additional distractions.	(DeLucia et al., 2025; Khademi et al., 2024; Kwon et al., 2022; Sobhani et al., 2017; Wessels & Oberfeld, 2024; M. Zhu et al., 2025)

The findings indicate that perception-oriented planning is crucial for transcending conventional visual designs. The integration of data on human estimation accuracy and individual vulnerabilities into immersive tools facilitates the identification of planning errors at an early stage, thereby enhancing intuitive safety and inclusivity in urban spaces.

3.3. Sustainability: Data Economy & Critical Digitalisation Perspective

The findings for the last category, “Sustainability,” are summarised in Table 4, outlining the economic, social, and ecological dimensions of sustainability, as well as key challenges related to digital participation.

Table 4. Synthesis of findings for sustainability and digitalisation.

Key findings of the subcategories	References
Economic dimension	
The early identification of planning errors in digital models has been shown to facilitate the avoidance of costly redesign processes. Digital twins have the potential to reduce the necessity for physical testing by up to 64%. The utilisation of open-source software (e.g., Blender, Unreal Engine) facilitates cost-effective production, thereby reducing economic barriers for municipalities.	(Dorostkar & Ziari, 2025; Kavouras et al., 2025; Schwarzkopf et al., 2023; Shrestha & Maharjan, 2019; van Leeuwen, Hermans, Quanjer, et al., 2018)
Social dimension	
Immersive technologies reduce cognitive barriers by acting as a “common language” instead of technical jargon. They increase citizen engagement and strengthen democratic quality through improved understanding of planning proposals. Simulated environments support preventive traffic safety, particularly for vulnerable groups. Inclusion can be enhanced through AI-supported feedback systems and low-cost hardware solutions (e.g., carton glasses).	(Gower et al., 2023; López-Álvarez et al., 2024; Nawaz et al., 2025; Rautanen et al., 2025; Schewenius & Wallhagen, 2024; Szczepańska et al., 2021; van Leeuwen, Hermans, Quanjer, et al., 2018)
Ecological perspective	
Digital twins facilitate precise monitoring of environmental indicators, including emissions and microclimate, in real time. The utilisation of VR-based visualisations has been demonstrated to enhance environmental awareness and foster emotional attachment to green-blue infrastructure. Data-driven approaches have been demonstrated to support the optimisation of cycling infrastructure and the promotion of emission-free mobility in virtual environments.	(Dembski et al., 2019; Disser & Rüppel, 2025; Dorostkar & Ziari, 2025; Schewenius & Wallhagen, 2024)
Key challenges and barriers	
The immersion-equity paradox highlights the risk of a digital divide for less technologically experienced groups. Concerns exist regarding transparency and potential bias in digital models. Technical limitations include high hardware requirements and simulation sickness. Institutional barriers, such as limited expertise and rigid administrative structures, hinder the implementation of digital participation.	(Dorostkar & Ziari, 2025; Gower et al., 2023; Kavouras et al., 2025; Schewenius & Wallhagen, 2024; Schwarzkopf et al., 2024; Szczepańska et al., 2021)

The scoping review identified a methodological gap between behavioural perception research and real-world citizen participation in urban planning, as perception-oriented approaches are only rarely integrated. Immersive technologies reduce planning complexity by translating abstract information into experiential environments and enabling intuitive evaluation. At the same time, perceptual discrepancies, such as differences in speed perception between real and virtual environments, define requirements for digital tool design. Overall, immersive technologies function as a bridge between technical planning, human perception, and sustainable urban development. It becomes evident that instruments designed to facilitate digital participation must be developed in such a way as to make perceptual barriers visible without creating new technological barriers to access.

4. Discussion

This work examines how perception-related aspects of traffic situations, particularly pedestrians' vehicle speed perception, can be integrated into digital participation in urban and transport planning. The findings reveal a methodological gap in current participatory planning approaches and suggest that immersive digital participation tools may better represent experiential aspects of urban environments. A central finding of the scoping review is the shift from static visual representations to immersive, experience-oriented tools (Guler et al., 2024; Jutraž & Moine, 2016; Schrom-Feiertag et al., 2020). These tools enable citizens to explore planning scenarios more intuitively while reducing cognitive barriers (Guler et al., 2024; Jutraž & Moine, 2016).

Immersive tools function as a bridge between expert-driven planning and citizens' subjective experience (J. Li et al., 2021). This bridging function is particularly relevant in mobility planning, where infrastructure acceptance is often shaped more by perceived safety than by objective safety indicators (Götschi et al., 2018; Winters et al., 2012). However, the findings of the review also highlight that immersive tools should not be seen as neutral representations of reality. Perceptual judgements in VR environments differ from those in real-world settings. Specifically, vehicle speed is frequently underestimated in VR (Angulo et al., 2023; Feldstein & Dyszak, 2020; Schrom-Feiertag et al., 2019). In addition, pedestrians rely more on spatial distance cues than on temporal indicators such as time-to-collision when making crossing decisions (Angulo et al., 2023; Bhagavathula et al., 2018).

This inconsistency can be attributed both to methodological diversity and to a multitude of influencing factors. Beyond individual characteristics such as age, gender, or driving experience (Ambros et al., 2021; Babić et al., 2022; Feldstein & Peli, 2020), vehicle-specific attributes, including size and type (Feldstein & Dyszak, 2020; Y. M. Lee & Sheppard, 2017; Mathieu et al., 2017), significantly shape speed perception through phenomena like the size-arrival effect. Behavioural indicators such as gap acceptance and time-to-arrival (Beggiato et al., 2017) also interact with contextual information, including traffic signs, lighting, weather conditions, and overall traffic volume, to determine how dynamic situations are assessed (Babić et al., 2022; Dong et al., 2022; Kim et al., 2017; Shi et al., 2020).

These perceptual discrepancies may encourage riskier behaviour and smaller safety margins. Technical limitations of immersive technologies such as VR, including low resolution and restricted fields of view, can hinder accurate looming perception (De Oliveira et al., 2025; Feldstein & Dyszak, 2020; Luque et al., 2024; Maruhn et al., 2020). Furthermore, the absence of multisensory integration, particularly realistic acoustic signals, fosters an erroneous first-order estimation strategy where acceleration is disregarded (Oberfeld et al., 2024; Wessels & Oberfeld, 2024). A reduced sense of presence, often described as "place illusion," can lower perceived threat levels and encourage hazardous crossing decisions (Bhagavathula et al., 2018; Feldstein & Dyszak, 2020). To avoid misinterpretation of behavioural responses, immersive environments must be designed and validated through multisensory cues, as auditory information is relevant for estimating acceleration and vehicle approach (Oberfeld et al., 2024; Wessels & Oberfeld, 2024), and enhancing the recall of planning scenarios (Meenar & Kitson, 2020).

Immersive environments support the preventive testing of infrastructure prior to implementation, allowing planners to evaluate subjective safety, place quality, and behavioural responses in a controlled setting (Angulo et al., 2023; Schrom-Feiertag et al., 2020; Schwarzkopf et al., 2023; W. Zhu et al., 2021). The scoping review demonstrates that physical characteristics, such as lighting, visibility, street layout, and vegetation, significantly shape perceived safety and comfort in urban spaces (Kwon et al., 2022; Llinares et al., 2020; Martinez et al., 2024; Shahi et al., 2025). By enabling planners to compare alternative design configurations before implementation, immersive tools support more resource-sensitive planning (Martinez et al., 2024; Schwarzkopf et al., 2023, 2024; van Leeuwen, Hermans, Quanjer, et al., 2018). This approach can reduce the need for costly physical testing and avoid repeated planning cycles or misaligned infrastructure decisions (Dorostkar & Ziari, 2025; Levy, 2010; Schwarzkopf et al., 2023; Shrestha & Maharjan, 2019).

Furthermore, immersive tools enhance the reach of participation by facilitating perspective-taking. Experience-oriented formats allow users to experience environments from the viewpoints of vulnerable groups, thereby strengthening empathy and supporting a more inclusive understanding of urban design (Schrom-Feiertag et al., 2020; van der Horst & Peeters, 2021).

However, the scoping review also highlights potential sustainability challenges. Immersive systems require specialised hardware, technical expertise, and institutional capacities that are not always available in municipal planning contexts (Goncalves et al., 2026; Kavouras et al., 2025; Simonofski et al., 2024). Without integration into existing governance structures, there is a risk of creating digital waste through extensive visualisation models that are not effectively utilised in final decision-making processes.

In addition to the challenges posed by institutional frameworks, the integration of immersive tools into various contexts gives rise to political and ethical considerations. High-fidelity visualisations may create an appearance of democratic legitimacy while decision-making authority remains largely technocratic. This may privilege communities with greater technical capacity while marginalising local everyday knowledge (Chan, 2025; Goncalves et al., 2026). Moreover, the aggregation of behavioural data necessitates the establishment of robust frameworks to address the "privacy paradox." This is characterised by the phenomenon whereby users trade sensitive information for immediate benefits, within the context of current legal ambiguities (Nizamani et al., 2026; Shakibamanesh et al., 2024; Shariatpour et al., 2025). Ensuring inclusivity requires the systematic removal of accessibility barriers that may limit participation in immersive environments. This involves complementing visually oriented interfaces with multimodal interaction options and adopting plain language standards to accommodate individuals with sensory or cognitive impairments (Hofmann et al., 2020; Labbé et al., 2023; Luo et al., 2025). The unequal distribution of digital resources, reflected in the high cost of hardware and the strong urban focus of current research, risks further marginalising rural communities that often lack both adequate infrastructure and the digital literacy required to benefit from immersive technologies (Luo et al., 2025; Shakibamanesh et al., 2024). To better capture the experiential depth that may not be fully reflected in immersive environments alone, future studies could adopt mixed-method approaches (Luo et al., 2025). Combining qualitative methods, including post-immersion interviews, ethnographic observations, and think-aloud protocols (Pouke et al., 2019; Rautanen et al., 2025; Szczepańska et al., 2021; van der Horst & Peeters, 2021), with neurophysiological measures such as EEG can provide complementary insights into both subjective experiences and unconscious responses (Llinares et al., 2020; Luque et al., 2024).

To bridge the identified gap between research-driven pilots and municipal practice, several implementation strategies and policy recommendations emerge from this scoping review. First, public administrations should institutionalise interdisciplinary frameworks, such as urban living labs, which can serve as formal operational frameworks and place-based intermediaries (Shariatpour et al., 2025). Following Chronéer et al. (2019), these labs are essential as they facilitate the open co-creation of solutions by engaging diverse stakeholders, including the public sector, private industry, and citizens, within a real-world setting. A structured ecosystem allows urban living labs to enhance the connection between digital models and the urban environment, supporting the transition of VR tools from experimental pilot projects to integrated planning instruments (Dorostkar & Ziari, 2025; Shariatpour et al., 2025).

Beyond institutionalisation, municipalities must establish clear regulatory guidelines regarding data transparency and the ethical use of algorithms to maintain public trust in digital governance (Berigüete et al., 2024; Othengrafen et al., 2025).

To resolve the immersion-equity paradox and thereby minimise the risk of widening the digital divide, a tiered infrastructure approach is proposed. Establishing stationary VR hubs in underserved or marginalised neighbourhoods can lower entry barriers before expanding to city-wide mobile or web-based applications (Dorostkar & Ziari, 2025). Immersive tools should also function as a complementary layer within hybrid participation models, maintaining traditional analogue formats and two-dimensional plans to ensure that citizens with limited digital literacy remain included (Goncalves et al., 2026; Jutraž & Moine, 2016). The practical success of such formats also depends on the presence of trained facilitators. On-site support has been shown to increase user confidence and the reliability of citizen feedback (Schwarzkopf et al., 2023; van Leeuwen, Hermans, Quanjer, et al., 2018).

For seamless process integration, immersive tools should be employed in the early conceptual planning phases, where they can most effectively identify design conflicts and optimise resources prior to physical implementation (Schwarzkopf et al., 2023). While AI-supported tools have the capacity to assist planners in the management of large volumes of qualitative feedback, for instance through automated speech recognition for transcription or thematic clustering, these should be regarded as supplementary instruments requiring human oversight to ensure accountability (Othengrafen et al., 2025; Rautanen et al., 2025). Long-term acceptance also depends on transparent communication. Planners should clearly communicate which immersive elements are technically feasible to avoid unrealistic public expectations, disappointment, and declining acceptance (Gower et al., 2023; Schrom-Feiertag et al., 2020).

Despite the contributions of this study, limitations should be acknowledged. As no independent duplicate screening was conducted, the single-researcher approach may have increased the risk of reviewer-related bias. However, the resulting synthesis and interpretation of the findings were reviewed and validated by all co-authors. Furthermore, the reviewed studies vary in design, context, and methodology, which limits direct comparison. Additionally, as no formal quality assessment was performed, studies with varying empirical rigour are synthesised with equal weight. This absence of critical appraisal requires caution when translating experimental results into planning processes. Consequently, the findings should be interpreted as a conceptual map of research rather than an evaluation of the effectiveness of specific immersive tools. The review also applied specific inclusion criteria related to immersive participation and perceptual relevance, excluding potentially relevant studies.

Future research should investigate the validity of immersive participation tools with a particular focus on perceptual offsets to correct for the systematic underestimation of vehicle speed. Moreover, immersive participation formats should be designed to minimise digital exclusion and reduce barriers related to technical complexity. Multisensory integration and user experience in immersive environments may enhance the realism and usability of such tools. Finally, future work should examine the integration of immersive participation tools into existing planning procedures and governance structures without reinforcing techno-deterministic assumptions or opaque decision-making processes.

5. Conclusion

The findings of this PRISMA-guided scoping review identify a significant methodological gap between perception-oriented research and current participatory planning practices. We conclude that immersive participation tools can bridge this gap by translating abstract planning proposals into experiential environments. By making pedestrians' speed perception and subjective safety visible, these tools support more informed and inclusive urban design decisions. These tools should not be understood solely as technological innovations but as instruments that bridge expert-driven planning and citizens' lived experience. To be effective, however, they must complement rather than replace existing participation strategies. Moreover, immersive participation enables resource-efficient planning through the early evaluation of planning scenarios, helping to identify design conflicts prior to physical implementation. The successful integration of these tools requires a critical reflection on accessibility and transparency.

Acknowledgments

The authors would like to thank Mary McDonnell and Brendan McDonnell for their contribution to the proofreading process of the manuscript.

Funding

This project is co-financed from tax revenues on the basis of the budget adopted by the Saxon State Parliament. Co-funded by the European Union.

Conflict of Interests

The authors declare no conflict of interests.

LLMs Disclosure

AI-based tools (ChatGPT and DeepL) were used to support language-related tasks during the preparation of this manuscript, specifically for translating text between German and English and for stylistic editing. The AI tools were not used to generate original scientific content, data, analyses, or interpretations. All scientific arguments, results, and conclusions were developed and verified by the authors.

Supplementary Material

Supplementary material for this article is available online in the format provided by the authors (unedited).

References

Abu Selo, T., Hussain, Z., Hussain, Q., Alhajyaseen, W., Al-Quradaghi, S., & Alqaradawi, M. Y. (2025). Exploring simulation sickness in virtual reality pedestrian scenarios: Effects of gender, exposure, and user perceptions. *Safety*, *11*(3), Article 63. https://doi.org/10.3390/safety11030063

Alam, T. (2024). Metaverse of Things (MoT) applications for revolutionizing urban living in smart cities. *Smart Cities*, *7*(5), 2466–2494. https://doi.org/10.3390/smartcities7050096

Almulhim, A. I. (2025). Integrating artificial intelligence into smart infrastructure management for sustainable urban planning. *Technologies*, *13*(11), Article 481. https://doi.org/10.3390/technologies13110481

Ambros, J., Turek, R., Šragová, E., Petr, K., Šucha, M., & Frič, J. (2021). How fast would you (or should you) drive here? Investigation of relationships between official speed limit, perceived speed limit, and preferred speed. *Transportation Research Part F: Traffic Psychology and Behaviour*, *83*, 164–178. https://doi.org/10.1016/j.trf.2021.09.003

Angulo, A. V., Robartes, E., Guo, X., Chen, T. D., Heydarian, A., & Smith, B. L. (2023). Demonstration of virtual reality simulation as a tool for understanding and evaluating pedestrian safety and perception at midblock crossings. *Transportation Research Interdisciplinary Perspectives*, *20*, Article 100844. https://doi.org/10.1016/j.trip.2023.100844

Arshi, A. N., Dias, C., Alhajyaseen, W. K. M., Hussain, Q., Samson, C., & Hussain, Z. (2026). Can pedestrians safely navigate shared sidewalks with e-scooters and bicycles? A behavioral analysis using surrogate safety measures. *Transportation Research Part F: Traffic Psychology and Behaviour*, *116*, Article 103407. https://doi.org/10.1016/j.trf.2025.103407

Babić, D., Čavka, M., Babić, D., & Hrabač, P. (2022). Young drivers' perception of speed: VR and video footage comparison study. *Transportation Research Procedia*, *64*, 205–214. https://doi.org/10.1016/j.trpro.2022.09.025

Beggiato, M., Witzlack, C., & Krems, J. F. (2017). Gap acceptance and time-to-arrival estimates as basis for informal communication between pedestrians and vehicles. In *AutomotiveUI '17: Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 50–57). Association for Computing Machinery. https://doi.org/10.1145/3122986.3122995

Berigüete, F. E., Santos, J. S., & Rodriguez Cantalapiedra, I. (2024). Digital revolution: Emerging technologies for enhancing citizen engagement in urban and environmental management. *Land*, *13*(11), Article 1921. https://doi.org/10.3390/land13111921

Berkemeier, A., Schwarzkopf, M., Hoffmann, H., & Bullinger, A. C. (2025, August 27-29). *Towards virtual reality supported participatory infrastructure planning processes: Assessing the safety of pedestrian choices* [Paper presentation]. 9th HUMANIST Virtual Centre of Excellence Conference, Chemnitz, Germany. https://doi.org/10.60687/2025-0194

Bhagavathula, R., Williams, B., Owens, J., & Gibbons, R. (2018). The reality of virtual reality: A comparison of pedestrian behavior in real and virtual environments. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *62*(1), 2056–2060. https://doi.org/10.1177/1541931218621464

Biancifiori, S., Torabi Moghadam, S., & Lombardi, P. (2025). Participatory digital solutions for nature-based solution urban projects: A systematic PRISMA literature review. *Sustainability*, *17*(17), Article 7945. https://doi.org/10.3390/su17177945

Burns, C. G., Oliveira, L., Hung, V., Thomas, P., & Birrell, S. (2020). Pedestrian attitudes to shared-space interactions with autonomous vehicles—A virtual reality study. In N. Stanton (Ed.), *Advances in human factors of transportation: Proceedings of the AHFE 2019 International Conference on Human Factors in Transportation* (pp. 307–316). Springer. https://doi.org/10.1007/978-3-030-20503-4_29

Carrigan, A. J., McGuckian, T. B., Wilson, P., Greene, D., Duckworth, J., Thong, L. P., Eldridge, R., Psarakis, M., McKinnon, A. C., Fearnley, P., & Bennett, J. M. (2025). The feasibility of a virtual reality hazard perception and gap acceptance task for older adults to improve pedestrian safety. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *35*(5), Article e70026. https://doi.org/10.1002/hfm.70026

Chan, T. H.-Y. (2025). Inclusive yet marginalising: Symbolic empowerment through open big data in citizen science for transport planning. *Big Data & Society*, *12*(1). https://doi.org/10.1177/20539517251325228

Chiappini, L., & Ferrari, V. (2024). Digital geographies of power: The scale of digital money infrastructures. *First Monday*, *29*(10). https://doi.org/10.5210/fm.v29i10.13786

Chronéer, D., Ståhlbröst, A., & Habibipour, A. (2019). Urban living labs: Towards an integrated understanding of their key components. *Technology Innovation Management Review*, *9*(3), 50–62. https://doi.org/10.22215/timreview/1224

De Oliveira, L. F. A., Schories, L., & Meywerk, M. (2025). Understanding how time-to-arrival and vehicle speed influence pedestrian crossing behavior at unsignalized intersections through a virtual reality experiment. In *2025 IEEE Intelligent Vehicles Symposium (IV)* (pp. 2565–2570). IEEE. https://doi.org/10.1109/IV64158.2025.11097752

DeLucia, P. R., Oberfeld, D., Kearney, J. K., Cloutier, M., Jilla, A. M., Zhou, A., Corona, S. T., Cormier, J., Taylor, A., Wykoff, C. C., & Baurès, R. (2025). Visual, auditory, and audiovisual time-to-collision estimation among participants with age-related macular degeneration compared to a normal-vision group: The TTC-AMD study. *PLoS One*, *20*(12), Article e0337549. https://doi.org/10.1371/journal.pone.0337549

Dembski, F., Wössner, U., & Letzgus, M. (2019). The digital twin tackling urban challenges with models, spatial analysis and numerical simulations in immersive virtual environments. In J. P. Sousa, G. C. Henriques, & J. P. Xavier (Eds.), *Proceedings of the 37th eCAADe and XXIII SIGraDi Joint Conference: Architecture in the Age of the 4th Industrial Revolution* (pp. 795–804). Blucher. https://doi.org/10.5151/proceedings-ecaadesigradi2019_334

Disser, M., & Rüppel, U. (2025). SPUR: Enhancing cyclist safety through digital city twins—A data-driven infrastructure planning and VR simulation approach. In *2025 21st International Conference on Intelligent Environments (IE)* (pp. 1–4). IEEE. https://doi.org/10.1109/IE64880.2025.11130085

Dong, W., Qin, T., Yang, T., Liao, H., Liu, B., Meng, L., & Liu, Y. (2022). Wayfinding behavior and spatial knowledge acquisition: Are they the same in virtual reality and in real-world environments? *Annals of the American Association of Geographers*, *112*(1), 226–246. https://doi.org/10.1080/24694452.2021.1894088

Dorostkar, E., & Ziari, K. (2025). Urban planning and metaverse technologies for sustainable cities: Reducing environmental footprints and enhancing social equity (A case study of Tehran, Iran). *Environmental and Sustainability Indicators*, *28*, Article 100913. https://doi.org/10.1016/j.indic.2025.100913

Feldstein, I. T., & Dyszak, G. N. (2020). Road crossing decisions in real and virtual environments: A comparative study on simulator validity. *Accident Analysis & Prevention*, *137*, Article 105356. https://doi.org/10.1016/j.aap.2019.105356

Feldstein, I. T., & Peli, E. (2020). Pedestrians accept shorter distances to light vehicles than dark ones when crossing the street. *Perception*, *49*(5), 558–566. https://doi.org/10.1177/0301006620914789

Goncalves, J. E., Slingerland, G., Sarabi, S., & Dane, G. (2026). Process first, tools second: A conceptual framework to embed digital participation in planning processes for citizen empowerment. *Cities*, *170*, Article 106645. https://doi.org/10.1016/j.cities.2025.106645

Götschi, T., Castro, A., Deforth, M., Miranda-Moreno, L., & Zangenehpour, S. (2018). Towards a comprehensive safety evaluation of cycling infrastructure including objective and subjective measures. *Journal of Transport & Health*, *8*, 44–54. https://doi.org/10.1016/j.jth.2017.12.003

Gower, A., Hotker, M., & Grodach, C. (2023). Digital participation models as public engagement tools in planning: A concept exploration. *Planning Theory & Practice*, *24*(5), 663–678. https://doi.org/10.1080/14649357.2023.2278099

Guler, M., Bekiri, V., Baldauf, M., & Zimmermann, H.-D. (2024). Virtual reality for home-based citizen participation in urban planning—An exploratory user study. In F. F.-H. Nah & K. L. Siau (Eds.), *HCI in business, government and organizations: 11th International Conference, HCIBGO 2024, held as part of the 26th HCI International Conference, HCII 2024* (pp. 38–49). Springer Nature. https://doi.org/10.1007/978-3-031-61318-0_4

Hofmann, M., Münster, S., & Noennig, J. R. (2020). A theoretical framework for the evaluation of massive digital participation systems in urban planning. *Journal of Geovisualization and Spatial Analysis*, *4*(1), Article 3. https://doi.org/10.1007/s41651-019-0040-3

Hori, C., Sakamoto, R., Hamada, T., & Koshizuka, N. (2025). Exploring perceived risk of passing sidewalk mobility using VR. In *2025 IEEE International Smart Cities Conference (ISC2)* (pp. 1–6). IEEE. https://doi.org/10.1109/ISC266238.2025.11293310

Jamei, E., Mortimer, M., Seyedmahmoudian, M., Horan, B., & Stojcevski, A. (2017). Investigating the role of virtual reality in planning for sustainable smart cities. *Sustainability*, *9*(11), Article 2006. https://doi.org/10.3390/su9112006

Jankowski, P., & Nyerges, T. (2003). Toward a framework for research on geographic information-supported participatory decision-making. *URISA Journal*, *15*, 9–17.

Joo, Y., Kim, S.-N., Kim, B.-C., Cho, G.-H., & Kim, J. (2023). Autonomous vehicles and street design: Exploring the role of medians in enhancing pedestrian street crossing safety using a virtual reality experiment. *Accident Analysis & Prevention*, *188*, Article 107092. https://doi.org/10.1016/j.aap.2023.107092

Jutraž, A., & Moine, J. L. (2016). Breaking out: New freedoms in urban (re)design work by adding immersive environments. *International Journal of Architectural Computing*, *14*(2), 103–118. https://doi.org/10.1177/1478077116638922

Kajosaari, A., Schorn, M., Hasanzadeh, K., Rinne, T., Rossi, S., & Kyttä, M. (2025). Beyond the backyard: Unraveling the geographies of citizens' engagement in digital participatory planning. *Environment and Planning B: Urban Analytics and City Science*, *52*(4), 770–788. https://doi.org/10.1177/23998083241271460

Kavouras, I., Rallis, I., Sardis, E., Protopapadakis, E., Doulamis, A., & Doulamis, N. (2025). Empowering communities through gamified urban design solutions. *Smart Cities*, *8*(2), Article 44. https://doi.org/10.3390/smartcities8020044

Khademi, N., Mazloum, S., Zabihpour, A., & Chen, A. (2024). Designing safer intersections: Exploring the impact of visual and auditory warnings on pedestrian behavior in a virtual simulated environment. *Safety Science*, *178*, Article 106604. https://doi.org/10.1016/j.ssci.2024.106604

Kim, J. D., Perrone, J. A., & Isler, R. B. (2017). The effect of differences in day and night lighting distributions on drivers' speed perception. *Perception*, *46*(6), 728–744. https://doi.org/10.1177/0301006616684236

Kluge, M., Kachel, J., & Knodt, M. (2025). Digital co-creation in urban mobility planning: What motivates people to participate? *Local Government Studies*, *51*(1), 24–49. https://doi.org/10.1080/03003930.2024.2310213

Krautwurm, J., Oberfeld-Twistel, D., Huisman, T., Maravich, M. M., & Altinsoy, E. (2025). Quality comparison of dynamic auditory virtual-reality simulation approaches of approaching vehicles regarding perceptual behavior and psychoacoustic values. *Acoustics*, *7*(1), Article 7. https://doi.org/10.3390/acoustics7010007

Kwon, J.-H., Kim, J., Kim, S., & Cho, G.-H. (2022). Pedestrians safety perception and crossing behaviors in narrow urban streets: An experimental study using immersive virtual reality technology. *Accident Analysis & Prevention*, *174*, Article 106757. https://doi.org/10.1016/j.aap.2022.106757

Labbé, D., Eisenberg, Y., Snyder, D., Shanley, J., Hammel, J. M., & Froehlich, J. E. (2023). Multiple-stakeholder perspectives on accessibility data and the use of socio-technical tools to improve sidewalk accessibility. *Disabilities*, *3*(4), 621–638. https://doi.org/10.3390/disabilities3040040

Lee, C., Yun, H., Lee, J., & Kim, S.-N. (2025). Safety on the line: Examining the impacts of crosswalk design on child's perceived safety, cautious behavior, and visual attention with VR technology. *Accident Analysis & Prevention*, *213*, Article 107959. https://doi.org/10.1016/j.aap.2025.107959

Lee, Y. M., & Sheppard, E. (2017). Differences in gap acceptance for approaching cars and motorcycles at junctions: What causes the size-arrival effect? *Transportation Research Part F: Traffic Psychology and Behaviour*, *50*, 50–54. https://doi.org/10.1016/j.trf.2017.07.006

Levy, S. M. (2010). *Construction process planning and management: An owner's guide to successful projects*. Butterworth-Heinemann.

Li, J., Gan, X., Li, M., & Zhang, K. (2021). Space simulation and environment construction of urban public facilities based on VR technology. In *2021 International Conference on Computers, Information Processing and Advanced Education (CIPAE)* (pp. 321–324). IEEE. https://doi.org/10.1109/CIPAE53742.2021.00083

Li, W., Feng, T., Timmermans, H. J. P., Li, Z., Zhang, M., & Li, B. (2020). Analysis of citizens' motivation and participation intention in urban planning. *Cities*, *106*, Article 102921. https://doi.org/10.1016/j.cities.2020.102921

Liu, Y.-C., & Tung, Y.-C. (2014). Risk analysis of pedestrians' road-crossing decisions: Effects of age, time gap, time of day, and vehicle speed. *Safety Science*, *63*, 77–82. https://doi.org/10.1016/j.ssci.2013.11.002

Llinares, C., Higuera-Trujillo, J. L., Montañana, A., & Castilla, N. (2020). Improving the pedestrian's perceptions of safety on street crossings. Psychological and neurophysiological effects of traffic lanes, artificial lighting, and vegetation. *International Journal of Environmental Research and Public Health*, *17*(22), Article 8576. https://doi.org/10.3390/ijerph17228576

Loorbach, D. (2010). Transition management for sustainable development: A prescriptive, complexity-based governance framework. *Governance*, *23*(1), 161–183. https://doi.org/10.1111/j.1468-0491.2009.01471.x

López-Álvarez, A., Piovano, L., Luque, F., & De Aldama, C. (2024). Improving safe pedestrian behavior through virtual reality: An empirical study. *Bordón. Revista de Pedagogía*, *76*(3), 99–123. https://doi.org/10.13042/Bordon.2024.100116

Lu, H., Gu, J., Li, J., Lu, Y., Müller, J., Wei, W., & Schmitt, G. (2018). Evaluating urban design ideas from citizens from crowdsourcing and participatory design. In T. Fukuda, W. Huang, P. Janssen, K. Crolla, & S. Alhadidi (Eds.), *Learning, adapting and prototyping: Proceedings of the 23rd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA 2018)* (Vol. 2, pp. 297–306). Association for Computer-Aided Architectural Design Research in Asia. https://doi.org/10.52842/conf.caadria.2018.2.297

Luo, J., Liu, P., Kong, X., Shen, J., Wu, Q., & Xu, D. (2025). Urban digital twins for citizen-centric planning: A systematic review of built environment perception and public participation. *International Journal of Applied Earth Observation and Geoinformation*, *143*, Article 104746. https://doi.org/10.1016/j.jag.2025.104746

Luque, F., Armada, V., Piovano, L., Jurado-Barba, R., & Santamaría, A. (2024). Understanding pedestrian cognition workload in traffic environments using virtual reality and electroencephalography. *Electronics*, *13*(8), Article 1453. https://doi.org/10.3390/electronics13081453

Maksimenko, V., Yuan, L., & Bansal, P. (2026). Do pedestrians respond differently to perceived vehicle automation in monitor-based and head-mounted immersive experiments? *Travel Behaviour and Society*, *43*, Article 101210. https://doi.org/10.1016/j.tbs.2025.101210

Martinez, A., Fernandez, J., George, B., Spooner, D., & Rezaeimalek, S. (2024). Determining the effect of alleyway design on perceived safety through virtual reality. *Journal of Digital Landscape Architecture*, *9*, 882–889. https://doi.org/10.14627/537752082

Maruhn, P., Dietrich, A., Prasch, L., & Schneider, S. (2020). Analyzing pedestrian behavior in augmented reality—Proof of concept. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (pp. 313–321). IEEE. https://doi.org/10.1109/VR46266.2020.00051

Mathieu, J., Bootsma, R. J., Berthelon, C., & Montagne, G. (2017). Judging arrival times of incoming traffic vehicles is not a prerequisite for safely crossing an intersection: Differential effects of vehicle size and type in passive judgment and active driving tasks. *Acta Psychologica*, *173*, 1–12. https://doi.org/10.1016/j.actpsy.2016.11.014

Meenar, M., & Kitson, J. (2020). Using multi-sensory and multi-dimensional immersive virtual reality in participatory planning. *Urban Science*, *4*(3), Article 34. https://doi.org/10.3390/urbansci4030034

Nawaz, I., Cuenen, A., Wets, G., Paul, R., & Janssens, D. (2025). Advancing online road safety education: A gamified approach for secondary school students in Belgium. *Applied Sciences*, *15*(15), Article 8557. https://doi.org/10.3390/app15158557

Nizamani, M. M., Zhang, H.-L., & Lai, Z. (2026). Human-centered AI: Advancing ethical, transparent, and context-aware systems for sustainable development. *Technology in Society*, *84*, Article 103121. https://doi.org/10.1016/j.techsoc.2025.103121

Oberfeld, D., Wessels, M., & Büttner, D. (2022). Overestimated time-to-collision for quiet vehicles: Evidence from a study using a novel audiovisual virtual-reality system for traffic scenarios. *Accident Analysis & Prevention*, *175*, Article 106778. https://doi.org/10.1016/j.aap.2022.106778

Oberfeld, D., Wessels, M., & Huisman, T. (2024). Auditory and audiovisual time-to-collision estimation and road-crossing decisions. In A. Astolfi, F. Asdrubali, & L. Shtrepi (Eds.), *Proceedings of the 10th Convention of the European Acoustics Association: Forum Acusticum 2023* (pp. 4315–4320). European Acoustics Association. https://doi.org/10.61782/fa.2023.0649

Othengrafen, F., Sievers, L., & Reinecke, E. (2025). From vision to reality: The use of artificial intelligence in different urban planning phases. *Urban Planning*, *10*, Article 8576. https://doi.org/10.17645/up.8576

Pissourios, I. A. (2014). Top-down and bottom-up urban and regional planning: Towards a framework for the use of planning standards. *European Spatial Research and Policy*, *21*(1), 83–99. https://doi.org/10.2478/esrp-2014-0007

Pouke, M., Ylipulli, J., Rantala, S., Alavesa, P., Alatalo, T., & Ojala, T. (2019). A qualitative study on the effects of real-world stimuli and place familiarity on presence. In *2019 IEEE 5th Workshop on Everyday Virtual Reality (WEVR)* (pp. 1–6). IEEE. https://doi.org/10.1109/WEVR.2019.8809590

Pugliese, B. J., Barton, B. K., Davis, S. J., & Lopez, G. (2020). Assessing pedestrian safety across modalities via a simulated vehicle time-to-arrival task. *Accident Analysis & Prevention*, *134*, Article 105344. https://doi.org/10.1016/j.aap.2019.105344

Rautanen, K., Andersson, S., Backholm-Nyberg, Y., Bengs, D., & Majors, J. (2025). Preparing for the metaverse: Civic Hub—A case study in using virtual reality and AI as tools for urban planning and citizen engagement. In C. Stephanidis, M. Antona, S. Ntoa, & G. Salvendy (Eds.), *HCI International 2025 posters: 27th International Conference on Human-Computer Interaction, HCII 2025* (pp. 368–375). Springer Nature. https://doi.org/10.1007/978-3-031-94165-8_40

Raynor, K. E., Doyon, A., & Beer, T. (2017). Collaborative planning, transitions management and design thinking: Evaluating three participatory approaches to urban planning. *Australian Planner*, *54*(4), 215–224. https://doi.org/10.1080/07293682.2018.1477812

Schewenius, M., & Wallhagen, M. (2024). Virtual reality in planning, design, and management of urban green and blue infrastructure. *Frontiers in Virtual Reality*, *5*, Article 1432556. https://doi.org/10.3389/frvir.2024.1432556

Schneider, S., Salloum, M., Gundel, K., & Boos, A. (2022). Estimating time to contact in virtual reality: Does contrast matter? In N. L. Black, W. P. Neumann, & I. Noy (Eds.), *Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021)* (Vol. V, pp. 224–231). Springer. https://doi.org/10.1007/978-3-030-74614-8_27

Schrom-Feiertag, H., Regal, G., & Schrammel, J. (2019). Speed experience: Assessing the quality of vehicle speed perception in virtual environments. In *2019 Eleventh International Conference on Quality of Multimedia Experience (QoMEX)* (pp. 1–3). IEEE. https://doi.org/10.1109/QoMEX.2019.8743224

Schrom-Feiertag, H., Stubenschrott, M., Regal, G., Matyus, T., & Seer, S. (2020). An interactive and responsive virtual reality environment for participatory urban planning. In *Proceedings of the 11th Annual Symposium on Simulation for Architecture and Urban Design (SimAUD 2020)* (Article 43). Society for Computer Simulation International.

Schwarzkopf, M., Dettmann, A., & Bullinger, A. C. (2024). What turns a bicycle street into a street for cyclists? A multimodal study on subjective safety of infrastructure measures on bicycle streets using an approach in virtual reality. *Traffic Safety Research*, *7*, Article e000066. https://doi.org/10.55329/cmdy6439

Schwarzkopf, M., Dettmann, A., Heinz, A., Miethe, M., Hoffmann, H., & Bullinger, A. C. (2023). Let's use VR! A focus group study on challenges and opportunities for citizen participation in traffic planning. In H. Krömker (Ed.), *HCI in mobility, transport, and automotive systems: 5th International Conference, MobiTAS 2023, held as part of the 25th HCI International Conference, HCII 2023* (pp. 358–371). Springer Nature. https://doi.org/10.1007/978-3-031-35678-0_24

Schwebel, D. C., Johnston, A., & McClure, L. A. (2024). Children's ability to estimate approaching vehicle time-to-arrival following training in a virtual pedestrian environment. *Traffic Injury Prevention*, *25*(7), 919–924. https://doi.org/10.1080/15389588.2024.2352171

Shahi, S., Debnath, A. K., Birrell, S., Horan, B., Alatrash, S., & Payre, W. (2025). Pedestrians' perception of road crossing while interacting with automated vehicles: A virtual reality experiment. In *CHItaly '25: Proceedings of the 16th Biannual Conference of the Italian SIGCHI Chapter* (Article 41). Association for Computing Machinery. https://doi.org/10.1145/3750069.3750110

Shakibamanesh, A., Ghorbanian, M., Izadi, S., Riahi, A., & Zeifodini, P. (2024). Utilizing virtual reality in the participatory urban policy-making process: A step toward facilitating effective citizen engagement. *International Journal of Human Capital in Urban Management*, *10*(2), 371–390. https://doi.org/10.22034/IJHCUM.2025.02.12

Shariatpour, F., Behzadfar, M., & Jalilisadrabad, S. (2025). A socio-technical framework for urban digital twins: Tehran in a global comparison. *Sustainable Cities and Society*, *134*, Article 106905. https://doi.org/10.1016/j.scs.2025.106905

Shi, J., Wu, C., & Qian, X. (2020). The effects of multiple factors on elderly pedestrians' speed perception and stopping distance estimation of approaching vehicles. *Sustainability*, *12*(13), Article 5308. https://doi.org/10.3390/su12135308

Shrestha, P. P., & Maharjan, R. (2019). Effect of change orders on cost and schedule for small low-bid highway contracts. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *11*(4), Article 04519025. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000323

Simonofski, A., Johannessen, M. R., & Stendal, K. (2024). Extended reality for citizen participation: A conceptual framework, systematic review and research agenda. *Sustainable Cities and Society*, *113*, Article 105692. https://doi.org/10.1016/j.scs.2024.105692

Sobhani, A., Farooq, B., & Zhong, Z. (2017). Distracted pedestrians crossing behaviour: Application of immersive head mounted virtual reality. In *2017 IEEE 20th International Conference on Intelligent Transportation Systems (ITSC)* (pp. 1–6). IEEE. https://doi.org/10.1109/ITSC.2017.8317769

Srivastava, P., Rimzhim, A., Vijay, P., Singh, S., & Chandra, S. (2019). Desktop VR is better than non-ambulatory HMD VR for spatial learning. *Frontiers in Robotics and AI*, *6*, Article 50. https://doi.org/10.3389/frobt.2019.00050

Szczepańska, A., Kaźmierczak, R., & Myszkowska, M. (2021). Virtual reality as a tool for public consultations in spatial planning and management. *Energies*, *14*(19), Article 6046. https://doi.org/10.3390/en14196046

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., Moher, D., Peters, M. D. J., Horsley, T., Weeks, L., Hempel, S., Akl, E. A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M. G., Garritty, C., . . . Straus, S. E. (2018). PRISMA extension for scoping reviews (PRISMA-ScR): Checklist and explanation. *Annals of Internal Medicine*, *169*(7), 467–473. https://doi.org/10.7326/M18-0850

van der Horst, S., & Peeters, J. (2021). What's going ön?: An experiential approach to perspective taking in urban planning through virtual reality. In *TEI '21: Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Article 92). Association for Computing Machinery. https://doi.org/10.1145/3430524.3446068

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

van Leeuwen, J. P., Hermans, K., Quanjer, A. J., Jylhä, A., & Nijman, H. (2018). Using virtual reality to increase civic participation in designing public spaces. In R. Bouzas-Lorenzo & A. Cernadas Ramos (Eds.), *Proceedings of the 18th European Conference on Digital Government* (pp. 230–239). Academic Conferences and Publishing International.

von Brackel-Schmidt, C., Kučević, E., Leible, S., Simic, D., Gücük, G.-L., & Schmidt, F. N. (2024). Equipping participation formats with generative AI: A case study predicting the future of a metropolitan city in the year 2040. In F. F.-H. Nah & K. L. Siau (Eds.), *HCI in business, government and organizations: 11th International Conference, HCIBGO 2024, held as part of the 26th HCI International Conference, HCII 2024* (pp. 270–285). Springer Nature. https://doi.org/10.1007/978-3-031-61315-9_19

Wessels, M., Kröling, S., & Oberfeld, D. (2022). Audiovisual time-to-collision estimation for accelerating vehicles: The acoustic signature of electric vehicles impairs pedestrians' judgments. *Transportation Research Part F: Traffic Psychology and Behaviour*, *91*, 191–212. https://doi.org/10.1016/j.trf.2022.09.023

Wessels, M., & Oberfeld, D. (2024). A binary acceleration signal reduces overestimation in pedestrians' visual time-to-collision estimation for accelerating vehicles. *Heliyon*, *10*(6), Article e27483. https://doi.org/10.1016/j.heliyon.2024.e27483

Winters, M., Babul, S., Becker, H. J. E. H., Brubacher, J. R., Chipman, M., Cripton, P., Cusimano, M. D., Friedman, S. M., Harris, M. A., Hunte, G., Monro, M., Reynolds, C. C. O., Shen, H., & Teschke, K. (2012). Safe cycling: How do risk perceptions compare with observed risk? *Canadian Journal of Public Health*, *103*(S3), S42–S47. https://doi.org/10.1007/BF03403834

Wolf, M., Söbke, H., & Wehking, F. (2020). Mixed reality media-enabled public participation in urban planning. In T. Jung, M. C. Tom Dieck, & P. A. Rauschnabel (Eds.), *Augmented reality and virtual reality: Changing realities in a dynamic world* (pp. 125–138). Springer Nature. https://doi.org/10.1007/978-3-030-37869-1_11

Yao, G., Yuan, T., Rui, Y., Chen, W., Duan, Z., Sun, L., Si, X., Zhang, M., Chen, K., Zhu, Y., & Chen, Y. (2021). Research on the scale of pedestrian space in underground shopping streets based on VR experiment.

Journal of Asian Architecture and Building Engineering, *20*(2), 138–153. https://doi.org/10.1080/13467581.2020.1782215

Zhu, M., Graham, D. J., Zhang, N., Wang, Z., & Sze, N. N. (2025). Influences of weather on pedestrian safety perception at mid-block crossing: A CAVE-based study. *Accident Analysis & Prevention*, *215*, Article 107988. https://doi.org/10.1016/j.aap.2025.107988

Zhu, W., Guo, S., & Zhao, J. (2021). Planning participants' preferential differences under immersive virtual reality and conventional representations: An experiment of street renewal. *Environment and Planning B: Urban Analytics and City Science*, *48*(7), 1755–1769. https://doi.org/10.1177/2399808320942776

About the Authors

Adelina Berkemeier is a PhD student at the Chemnitz University of Technology, Chair for Ergonomics and Innovation, with a background in human factors. Her research focuses on human-centred approaches to urban environments, perception in mobility contexts, and immersive technologies for participatory planning and infrastructure-related decision-making.

Holger Hoffmann (Dr. habil.) is a researcher at Chemnitz University of Technology specialising in human-centred system design, with a focus on virtual reality, telepresence, and intelligent mobility. His work integrates human behaviour, technology, and ergonomics to improve participatory urban planning, remote collaboration, and safety-critical human–machine interactions.

Angelika C. Bullinger is a professor of ergonomics and innovation management at Chemnitz University of Technology. Her research focuses on human–technology–AI interaction in mobility, city planning, and robotics. She studies socio-technical systems and digital work, examining how humans interact with emerging technologies in complex environments.