Table S1. Keyword categories used in the search strategy.

Keyword category	Keywords
Citizen participation	citizen participation, public participation, participatory planning, civic engagement, digital participation, e-participation, public consultation, online citizen engagement
Immersive technologies	virtual reality, VR, immersive technology, 360 video, 360° video, spherical video, head-mounted display, HMD, digital twins
Planning context	urban planning, transport planning, traffic planning, infrastructure planning, mobility planning
Perception & experience	perception, perceived safety, risk perception, speed perception, perceived speed, time-to-arrival, TTC, presence, immersion, realism, ecological validity
Acceptance & evaluation	acceptance, trust, usability, user experience, legitimacy
Sustainability & critique	digital waste, techno-determinism, solutionism, carbon footprint, energy consumption, water use, resource exhaustion, data excess
Participation tools & frameworks	toolkit, participation framework, method toolbox, digital tools
Digital inequality & cognition	digital literacy, brain-junk, cognitive pollution, unevenness

Table S2. Complete set of search strings.

ID	Search strings
1	("citizen participation" OR "public participation" OR "participatory planning" OR "digital participation" OR "public consultation" OR "Civic Engagement") AND ("virtual reality" OR "VR" OR "immersive technology" OR "head-mounted display" OR "HMD" OR "360 video" OR "360° video") AND ("urban planning" OR "transport planning" OR "traffic planning" OR "Mobility Planning")
2	("citizen participation" OR "public participation" OR "participatory planning") AND ("virtual reality" OR "VR" OR "360 video" OR "360° video" OR "head-mounted display" OR "HMD") AND ("perception" OR "perceived safety" OR "risk perception" OR "speed perception" OR "perceived speed" OR "time-to-arrival" OR "TTC") AND ("traffic" OR "transport" OR "pedestrians" OR "street")
3	("citizen participation" OR "public participation" OR "civic engagement" OR "participatory planning" OR "digital participation" OR "e-participation") AND ("urban planning" OR "transport planning" OR "traffic planning" OR "infrastructure planning") AND ("acceptance" OR "user acceptance" OR "public acceptance" OR "trust" OR "legitimacy")
4	("Digital Participation" OR "E-Participation" OR "Online Citizen Engagement" OR "Toolkit" OR "Participation Framework" OR "Method Toolbox") AND ("Urban Planning" OR "Infrastructure Planning" OR "Traffic Planning" OR "Mobility Planning")

5	("pedestrian" OR "road user") AND ("virtual reality" OR "VR" OR "360 video" OR "spherical video" OR "head-mounted display") AND ("speed perception" OR "perceived speed" OR "risk perception" OR "perceived safety" OR "time-to-arrival" OR "TTC")
6	("virtual reality" OR "360 video" OR "immersive media" OR "head-mounted display" OR "HMD") AND ("immersion" OR "presence" OR "realism" OR "ecological validity") AND ("acceptance" OR "trust" OR "usability" OR "user experience") AND ("traffic" OR "transport" OR "pedestrian" OR "pedestrians" OR "street")
7	("virtual reality" OR "VR" OR "360 video" OR "360° video" OR "head-mounted display" OR "HMD") AND ("urban planning" OR "transport planning" OR "traffic planning" OR "infrastructure planning") AND ("citizen participation" OR "public participation") AND ("digital waste" OR "critique" OR "solutionism" OR "sustainability" OR "carbon footprint" OR "energy consumption" OR "resource exhaustion")
8	("digital participation" OR "citizen participation" OR "public participation" OR "participatory planning") AND ("immersive tools" OR "VR" OR "virtual reality") AND ("urban planning" OR "transport planning") AND ("digital waste" OR "techno-determinism" OR "data excess")
9	("citizen participation" OR "digital tools") AND "urban planning" AND ("digital literacy" OR "brain-junk" OR "cognitive pollution" OR "perception" OR "unevenness")
10	("virtual reality" OR "VR" OR "digital twins") AND ("urban planning" OR "citizen participation") AND ("carbon footprint" OR "energy consumption" OR "water use" OR "resource exhaustion" OR "sustainability")
11	("Virtual Reality" OR "digital participation") AND ("urban planning") AND ("digital waste" OR "critique" OR "solutionism" OR "sustainability")

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5 **Table S3.** Overview of Included Papers in the Scoping Review.

Title	Authors & Year	Tool/Technology	Participants/Sample	Setting	Study Design	Measures	Results
Exploring Simulation Sickness in Virtual Reality Pedestrian Scenarios: Effects of Gender, Exposure, and User Perceptions	Abu Selo et al., 2025	HTC VIVE Pro HMD with SteamVR Tracking 2.0; real-time head-tracking.	N = 145 (71% male); avg. age 24 years; multi-cultural.	Crosswalk and sidewalk (interaction with e-scooters/bikes) scenarios.	Experimental: Assessment of Simulator Sickness (SS) using the SSQ (Kennedy et al., 1993).	SS total score, subscales, perceived realism, perceived disengagement.	Females suffer significantly more from SS than males; longer exposure in sidewalk scenarios induced more nausea.
Demonstration of virtual reality simulation as a tool for understanding and evaluating pedestrian safety and perception at midblock crossings	Angulo et al., 2023	HTC Vive Pro Eye HMD with wireless adapter; Unity software.	N = 40 evaluable participants; avg. age 33.7 years.	1:1 replication of Water Street in Charlottesville based on site textures.	Comparative: Real-world video observation vs. controlled VR experiment.	Accepted gap size, crossing speed, subjective realism.	No significant differences in crossing speed; VR participants were more conservative in gap selection.
Can pedestrians safely navigate shared sidewalks with e-scooters and bicycles? A behavioral analysis using surrogate safety measures	Arshi et al., 2026	HTC VIVE Pro with Wireless Adapter and SteamVR; Unity3D.	N = 75 (52 male, 23 female); age 19–56; 16 nationalities.	Virtual urban space: local roads in Qatar (2.5m sidewalk width).	Controlled VR experiment: 18 scenarios (3 speeds x 3 positions x 2 vehicle types).	Objective: Post-Encroachment Time (PET), lateral distance; Subjective: Perceived safety and comfort.	Higher speeds lead to earlier avoidance and lower perceived safety; comfort levels drop significantly at 30 km/h.
The reality of virtual reality: A comparison of pedestrian behavior in real and virtual environments	Bhagavathula et al., 2018	HTC Vive HMD with Lighthouse sensors; Unity; 360° video.	N = 16 (11 male); age 18–35.	Virginia Smart Road (2.2 mile test track) vs. digital replication.	Repeated Measures: Participants go through three environments (Real, Unity, Video).	Perception: Risk and safety ratings (1–7 scale). Behaviour: Intention to cross (Yes/No). Presence: Composite Presence Rating.	No significant differences were found in terms of intention to cross, risk, safety and distance. However, speed was perceived to be significantly higher in VR than in reality.
The Feasibility of a Virtual Reality Hazard Perception and Gap Acceptance Task for Older Adults to Improve Pedestrian Safety	Carrigan et al., 2025	VivePro Eye HMD; IMU sensors for leg tracking.	N = 28 (14 younger, 14 older adults); snowball sampling.	Lab environment: 360° video material of real streets in Sydney/Melbourne.	Mixed-Method Feasibility Study: Performance data and feedback.	Hazard Perception (HP), Gap Acceptance (GA), SSQ scores.	Older adults react significantly slower during gap acceptance; protocol length induced high levels of fatigue.
Understanding how Time-to-Arrival and Vehicle Speed Influence Pedestrian Crossing Behavior at Unsignalized Intersections Through a Virtual Reality Experiment	De Oliveira et al., 2025	Meta Quest Pro HMD; built-in sensors for motion tracking (no external system required); software: Unreal Engine 5 (UE5).	N = 33 (final sample: 31 men, 2 women); average age 36.5 years; employees of ZF Friedrichshafen AG.	Single-lane urban road (3.5 m wide); realistic environment with trees, buildings and street furniture; walking area of max. 7 x 7 m.	Within-subject design: 12 scenarios combining 3 speeds (20, 30, 40 km/h) and 4 TTA intervals (3, 4, 5, 6 s).	Decision: Crossing Decision (Yes/No). Time metrics: Crossing Duration, Safety Margin, Time-to-Crossing Decision.	TTA is the dominant factor: Longer TTAs significantly increase the probability of crossing. Vehicle speed has a lesser effect on safety metrics.
Visual, auditory, and audiovisual time-to-collision estimation among participants with age-	DeLucia et al., 2025	HTC Vive Pro Eye HMD (110° FOV);	N = 50 older adults; 25 with age-related macular degeneration (IV	Virtual recreation of a flat rural landscape with a single-lane	Prediction-Motion-Task: 3 modality conditions.	Mean absolute error of TTC, intraindividual variability, cue weights.	Both groups use visual and auditory cues. The IV group relies more heavily on heuristics (distance, apparent size) than

related macular degeneration compared to a normal-vision group: The TTC-AMD study		Unity3D; TASCAR for 3D audio.	group), 25 with normal vision (NV group).	road; viewed from a pedestrian's perspective.			the NV group. No multimodal advantage (AV) was observed.
The Digital Twin Tackling Urban Challenges with Models, Spatial Analysis and Numerical Simulations in Immersive Virtual Environments	Dembski et al., 2019	5-sided CAVE; mobile VR; OpenCOVER software; COVISE.	N ~ 1,000 citizens of various ages and backgrounds.	City of Herrenberg (Germany); IMEP-2030 development.	Mixed-Method: Space Syntax, traffic and wind analysis simulations.	Quality of stay, legibility of the city, movement patterns.	VR perceived as more understandable than conventional tools; enabled deep understanding of planning consequences.
SPUR: Enhancing Cyclist Safety through Digital City Twins – A Data-Driven Infrastructure Planning and VR Simulation Approach	Disser & Rüppel, 2025	Unity Game Engine; SUMO simulation; VR setup with functional bike.	Expert interviews (Planners, Engineers).	Case studies in Munich and Darmstadt; pointclouds and LiDAR data.	Design-Science-Research: Developing "Planning Editors" for safety indicators.	Perceived safety (subjective); distances to obstacles.	SPUR enables planners to identify infrastructure vulnerabilities and test alternatives virtually.
Urban planning and metaverse technologies for sustainable cities: Reducing environmental footprints and enhancing social equity (A case study of Tehran, Iran)	Dorostkar & Ziari, 2025	Metaverse technologies; VR/AR integrated with GIS and AI.	N = 32 Stakeholders (Planners, experts, marginalized groups).	Tehran, Iran; focus on air pollution and social inequality.	Systematic Review (PRISMA), Expert Interviews, Focus Groups.	Environmental footprints (AQI), social equity, energy consumption.	Metaverse technologies improve public participation and data-driven insights for social equity.
Road crossing decisions in real and virtual environments: A comparative study on simulator validity	Feldstein & Dyszak, 2020	Oculus Rift DK2 HMD; Silab Traffic Simulation; Vicon MoCap.	N = 30 (19 male, 11 female); avg. age 21 years; students.	Garching Campus (TUM): 1:1 replication of a one-way street (4.4m).	Intra-subject design: comparison of reality vs. VR; step-back method (participant steps back if crossing appears unsafe); speeds: 30, 35, 40 km/h.	Time-to-Contact (TTC) at the moment of stepping back; spatial distance; influence of gender, height and order of exposure.	TTC in VR (2.06 s) was significantly (26%) lower than in reality (2.80 s). In reality, decisions are based on time (TTC), whereas in VR they are based on spatial distance.
Digital Participation Models as Public Engagement Tools in Planning: A Concept Exploration	Gower et al., 2023	Melbourne Digital City Model (MDCM); 3D model with interactive sliders.	N = 21 planning experts (national to local government).	Virtual Focus Groups; Australia.	Qualitative Content Analysis of transcripts.	Perceived effectiveness in communication, comprehension, and transparency.	DPMs improve understanding of trade-offs and reduce conflicts through visualization.
Virtual Reality for Home-Based Citizen Participation in Urban Planning – An Exploratory User Study	Guler et al., 2024	Meta Quest 2; Arkio app; customized building blocks.	N = 14 (Heterogeneous group; avg. age 41.4 years).	Private homes of participants; Wil, Switzerland (Bahnhofplatz).	Explorative User Study (5 steps: Intro, VR-Exploration, Feedback).	Overall impression, willingness to participate, usability.	Home-based VR is a cost-effective tool to lower barriers for public assembly participation.
Exploring Perceived Risk of Passing Sidewalk Mobility Using VR	Hori et al., 2025	Meta Quest 2 HMD; Unity 6000; dynamic POV adjustment.	N = 22 participants; varying VR experience.	2-meter wide virtual sidewalk; e-scooters, wheelchairs, and robots.	Within-subjects design: user-controlled interaction (speed adjustment in 1 km/h increments) rather than passive observation.	Critical speed, as well as five psychological constructs: physical threat, surprise, lack of control, norm violation, and violation of personal space.	Critical speed is significantly lower when overtaking than when meeting oncoming traffic. E-scooters are perceived as less dangerous but as a more serious violation of social norms.

Autonomous vehicles and street design: Exploring the role of medians in enhancing pedestrian street crossing safety using a virtual reality experiment	Joo et al., 2023	HTC Vive Pro HMD (4K); wireless setup.	N = 99 adults (20-30 years); 52.5% experts.	VR simulation of a two-lane urban street.	Experimental: 9 scenarios varying medians and platooning.	Perceived Safety (7-point Likert); Performance-based safety (Collisions).	Medians significantly reduce collisions, especially at high speeds (30 km/h) and small gaps.
Breaking out: New freedoms in urban (re)design work by adding immersive environments	Jutraž & Moine, 2016	Urban Redesign Terf (UR Terf): Immersive 3D walk-throughs.	Qualitative and quantitative pre-studies.	Virtual Lab / Virtual City: Connected spaces with user access.	Tool-Development & Case Study for urban (re)design.	Degree of freedom, immersion level, learning curve (15 min).	VR increases motivation and spatial understanding through avatar-based experiences.
Empowering Communities Through Gamified Urban Design Solutions	Kavouras et al., 2025	euPOLIS Game: Unreal Engine 5; Open GIS data.	N = 30 persons from diverse backgrounds.	Digital Twins of Piraeus, Łódź, Belgrade, and Gladsaxe.	Workshop-Evaluation: Feedback and Co-Creation modes.	User comfort metrics (Heat, CO_2, humidity), happiness, health.	Over 80% rated the tool as highly suitable for urban discussions; positive effects on user well-being.
Designing safer intersections: Exploring the impact of visual and auditory warnings on pedestrian behavior in a virtual simulated environment	Khademi et al., 2024	HTC Vive Pro Eye HMD (120 Hz eye-tracking); Unity-2019.	N = 245 (148 male); age 18–40; 67% with VR experience.	Virtual urban Tehran: two-lane intersections.	Experimental: 16 scenarios; SEM analysis.	Red-light violations, fixation rates (AOIs), risk awareness.	Laser-wall warnings significantly reduced violations; visual signals increase awareness more than auditory ones.
Quality Comparison of Dynamic Auditory Virtual-Reality Simulation Approaches of Approaching Vehicles Regarding Perceptual Behavior and Psychoacoustic Values	Krautwurm et al., 2025	Comparison of WFS and HOA audio systems.	N = 24 (18 male); age 19–61; normal hearing.	Recording of a real test track (Darmstadt) in a virtual lab.	Listening Test: Simulation vs. original test-track recordings.	Sharpness (S), Loudness (N); speed perception threshold.	High agreement between systems; EVs were perceived as faster than HOA recordings.
Pedestrians safety perception and crossing behaviors in narrow urban streets: An experimental study using immersive virtual reality technology	Kwon et al., 2022	HTC Vive Pro Eye HMD; Unity 5; SteamVR.	N = 200 students (avg. age 26.9); 44% female.	8-meter-wide residential street (narrow street); comparison between “shared space” (mixed traffic) and physically separated sidewalks.	VR experiment with 35 scenarios; variation of 6 attributes; analysis via Multi-level Structural Equation Model (MSEM).	Perception: accident probability, severity, unpleasantness Behavior: waiting time, reaction time, speed, gait analysis (gait variability).	Perceived risk moderates behavior; speed limits had no significant effect on safety perception.
Safety on the Line: Examining the impacts of crosswalk design on Child's perceived Safety, cautious Behavior, and visual attention with VR Technology	Lee et al., 2025	Oculus Quest 2 HMD; Backpack PC; Unity Engine.	N = 178 (89 parent-child pairs); children aged 8–12.	Virtual 1:1 replication of a Seoul school intersection.	Within-subject design: manipulation of speed (20/30 km/h), parked cars (0/1/2), and crosswalk design (zebra, scramble, decorative).	Perceived safety (7-point Likert), cautious behavior (attentive, preventive, adaptive), jaywalking rate, and visual occlusion via pixel analysis.	Younger children recognize dangers (parked cars) less well and do not adjust their behavior. Decorative zebra crossings reduce the feeling of safety and promote diagonal jaywalking.

Space Simulation and Environment Construction of Urban Public Facilities Based On VR Technology	Li et al., 2021	VR integration of graphics, language, and audio.	Public, city officials, and designers.	Community facilities (streets, squares, parks).	Experimental verification through participation experiments.	Time Cost; cognitive habits; psychology; information accuracy.	VR significantly shortens the design process (6 vs 19 units); improves departmental efficiency.
Improving the Pedestrian's Perceptions of Safety on Street Crossings. Psychological and Neurophysiological Effects of Traffic Lanes, Artificial Lighting, and Vegetation	Llinares et al., 2020	HTC Vive HMD; EEG system; Sennheiser HD 558.	N = 60; balanced gender; 9% > 65 years.	Virtual 1:1 replica of an intersection in Valencia, Spain.	VR Experiment: 16 scenarios (lanes, lighting, vegetation).	Dominance, Presence; EEG (C3-Highbeta, F4-Gamma).	Safety highest with fewer lanes and more vegetation; night scenarios were significantly more stressful.
Improving safe pedestrian behavior through virtual reality: an empirical study	López-Álvarez et al., 2024	Oculus Quest 2 HMD; Unity3D.	N = 43 students (avg. age 24.5 years).	Gym hall (414m²) for physical mobility while immersed.	2x2 Factorial: (1) accident vs no-accident, (2) debriefing.	Eye-tracking, red-light violations; Walking Behavior Questionnaire (WBQ).	VR accidents significantly reduced red-light crossing in post-measures; debriefing had no extra effect.
Understanding Pedestrian Cognition Workload in Traffic Environments Using Virtual Reality and Electroencephalography	Luque et al., 2024	Oculus Quest 2 HMD; wireless data transmission via Meta Quest Air Link; Brain Products wireless 32-channel EEG cap; LiveAmp amplifier.	N = 12 healthy adults (10 men, 2 women); average age: 25 years.	Obstacle-free area (8 m × 3.4 m); virtual replication of a typical Madrid street crossing.	Within-subject design with 4 tasks: (1) familiarization/rest, (2) TTA estimation, (3) oddball task (bimodal), (4) dual-task (oddball + crossing).	Neurophysiological: ERPs (P3 for attention, CNV for decision/preparation); Subjective: NASA-TLX (workload), SSQ (cybersickness), PQ (presence)	VR effectively mimics real cognitive load; P3 amplitude was higher in the dual-task than in the oddball task, indicating increased engagement during walking.
Determining the Effect of Alleyway Design on Perceived Safety Through Virtual Reality	Martinez et al., 2024	HTC-Vive-Cosmos HMD; SketchUp/Twinmotion workflow.	N = 112 university students; 64.29% female, 32.14% male; 91% aged 18–25.	Comparison: typical vs. designed urban alleyway.	Experimental: Comparing perceptions in two test environments.	Perceived Safety (Threat, fear), Design elements (Lighting, seating).	Designed environment increased perceived safety by 32%; lighting/planting were the most effective elements.
Analyzing Pedestrian Behavior in Augmented Reality - Proof of Concept	Maruhn et al., 2020	HTC-Vive-Pro with ZED-Mini stereo camera (AR).	N = 43 total (N=30 Real, N=13 AR).	Large university parking lot (450m campus road).	Between-subject design: comparison of an AR simulator with a real-world experiment (gap acceptance).	Gap acceptance rates (gap acceptance) and crossing initiation time (CIT).	Behavior in AR was similar to reality, but “shifted”: participants in AR were more conservative (higher/later CIT, lower acceptance rates).
Using Multi-Sensory and Multi-Dimensional Immersive Virtual Reality in Participatory Planning	Meenar & Kitson, 2020	4D Immersive VR (IVE); tactile/olfactory (Popcorn/Grass).	N = 40 (4 focus groups of 10 people).	Glassboro, New Jersey: 3-block section of the historic city center, fictitious scenario of an arts and entertainment district.	Comparative study (experimental): 2D video vs. 3D IVR vs. 4D IVR (audio + smell); use of mental maps and emotional mapping.	Number of comments/questions, number of remembered design elements (memory recall), positive/negative emotions	4D IVR increased engagement by up to 352% over 2D video; enhanced memory recall of planning details.
Advancing Online Road Safety Education: A Gamified Approach for Secondary School Students in Belgium	Nawaz et al., 2025	Route-2-School (R2S): VR, 360°, drone footage.	> 600 students (13–17 years); detailed survey for 212.	Schools and municipalities in Flanders, Belgium.	Mixed-Methods: Learning performance and survey.	Traffic knowledge, risk detection, risk management behavior.	VR received the most positive response; girls excelled in risk management, boys in detection.

Overestimated time-to-collision for quiet vehicles: Evidence from a study using a novel audiovisual virtual-reality system for traffic scenarios	Oberfeld et al., 2022	HTC Vive Pro HMD; 16 Genelec-speaker.	N = 28 (22 female, 6 male); avg. age 24 years.	1:1 replication of Eislebener Straße, Berlin (300m).	Prediction-motion-task: speed (10, 30, 50 km/h) x Loudness.	Time-to-Collision (TTC) estimates; Intensity-arrival effect.	Quieter vehicles lead to a significant overestimation of TTC; pedestrians use auditory heuristic.
Auditory and audiovisual time-to-collision estimation and road-crossing decisions	Oberfeld et al., 2024	HTC Vive Pro Eye (HMD) with Head-Tracking; synchronized with a 3D speaker array (40 Genelec speakers).	Various experiments (N=13 to N=30 per session).	Virtual reality simulations of passing vehicles (ICEV/EV).	Prediction-motion task (TTC-estimation); Street-crossing decisions (Gap Acceptance).	Estimated TTC; Collision probability.	EVs are perceived as farther/slower (longer TTC); ICEV engine sounds provide life-saving info.
A Qualitative Study on the Effects of Real-World Stimuli and Place Familiarity on Presence	Pouke et al., 2019	Oculus Rift CV1 with touch controllers; software: Unreal Engine 4.	N = 16 adults (11 men, 5 women); mixed passersby (12) and targeted recruitment (4).	On-site experiment: pedestrian zone in the city center of Oulu, Finland.	Qualitative primary study: experimental on-site setup with subsequent thematic, semi-structured interviews.	Subjective presence (place illusion), breaks in presence (BIPs), plausibility, usefulness for urban planning.	VR enables spatial expansion understanding; familiarity with the environment enhances the feeling of presence.
Assessing pedestrian safety across modalities via a simulated vehicle time-to-arrival task	Pugliese et al., 2020	High-Fidelity-Simulator.	N = 80 total (balanced Exp 1 and 2).	Virtual suburban environment: two-lane street.	Prediction-motion-task: vehicles vanish at 3, 5, or 7 seconds.	TTA estimation (deviation in meters/kph).	Visual-auditory modalities are significantly more accurate than visual-only; precision drops at 65 dB noise.
Preparing for the Metaverse: Civic Hub - A Case Study in Using Virtual Reality and AI as Tools for Urban Planning and Citizen Engagement	Rautanen et al., 2025	WebXR and Three.js framework; VR solution as a “mass app”; high-fidelity 3D models created via drone scanning and photogrammetry.	Involvement of citizens, city staff, and decision-makers; evaluation through user tests, surveys, and interviews.	Market square of Nykarleby, Finland; virtual design environment with practical elements (benches, trees, lighting).	Comparing VR vs. conventional co-design processes.	Transparency, inclusivity, data quality, complexity processing.	VR allows citizens to present their own solutions; complex data becomes comprehensive and accessible.
Virtual Reality in planning, design, and management of urban green and blue infrastructure	Schewenius & Wallhagen, 2024	Oculus Go HMDs; GoPro Fusion 360° camera (5K resolution); non-interactive 360° video.	N = 25 (12 experts from academia/planning, 13 design students); 10 women, 15 men.	Residential areas in Gävle, Sweden (Hemsta & Ulvsäter districts); focus on shared green spaces.	Exploratory qualitative experiment: inductive data analysis; questionnaires, observations, and interviews.	Themes: level of detail (27%), context (22%), emotions (20%), development potential (7%), immersion (24%).	VR improves understanding of nuances; participants identify details (e.g., tree species, materials) that are lost in 2D plans.
Estimating Time to Contact in Virtual Reality: Does Contrast Matter?	Schneider et al., 2022	Oculus Rift DK2; Unity3D.	N = 27 (12 female, 15 male); avg. age 24.3 years.	Virtual urban street; vehicles approaching observer.	Within-subject: Manipulation of speed (30-50) and contrast.	TTC relative error (%); Presence-Score; subjective effort.	Contrast reductions up to 25% have no significant effect; TTC generally overestimated by 6.1%.
Speed Experience: Assessing the Quality of Vehicle Speed Perception in Virtual Environments	Schrom-Feiertag et al., 2019	HTC Vive HMD; software: Unity 3D; control via Vive controllers.	N = 20 (10 men, 10 women); average age: 33.7 years; 75% with VR experience; 75% with a driver’s license.	Three scenarios: (1) empty room, (2) realistic street (left-to-right, right-to-left), (3) realistic street (right-to-left).	Participants estimate speeds (30, 50, 70 km/h) in random order.	Participants estimate speeds (30, 50, 70 km/h) in random order.	Systematic underestimation of speed across all scenarios; 70 km/h cars underestimated by up to 50 km/h.

An Interactive and Responsive Virtual Reality Environment for Participatory Urban Planning	Schrom-Feiertag et al., 2020	HTC Vive and HTC Vive Pro with room scaling; software: Unity Engine; synchronized with multimodal traffic simulation.	N = 59 (Aspern Seestadt N=30, Kapfenberg N=29).	Redesign of a square and a railway station in Austria.	Mixed-Methods: Gamification and storytelling evaluation.	UX (Fun, usability), presence, SS (nausea/orientation).	VR was perceived as very helpful and playful; no significant cybersickness; dynamic traffic rules significantly increased realism.
Let's Use VR! A Focus Group Study on Challenges and Opportunities for Citizen Participation in Traffic Planning	Schwarzkopf et al., 2023	HTC Vive HMD; VR application for evaluating subjective safety of cycling infrastructure using 360° images.	N = 7 experts in urban planning from Chemnitz.	Structured requirements workshop; cycling infrastructure.	Qualitative Requirements Analysis.	Barriers (resources, regulations); potentials (citizen engagement); requirements (simplicity, efficiency).	Planners see VR as an opportunity to make complex content (maps) accessible; biggest problem: citizens are often involved only in phase 5 (HOAI), when changes are already too expensive.
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	Schwarzkopf et al., 2024	VR headsets with integrated computing units (standalone); stereoscopic 360° images; self-developed VR app.	Study I: N = 182 (users of bicycle streets); Study II (VR): N = 32 (experienced and inexperienced cyclists, including non-users).	Bicycle street Reichenhainer Straße, Chemnitz; continuous motor vehicle traffic; real overtaking and hazard situations.	Multimodal approach: Online questionnaire vs. VR evaluation.	Subjective Safety (6-point Likert); Influence of width/curbs.	VR method is highly effective and representative; lane width/separation are key safety indicators for laypeople.
Children's ability to estimate approaching vehicle time-to-arrival following training in a virtual pedestrian environment	Schwebel et al., 2024	Comparison between kiosk VR (semi-immersive) and smartphone-based VR (fully immersive).	N = 500 children (7 and 8 years old); ethnically diverse; 51% male.	Virtual street crossing (midblock crossing) with traffic approaching from both directions.	Randomized controlled trial (RCT): multiple training sessions up to adult-level performance.	Time-to-arrival (TTA) estimation (deviation in seconds) for different speeds (25, 30, 35 km/h)	Children underestimate TTA by 3–4 seconds; VR training improved performance for 6 months.
Pedestrians' perception of road crossing while interacting with Automated Vehicles: A Virtual Reality experiment: Pedestrians' perception of road crossing while interacting with Automated Vehicles	Shahi et al., 2025	HTC VIVE Pro Eye HMD; Software: Unreal Engine.	N = 30 (15 women, 15 men); age groups 18–25 and 25–34 (40% in the 25–34 group).	7 m wide roadway; digital replication of the environment from the authors' research lab.	Longitudinal VR-Experiment: 2 sessions; 16 scenarios each (weather, distance, vehicle type, gradients).	Bespoke questionnaire (5 items): unreliability, unpleasant reaction, perceived danger for self and others.	Women feel 81.4% higher risk and 64.6% more danger than men; downhill interactions feel 62% more dangerous.
Distracted pedestrians crossing behaviour: Application of immersive head mounted virtual reality	Sobhani et al., 2017	Oculus Rift (headset and headphones) with Oculus Touch controllers (simulated as mobile phone) and three sensors.	N = 25 (after exclusion of 5 participants); 45% women; age 20–45; 65% without prior VR experience.	On-site replication: simulation of a private street (near Metro Laurier) in Montreal, based on real traffic data.	Within-subjects Design: three conditions (no distraction, distraction via labyrinth game on mobile phone, distraction + LED safety signal).	Waiting time, crossing time, speed, acceleration, time-to-collision (TTC), post-encroachment time (PET).	Distracted pedestrians made more unsafe decisions, waited longer at the curb (4.5–8%), and crossed the street more slowly (especially men); LED signals increased success rates.

Desktop VR Is Better Than Non-ambulatory HMD VR for Spatial Learning	Srivastava et al., 2019	Oculus Rift CV1 vs. Desktop (24-inch Monitor).	N = 40 (27 male); avg. age 22.6 years.	Virtual outdoor environment (1500 m × 2000 m) with 21 routes, 15 intersections, and 10 landmark objects.	Between-group design: comparison of desktop VR and non-ambulatory (seated) HMD VR.	Spatial memory (sketch maps): accuracy for street segments, intersections, object associations, cyclical order; exploration time; motion sickness; workload (NASA-TLX).	Desktop VR was superior in recalling junctions and cyclic order; HMD induced higher motion sickness.
Virtual reality as a tool for public consultations in spatial planning and management	Szczepańska et al., 2021	ArchitectVR App (Android); Google Cardboard.	N = 10 (5 female); background in design/planning.	Post-gravel pit site: Suwałki, Poland; leisure redevelopment.	Proof-of-Concept: mobile app development and interviews.	Item readability, proportions, intuitive understanding.	VR serves as a "common language"; participants understand plans better than verbal descriptions.
What's Going Ön?: An Experiential Approach to Perspective Taking in Urban Planning through Virtual Reality	van der Horst & Peeters, 2021	WebVR framework (A-Frame); use via browser on participants' own smartphones combined with low-cost HMDs such as Google Cardboard.	N = 8 experts in design/urban planning.	Stadt-Umeå, Sweden; focus on bridge redesign.	2-part VR experience: "The Gallery" vs. "Perspectives".	Creativity level, perspective taking, ambiguity, immersion.	VR stimulated creativity and promoted open-mindedness towards counter-plans; reduced emotional bias.
Effectiveness of virtual reality in participatory urban planning	van Leeuwen et al., 2018	Immersive VR headsets (smartphone-based), tablets, PCs, and 2D paper plans (baseline).	N = 1302 (Ballot); N = 76 (Lab study).	Park redesign Den Haag, Netherlands.	Mixed-Methods: Field study and laboratory measurement.	Engagement, Immersion, Memory Recall, Confidence.	VR offers significantly higher engagement and vivid recall; accuracy comparable to laptop use.
Using virtual reality to increase civic participation in designing public spaces	van Leeuwen et al., 2018	VR headsets (stereoscopic); smartphones; tablets; computers; comparison: 2D paper plans.	N = 1302 valid votes; Mariahoeve, Den Haag.	Neighborhood park in The Hague, Netherlands; redesign based on resident feedback.	Combined design: co-creation workshop (co-production) and public referendum (co-decision) via VR ballot.	Net Promoter Score (NPS) for measuring engagement; perceived safety of choice; perception of differences.	VR users showed significantly higher engagement than laptop users; VR helps better identify design differences compared to smartphones.
A binary acceleration signal reduces overestimation in pedestrians' visual time-to-collision estimation for accelerating vehicles	Wessels & Oberfeld, 2024	HTC Vive Pro HMD; laser head-tracking; Software: WorldViz Vizard 5.	N = 26 (18 women, 8 men); average age: 31.42 years; all with normal visual acuity.	VR traffic scenario: simulation of Eislebener Straße in Berlin (typical urban environment); perspective of a pedestrian at the curb.	Prediction-motion task: 2×2×2×4 factorial design (acceleration signal, acceleration rate, speed, TTC).	Mean estimated TTC (TTCest); estimation precision (intra-individual standard deviation).	Without signal, participants underestimated acceleration (TTC overestimation/error); the binary light signal (cyan) significantly reduced this dangerous bias.
Audiovisual time-to-collision estimation for accelerating vehicles: The acoustic signature of electric vehicles impairs pedestrians' judgments	Wessels et al., 2022	HTC Vive Pro HMD; sound via circular array of 16 loudspeakers (2D 7th-order Ambisonics).	N = 30 (25 women, 5 men); average age: 26.37 years; normal vision and hearing.	Virtual urban scene: replica of Eislebener Straße in Berlin; perspective of a pedestrian standing 50 cm from the curb.	Prediction-motion task: comparison of ICEV vs. EV (with/without AVAS) and EV (with AVAS) at constant speeds (10–50 km/h) and accelerations (0.6–8.2 m/s²).	TTC estimates (time interval between occlusion and manual response).	Massive overestimation of TTC for accelerating EVs (first-order error); AVAS reduces the error only slightly; ICEVs are estimated significantly more accurately.

Influences of weather on pedestrian safety perception at mid-block crossing: A CAVE-based study	M. Zhu et al., 2025	Immersive 4-screen CAVE; Shutter-glasses.	N = 50 adults (25 female); age 31.6 years.	Mid-block crossing replica: Hong Kong.	Causal Inference: Propensity-Score-Matching	Perceived Risk (10-point Likert); Gap acceptance (1-5s).	Risk perception increases significantly in rain/fog, especially at dusk; older/female participants are more risk-averse.
Planning participants' preferential differences under immersive virtual reality and conventional representations: An experiment of street renewal	W. Zhu et al., 2021	HTC Vive HMD; Shutter-glasses vs. 58-inch Monitor.	N = 48 students (20 female); non-design majors.	Street renewal project: Funan Street, Jiaxing, China.	Stated-Choice-Experiment (Mixed-Logit Model).	Time spent, preference reversals, decision mechanisms.	VR leads to more homogeneous decisions; time spent in VR (23.1 min) was 4x higher than conventional representation (4.7 min).

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