

DISSERTATION

USING VIRTUAL REALITY TO PROMOTE OUTDOOR WALKING ON A COLLEGE CAMPUS

Submitted by

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In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Summer 2026

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ABSTRACT

USING VIRTUAL REALITY TO PROMOTE OUTDOOR WALKING ON A COLLEGE CAMPUS

Walking carries many individual and community-level benefits, including physical and mental health effects, climate action, community building, and equitable transportation options. When designing for walkability, transportation planners are underserved by the traditional design process and have voiced a need for more rigorous research. Common research approaches into built environmental factors of walking struggle to address local context and causality. As a research method, virtual reality (VR) has the ability to provide this much-needed site-specific experimental data. The purpose of this dissertation is to use VR to pretest potential changes to the built environment on a college campus in order to promote safe walking. In two studies, this dissertation (1) assesses the feasibility and acceptability of a novel VR simulation and study protocol examining the effects of street modifications to a real-world university campus and (2) pretests two potential interventions under consideration by decisionmakers.

Study 1 details the development of a VR simulation depicting a 104,000 m² section of Colorado State University's (CSU) campus. Collaboration with CSU Transportation and the City of Fort Collins aided in identifying appropriate features to render in VR and in designing a study protocol which addresses safety concerns in the area. This protocol and the simulation are piloted in a feasibility and acceptability study (n = 21) following the guidelines of the CONSORT standards' extension to feasibility studies. The pilot study's objectives are to (1) detect issues

with the VR simulation and protocol and (2) monitor induction of cybersickness and presence. The pilot data met prespecified criteria for missingness, cybersickness, and presence but failed to pass the study duration criterion, indicating that efficacy study (Study 2) sessions should be scheduled for a longer duration. Pilot data revealed limited variability in behavioral measures and a strong possibility of learning and differential carryover effects confounding the investigated factors. Solutions to these unexpected issues are discussed in Study 1 and implemented in Study 2. Study 1 centers reproducibility by outlining a VR development workflow and study design recommendations for academic-governmental collaboration. Thus, Study 1 will support additional universities and municipalities interested in conducting similar research to efficiently alter their built environments to promote walking for transport.

Study 2 used this VR simulation to quantify the effects of two types of separated bike lane on pedestrians, a notable gap within active transportation literature. Specifically, this study investigates how perceptions of Alfonzo's four environment-related walking needs (accessibility, safety, comfort, & pleasurability), walking routes, and community opinion are affected by the City of Fort Collins and CSU Transportation's intervention options: (1) two new marked crosswalks and a separated bike lane created with flexible delineators and (2) two new marked crosswalks and a separated bike lane created with concrete barriers. To do so, 75 university students and employees who frequently visit the intervention area participated in a within-subjects protocol. Over 12 trials, they were asked to repeatedly cross a virtual campus street depicting the two interventions and the as-built conditions. At the end of each trial, participants self-reported their perceptions of walking needs. Multilevel structural equation modeling indicated that both interventions boosted perceived safety and comfort compared to the as-

built condition when accounting for control variables; however, the flexible delineator condition also enhanced perceptions of accessibility and pleasurability. Furthermore, the four assessed walking needs created a within-level latent variable, representing exposure-based audiovisual walkability perceptions, which provides additional support for Alfonzo's walking needs model. Both interventions resulted in higher values of the exposure-based audiovisual walkability perceptions variable. Based on multilevel logistic regression models, the contiguous concrete barrier condition resulted in the highest odds of using a marked crosswalk although the flexible delineator environment also showed improvement compared to the as-built condition. In a post-VR survey, participants showed an overwhelming preference for the flexible delineator environment, noting in free response items that it promoted safety while preserving a pleasant, open environment and allowing free movement of road users. Discrepancies between data collected in-VR and post-VR are discussed with reference to salience and recall bias. Thus, this study highlights the value of simulation-based research enabling real-time data collection in a controlled setting. This study progresses walkability research through reinforcing the influence of street-scale interventions and addressing a gap in the literature regarding a common type of safety countermeasure. Lastly, this dissertation provides an actionable recommendation to local decisionmakers based on site-specific causal evidence for the design of CSU's campus.

ACKNOWLEDGEMENTS

To my wonderful advisor, Dr. Dan Graham- Thank you very much for encouraging me to think big and guiding me through this complex research problem. Reflecting on my time at CSU, I have grown extensively as a researcher over the last five years, and your positive mentorship, multifaceted expertise, and unwavering support has been central to this growth.

To my committee members- Thank you very much for sharing your multidisciplinary expertise with me. Your counsel has enriched this project and helped me to develop as a scholar. Dr. Francisco Ortega- Thank you for your collaboration over the years and your support of my education in mixed reality. Dr. Mark Prince- Thank you for generously giving your time to mentor me through the SEM analyses in this dissertation. Dr. Niccole Nelson- Thank you for your advice on navigating academia and for always having words of encouragement. Dr. Laura Malinin- Thank you for your mentorship over my five years at CSU, which has greatly shaped my multidisciplinary approach.

To my collaborators, Rachel Ruhlen, Jamie Gaskill, and Aaron Fodge- Thank you for championing this project. When I began my graduate work, my goal was to complete applied research that would directly inform the design of the real world. Through your partnership and support, this dissertation fulfills this goal.

To Donna and Ginger- Thank you for troubleshooting countless roadblocks with me. You have been an incredible source of wisdom, mentorship, and support throughout my time at CSU.

To Aashay- For every “I’m in your corner,” “I’m proud of you,” and “All sides;” for every Caamp song that made me smile in the process of this dissertation; for every weekend and night you spent in the lab with me debugging code; for every weekend and night you made sure I got away from it all and took a breath; for every time I thought I couldn’t do this, saw our picture, and was reminded that you *knew* I could; thank you.

To Queen Palm, who sat next to me while I wrote this entire dissertation- Thank you for grounding me in the present, checking on me in hard moments, taking me out into the sun, and reminding me to play.

To Mom- Thank you for picking up the phone multiple times a day over my entire higher education career, flying out to care for me when I needed you, and even being in the lab with me late into the night the eve of Study 2 data collection.

To Mom and Dad- Thank you for instilling values of perseverance, integrity, initiative, and curiosity in us. You taught us the value of education and critical thinking as well as the responsibility to apply our skills to make a difference. I hope with this dissertation, I have made CSU’s campus a little bit safer. I love you.

DEDICATION

To Dr. Monica Spitzer Chisholm and Dr. Courtney Spitzer

My heroines

I cannot describe the inspiration and strength I draw from you.

Thank you for being the most supportive and loving big sisters.

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STUDY 1: APPLYING VIRTUAL REALITY AND CROSS-SECTOR COLLABORATION TO COLLECT SITE-SPECIFIC EVIDENCE FOR WALKABILITY INTERVENTIONS: A PILOT STUDY AND GUIDELINES

Contemporary urban design discourse strives toward walkability for its individual and community-level benefits. As a form of physical activity, walking reduces an individual's risk of multiple noncommunicable diseases listed on the top ten leading causes of death in the US (Murphy et al., 2024), including cardiovascular disease (#1) (Arnett et al., 2019; Tian & Meng, 2019), numerous cancers (#2) (Friedenreich et al., 2021; Mctiernan et al., 2019; Rezende et al., 2018), and type 2 diabetes (#8) (Cleven et al., 2020). Walking is also connected to a lower risk for (Firth et al., 2020) and fewer symptoms of anxiety and depression (Z. Xu et al., 2024). In the absence of pathology, walking behavior correlates with wellbeing (Kelly et al., 2018; Singleton, 2019), and walking for transport, specifically, is related to positive affect (Scrivano et al., 2024; Singleton, 2019). At the community level, walking is linked to subcategories of social capital, such as community action (Stroope, 2021). It also may lead to increased stewardship of a neighborhood by prompting a sense of belonging (Soni & Soni, 2016).

Promoting active transportation is a form of climate action. Greater than a quarter of the US's total greenhouse gas emissions originates from transportation, half of which is released by passenger cars, SUVs, and light-duty trucks (U.S. Environmental Protection Agency Office of Transportation and Air Quality, 2024). Creating neighborhoods that facilitate active commuting can attenuate the transport-related use of fossil fuels and greenhouse gas emissions (Alessio et al., 2021; Hinckson et al., 2026). Furthermore, designing communities such that residents can access needed resources (e.g., groceries) without personal vehicles is a form of equitable design

(Arellana et al., 2021; Rojas-Rueda et al., 2024). Specifically, walkable neighborhoods enable a form of transportation in which equipment and specialized skills are not needed.

Literature review

When tasked with investing budgeted funds in interventions that will promote walkable environments, design practitioners (e.g., urban planners, transportation planners) are underserved by the traditional design process, which prioritizes motor vehicles (Global Designing Cities Initiative & National Association of City Transportation Officials, 2016). Furthermore, Marshall (2024) contends that the current process for traffic design is primarily based on historic precedents and faulty outdated metrics. Indeed, design professionals have voiced a need for more rigorous research into the pedestrian experience (Bozovic et al., 2021). Keil and colleagues (2023) states that current urban design practices elicit verbal user input (e.g., town halls), but practitioners should collect and incorporate *behavioral* data. When transportation planners search for scientific research to inform their practice, they find study designs that cannot address their core question, which centers around causality (i.e., “Which of the available interventions will cause additional and/or safer walking in a specific location?”). In built environmental research such as that examining the impact of street design, study designs that support causal claims have been challenging (Ghanbari et al., 2024; Spitzer & Graham, 2025). For example, researchers cannot randomly assign participants to live in identical neighborhoods save for a manipulated variable. Consequently, walkability researchers have settled for correlational designs and natural experiments, both of which advance understanding of where people choose to walk but cannot provide robust causal evidence for how to encourage people to walk.

Recent correlational research quantified associations of walking with street-level greenness (Cao et al., 2022; Chandrabose et al., 2024; Koo et al., 2022; Pontin et al., 2022; C. Yang et al., 2022), availability of public transportation (Peng et al., 2024; C. Yang et al., 2022; L. Yang et al., 2022), land use (Suminski et al., 2023; C. Yang et al., 2022; L. Yang et al., 2022; Yin et al., 2023), density (Pontin et al., 2022; X. Wang et al., 2022; C. Yang et al., 2022), active transportation infrastructure (e.g., multiuse paths) (Pontin et al., 2022), and this infrastructure's quality (Cao et al., 2022; Peng et al., 2024). Yet, correlational studies can struggle to eliminate confounds, such as regular walkers self-selecting into walkable neighborhoods. On the other hand, many natural experiments compare behavior in an environment before an intervention with that after the intervention has been implemented. In reviewing natural experiments concerning multiuse paths, Fast and others (2025) concluded that regions generally see an increase in active transportation after the creation of new trails. Similarly, boosts in physical activity are commonly observed after active transportation infrastructural improvements and park renovations (Y. Zhang et al., 2022). Natural experiments are also an important source of evidence regarding whether a given intervention was effective, such as whether a new park boosted walking (Anderson et al., 2024). Still, they are limited by the suboptimal selection of comparison environments (Sun et al., 2023).

In addition to challenges with causal inferences, correlational and natural experimental research can be difficult to apply to a specific location. Both social ecological models of behavior (Sallis et al., 2008) and transportation planning principles (U.S. Department of Transportation Federal Highway Administration, 2007) emphasize that local factors, including culture, policies, and existing infrastructure, can modify the effectiveness of new interventions. The context

within which a transportation planner is working may not match with the specific characteristics of existing literature. Some researchers adjust for this location effect within their own results by collecting data across regions and controlling for factors of local context within analyses (i.e., location, neighborhood socioeconomic status) (Brakenridge et al., 2025; Cerin et al., 2022; Chandrabose et al., 2024; Suminski et al., 2023). Still, the root query of transportation planners involves predicting how potential interventions will perform within a specific local context, not how interventions perform controlling for context. Thus, to progress the effort to design healthy, connected, and sustainable cities, it is vital to develop new approaches to proactively identify which built environmental interventions are most effective at promoting safe walking when applied to a given context.

Virtual reality (VR), an assortment of immersive technologies that surround users with a simulated world, has the ability to provide this much-needed site-specific scientific data (Newman et al., 2022; C. Wang et al., 2024). Through exposing individuals into potential futures via VR, research teams can predict the effects of interventions in a specific location and community. Confounding variables, such as weather and traffic variability, can be standardized so that the direct causal effect of the potential interventions can be more clearly observed. Furthermore, VR can be employed to collect data regarding unsafe pedestrian behaviors such as crossing a street without a marked crossing (Mukoya et al., 2024).

Limited research has used VR to investigate how the built environment alters walking (Ghanbari et al., 2024; Spitzer & Graham, 2025). Some studies have harnessed VR to examine conceptual models and advance walkability theories (Facchini et al., 2025; Silvennoinen et al., 2022). More commonly, VR has also been employed in applied research, comparing street

design options. The influence of sidewalk width (Facchini et al., 2025; Hori et al., 2024; Park & Kwon, 2023) and added greenery (Batistatou et al., 2022; Birenboim et al., 2021; Facchini et al., 2025; Ghanbari et al., 2024; Park & Kwon, 2023) on pedestrians are frequently tested in VR. Several researchers have examined pedestrian responses to unconventional street designs (Sim & Cho, 2025; Vo & Kim, 2024), such as shared streets (H. Lee & Kim, 2021; L. Xu et al., 2022). In fact, several studies have measured pedestrian crossing behavior in the context of shared streets (Argota Sánchez-Vaquerizo et al., 2024; Kwon et al., 2022). VR research into crossing decisions has frequently investigated visibility obstructions (Kwon et al., 2022; Llinares et al., 2020; Luu et al., 2022), and crosswalk design (Argota Sánchez-Vaquerizo et al., 2024; C. Lee et al., 2025; Luu et al., 2022). Lastly, VR offers a controlled paradigm to study environmental influences on pedestrian wayfinding, the act of planning and executing a route to a specified location (Chen et al., 2023).

Of course, this research must be contextualized within the absolute and relative similarity among responses to environments rendered through VR, those depicted through other 2D media, and those experienced in the real world. Existing research indicates that many psychological, physiological, and behavioral responses can be simulated relatively well in VR although they are not identical to behavior in the real world. For example, VR can elicit realistic physiological and psychological fear responses (Baldini et al., 2022; Leichtweiß & Yigitbas, 2024). Relatedly, pedestrians estimate the risk of crossing a virtual street comparably to the same street in real life (Bhagavathula et al., 2020). Despite this, literature indicates that individuals alter aspects of their gait in VR (Renaux et al., 2022), such as cadence and duration of the walking phase on two feet, reflecting apprehension (Mason et al., 2023). The size of these gait

modifications has been linked to experience in VR (Nasiri et al., 2022) and are not observed in all studies (Palmisano et al., 2022). Furthermore, individuals display more cautious street-crossing behavior in VR than in real life, such as observing traffic longer before attempting to cross; however, research is unclear whether individuals select similarly-sized gaps in traffic as in the real world when they choose to cross (Angulo et al., 2023; Schneider et al., 2022).

Like much research into the similarity of real-world responses and those simulated in VR, research is mixed regarding walking decisions and walking intensity. Walking intensity based on heart rate has been shown to both be similar and lower in VR depending on the selected metric (Spitzer et al., 2025). Accelerometry data indicates that individuals choose to walk at a lower intensity in VR than in the real world (Spitzer et al., 2025), which aligns with the observed cautious alterations to gait (Mason et al., 2023). Research comparing self-selected walking duration in real-world and VR environments observes that these can match under particular circumstances but also reports discrepancies based on the order in which the environments are experienced (Spitzer et al., 2025, 2026). These results may be influenced by extraneous factors such as participant fatigue and the previously mentioned differences in walking mechanics (Mason et al., 2023). Generally, wayfinding behavior is similar in VR and the real world (Dong et al., 2022).

Regarding perceptions, virtual environments are judged to be similarly relaxed (Spitzer et al., 2025), pleasant (Spitzer et al., 2025), and beautiful (Shi et al., 2020) compared to their real-life counterparts. Still, perceptions of spaciousness (Nishio & Ito, 2020; Spitzer et al., 2025) and broadness (Nishio & Ito, 2020) differ, which is in accordance with research indicating distance is underestimated in VR (Creem-Regehr et al., 2023). Despite these differences, individuals rate

their motivation to walk as equivalent in real spaces and virtual replicas (Spitzer et al., 2025). Most importantly, environmental perceptions and affective responses based on VR exposures are more realistic than those elicited from 2D representations (Higuera-Trujillo et al., 2017; Newman et al., 2022).

The high heterogeneity of results regarding the degree to which responses in VR match those of the real world may be explained by the wide diversity of technologies encompassed by VR. VR approaches vary in many key features, such as hardware (e.g., head-mounted display (HMD) vs. CAVE system), traveling techniques (e.g., overground/real walking, omnidirectional treadmills, joysticks), rendering speed (i.e., frames per second), latency (i.e., delay between user input and simulation response), and visual realism (e.g., stylized vs. photorealistic). Namely, each of the previously mentioned VR features can influence the experience of presence (Buttussi & Chittaro, 2018; Mayor et al., 2021; Newman et al., 2022), defined as the sense of “being there” (Heeter, 1992, p. 262), and cybersickness (Ang & Quarles, 2023; Caserman et al., 2021; Mayor et al., 2021), which describes the motion sickness-like symptoms that can accompany VR exposure (Jerald, 2015). Immersive technologies’ ability to induce presence is one of their primary benefits as research methods (Felton & Jackson, 2022). Rather than imagining being in a street setting based on a 2D image, which can lead to biased predictions of traffic safety (Fitch & Handy, 2018), participants immersed in VR can judge while feeling as though they are really in the depicted environment. Unfortunately, the current generation of immersive technology carries varying risk of cybersickness. The mechanism by which these symptoms occur is debated with theories spanning from the conflict between proprioceptive and visual stimuli to the disparity between the simulated distance from the eye to a virtual

object and the actual distance to the pixels rendering that object (Caserman et al., 2021). Regardless of origin, cybersickness risk should be minimized both due to ethical reasons and because cybersickness is negatively correlated with performance on study tasks (Weech et al., 2019). Thus, VR is a viable approach to address the identified gaps present in walkability discourse, but researchers and practitioners should be aware of its limitations. Because of the diversity of VR technologies and their induced levels of presence and cybersickness, it is valuable to test a particular VR use case before it is employed in a large-scale study.

A pilot study appraises the ability and utility of executing a study protocol by performing a scaled-down version of the proposed study (Eldridge, Lancaster, et al., 2016). Data collection for environmental exposures in VR can be challenging and fraught with unexpected errors (Birenboim et al., 2021). A pilot study can assess the feasibility of a large-scale data collection effort and identify unexpected problems (Viechtbauer et al., 2015), such as these simulation errors. Indeed, there are several examples of pilot studies testing a VR protocol for identification of built environmental features affecting physical activity (Birenboim et al., 2021; Guo et al., 2022; Oselinsky et al., 2023; Ramirez Juarez et al., 2023; Ullmann et al., 2020).

The current pilot study assesses the feasibility and acceptability of a study protocol using a novel VR simulation. Aligned with Spitzer and Graham's (2025) call for researchers to collaborate with local decisionmakers to advance applied VR walkability research, the study protocol tested in the current investigation was developed with input from local municipal transportation planners. Through cross-sector collaboration, this research project pretests two potential interventions and provides site-specific data to be used to *directly and immediately* inform the design of a real built environment to promote safe walking. Namely, this work was

completed in partnership with the City of Fort Collins and Colorado State University (CSU) Transportation to examine options for an intervention along Lake St, a city-owned street through CSU's campus. Following the extension of CONSORT's guidelines to feasibility trials (Eldridge, Chan, et al., 2016), specific objectives for the current pilot study have been formulated:

Feasibility objective: To detect issues with the VR simulation and protocol.

Acceptability objective: To monitor induction of cybersickness and presence.

Feasibility and acceptability criteria

As outlined by the pilot studies extension of CONSORT 2010's statement (Eldridge, Chan, et al., 2016), criteria for feasibility and acceptability were prespecified. This statement clarified that failing to meet prespecified criteria does not necessarily signal that a larger trial is infeasible, but that changes to the protocol are necessary. The CONSORT extension recommended a "stoplight" approach: If observed measures fall between a target threshold (i.e., a green light) and a lower threshold indicating infeasibility (red light), efficacy studies can proceed with proper protocol adjustments (yellow light).

Following Bennett's (2001) guideline that $\geq 10\%$ missing data can result in biased statistical models, a study completion criterion was formulated: $> 90\%$ of participants will complete all study protocols within 1 hour. For this criterion, there was no lower threshold: If the target threshold was not met, sessions for subsequent studies would be lengthened to an appropriate duration estimated using the present data. A missingness criterion adhered to the same guideline: $< 10\%$ of study sessions will result in unusable primary outcome data due to VR

simulation errors. A lower threshold was set at $< 30\%$. The primary outcomes for the future efficacy study are environmental judgements reported at the culmination of each trial.

Specifying acceptability criteria involved identifying published thresholds for the employed measures of cybersickness and presence. The VR Neuroscience Questionnaire (VRNQ, Kourtesis et al., 2019) outlines cutoffs for usability, in which higher scores indicate greater usability even for the domain measuring cybersickness. Thus, the target threshold for the present investigation was set at the upper cutoff of the VRNQ's scale (median ≥ 30) and the lower threshold set at the minimum cutoff (≥ 25). Concerning presence, Melo et al. (2023) created a grading scale for the survey utilized in this study (igroup Presence Questionnaire [IPQ], Schubert et al., 2001). An "acceptable" grade was applied at mean scores ≥ 3.86 , the current study's target threshold (Melo et al., 2023). "Marginally-acceptable" described scores between this upper cutoff and ≥ 3.47 , selected as the lower threshold of this study. "Not acceptable" or failing grades were applied below this cutoff.

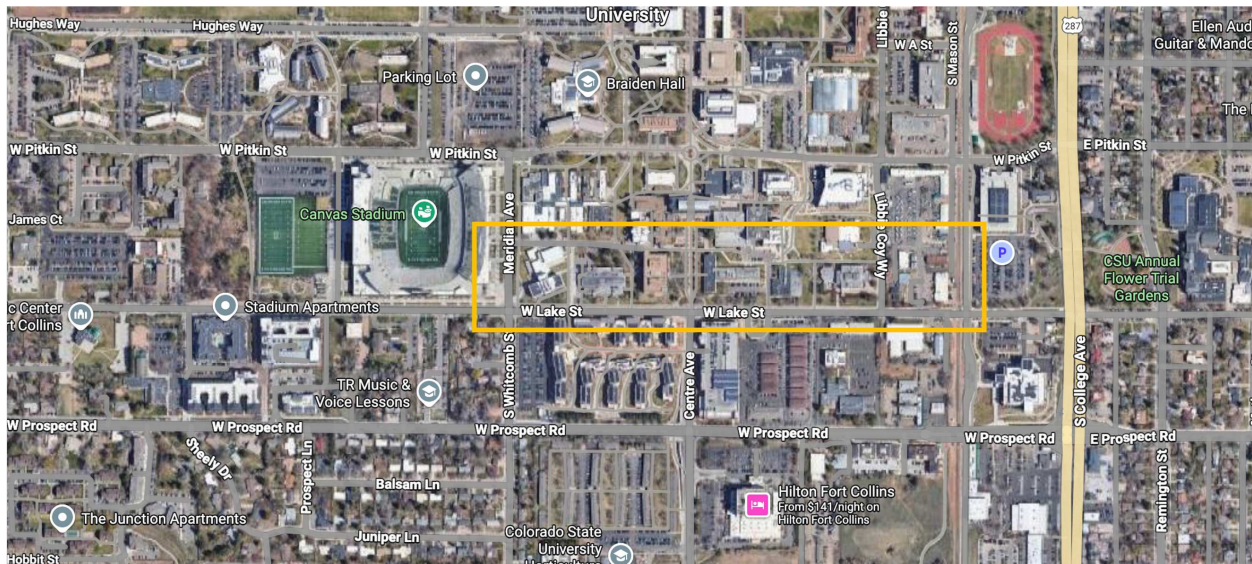
STUDY 1 METHOD

VR simulation

The simulation employed in this study depicts the 104,000 m² intervention area (Figure 1), complete with buildings, cross streets, sidewalks, signage, street furniture, and greenery to match the real environment. The simulation was highly immersive with HMD tracking providing 6 degrees of freedom (6 DoF) (LaViola et al., 2017), meaning the simulation was responsive to the HMD's rotational movement around the X, Y, and Z axes (+3 DoF) and its translational movement along these axes (+3 DoF). I independently developed this simulation following the workflow presented in Figure 2.

Figure 1

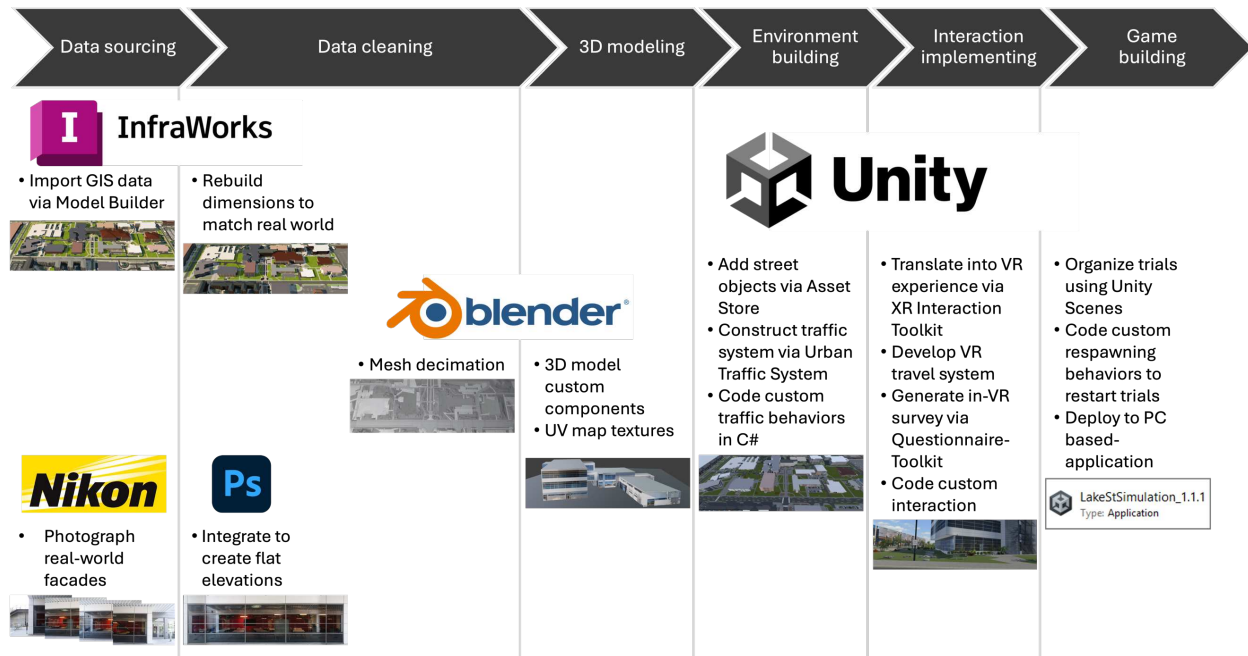
Map of intervention area



Note. Gold rectangle represents VR simulation boundary. Satellite image limits denote boundary originally built using Autodesk InfraWorks Model Builder (2024).

Figure 2

VR simulation development workflow



Data sourcing

Ground and building geometries. The Model Builder feature of Autodesk InfraWorks (Version 24.1.3.129, 2024) was used to import OpenStreetMaps GIS data (n.d.) containing street and building geometries and transform the GIS data into meshes (i.e., 3D models). The ground geometries created by Model Builder incorporated topography data at a resolution of 10 m from the National Elevation Dataset (U.S. Geological Survey, 2024). The building geometries are modeled using building footprint, roof style (e.g., pitched or flat), and approximate building height data from OpenStreetMaps (n.d.). The Model Builder feature also applies default textures to building facades. Although the boundary of the navigable simulation was set at 104,000 m², the area imported via Model Builder was much larger (1,572,000 m²) so that the

simulation displayed context around the intervention area. This protects against VR users discovering the edge of the simulated environment. As additional meshes can greatly increase the required processing power and reduce simulation performance (e.g., stuttering frames) (Singh et al., 2022), I deleted context geometries occluded from vantage points in the navigable intervention area.

Building facades. Using a Nikon DSLR camera (Model 5600), I captured high-resolution photographs of the existing building exteriors within the intervention area.

Data cleaning and 3D modeling

Ground geometries. Meshes representing the ground plane within the 104,000 m² intervention area were rebuilt to better match the real-world dimensions by using photographs of the real environment and Google Maps satellite data. Notable features of the virtual street that were altered to match the real world include curbs, curb cuts, lane delineation, mixed use and pedestrian paths, and sidewalks.

Once rebuilt, the mesh geometries were imported into Blender (Version 4.4.0, 2025), where they underwent mesh decimation, which reduces the complexity of the meshes, to improve simulation performance (Singh et al., 2022). I manually 3D-modeled the intersection in which a railroad crosses Lake St in Blender to match Google Street View because InfraWorks's default solutions for this intersection did not match the real-world conditions. Any other areas that were inaccurate to real life, such as certain street grading regions, were manually remodeled. Micro-scale topography, such as bumps and divots in softscape (e.g., grass) were modeled using the "sculpt" tools of Blender. Next, I completed "UV-mapping." Named after the letters used to denote the axes of an image texture, UV-mapping is the process of aligning 3D

mesh vertices with locations on flat textures, ensuring that materials will be applied in the correct locations and scales (Flavell, 2010).

Buildings. Similar to the treatment of ground geometries, InfraWorks buildings were imported into Blender, and their meshes were decimated. The approximate heights of buildings within the simulation boundary were checked and adjusted, if necessary. In Adobe Photoshop (Version 25, 2024), I edited the high-resolution photographs of building exteriors into elevations (i.e., flat projections of building facades). In Blender, I aligned the resulting elevations onto their respective buildings via UV-mapping. There were several notable buildings that were not within the necessary boundaries to warrant this long process of creating custom facades. Still, these buildings were salient; consequently, I UV-mapped them with one of the other custom elevations which was similar to the notable building's design. For example, a parking garage located outside the boundary, but in clear view of the user was UV-mapped with elevations of the parking garage located within the boundary. Remaining buildings retained the default textures applied by InfraWorks.

Environment building

Ground and building materials. The building and ground geometries were imported into Unity Game Engine (Version 6000.1, 2025a). Using packages from the Unity Asset Store listed in Appendix A, I applied materials representing multiple textures of grass, asphalt, pavement, gravel, and dirt to the ground geometries in locations matching the real world.

Street-scale elements. In Unity, street-scale elements including signage, street furniture, fences, and parked bikes/vehicles were added in their real-world locations based on satellite data, real-world photographs, and Google Street View. Basic components for these elements

were downloaded via the Unity Asset Store through packages listed in Appendix A. As needed, I generated custom components by altering the downloaded components, such as railroad crossing barriers developed from generic road barriers. Notably, custom street and building signage was created to help participants navigate in the virtual environment (Figure 3). In addition to the landmarks created by realistic building facades, signage can help facilitate wayfinding through computer-generated interfaces (LaViola et al., 2017).

Figure 3

Examples of custom signage aiding in wayfinding



Greenery. The “Nature Starter Kit 2” package (Shapes, 2016) was used to create bushes and trees each with several small, medium, and large variations within Unity Game Engine. The geometries of the variations were imported into Blender and decimated to create three level-of-detail (LOD) versions for each greenery element, which were subsequently imported back into Unity. LOD settings render the highest-definition version of an object (called LOD0) when the VR user is close to the object. Lower-definition versions (called LOD1, LOD2...) are rendered when the object is in the distance. Because this practice minimizes the total complexity of the

rendered meshes, it conserves processing power and improves performance (Singh et al., 2022). When the highest resolution of a tree was presented (LOD0), it swayed softly as if a breeze was blowing. Additionally, the hue and saturation of the downloaded greenery was altered to be more realistic and varied. Using satellite Google Maps data, real-world photographs, and Google Street View, I placed the updated trees and bushes into the virtual environment in the appropriate areas based on size.

The real-world area also features several prominent pine trees which were added separately from the “Foliage Pack Free” package (Sullivan, 2017). The simulation featured spatial audio, and bird song played from pine trees. I placed flowers (with two LOD versions) and additional bushes (either with four LOD versions or no LOD settings) in locations matching the real world using additional packages named in Appendix A.

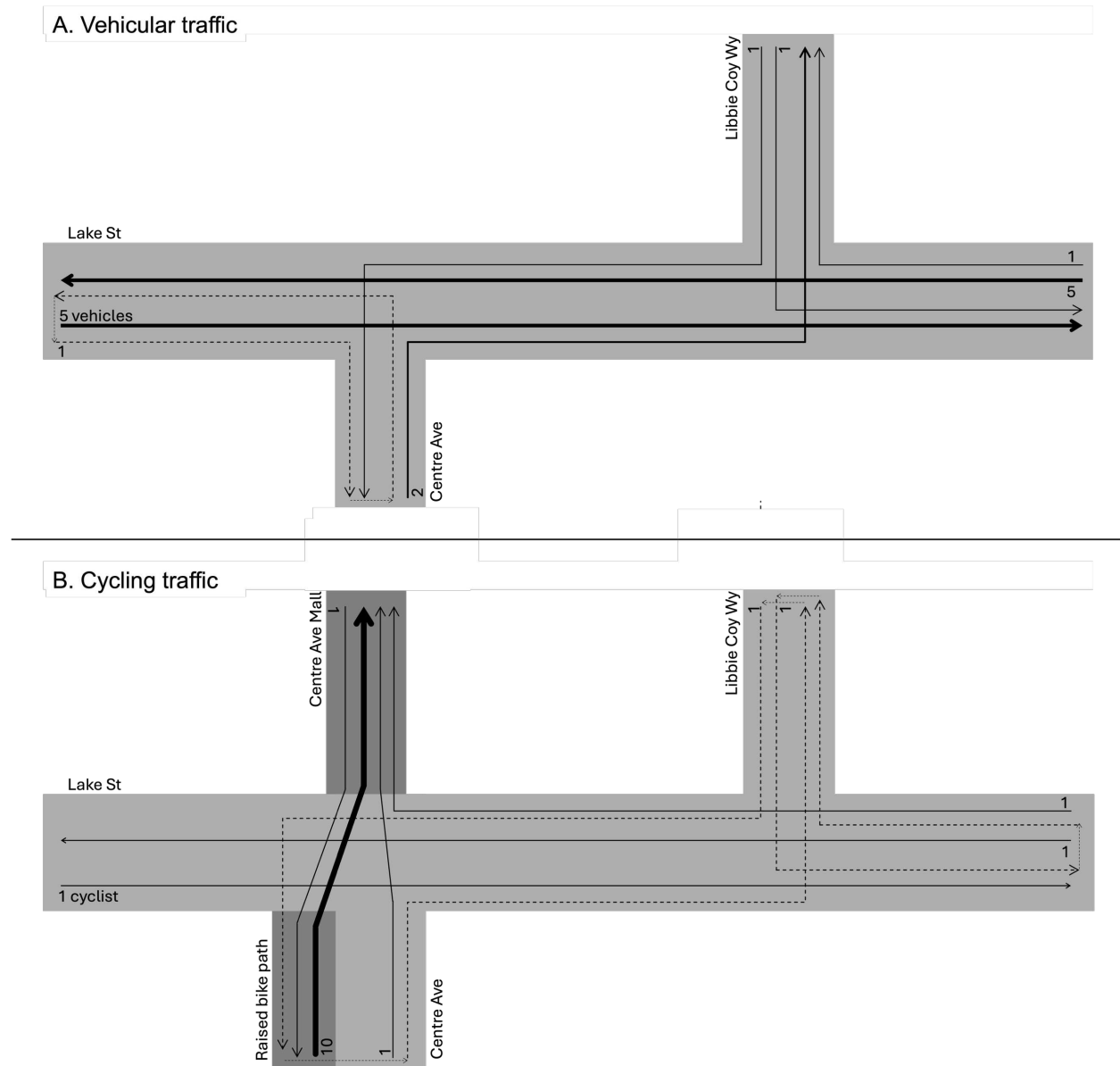
Ambient environment. A 360° photograph of Northern Colorado from Google Street View created a “skybox” for the simulation, meaning that when the participant looked into the distance or to the sky, they saw a real photograph of the region rather than the Unity default background. The skybox depicted a sunny day with scattered cumulous clouds common for the area (Doesken et al., 2003). Greenery was visible near the horizon.

Traffic. Using the Unity Asset “Urban Traffic System Full Pack” as a base (AGLOBEX, 2025), I added motor vehicle and cyclist traffic to the simulation. The default LOD settings in the package were retained. I matched the routes and volumes of virtual traffic to real-world data from CSU’s Traffic Cordon Study – Fall Semester 2024 (Kimley-Horn and Associates, Inc., 2024). The virtual traffic volumes of motor vehicles and cyclists are presented in Figure 4. I developed additional code so that these virtual road users would follow all traffic laws, including correct

behaviors at 4-way stops, 2-way stops, unprotected left turns, and traffic signals. I programmed them to yield to the VR user if the user was at a marked crosswalk landing. See Figure 5. Additionally, the virtual vehicles and cyclists tracked the virtual space 20 m and 1.5 m ahead of them, respectively. They slowed and stopped if the VR user entered this space for any reason, such as crossing without a marked crosswalk. Virtual motor vehicles emitted varying engine sounds (e.g., electric, gasoline, diesel engines). A custom recording of moving bicycle spokes accompanied cyclists.

Figure 4

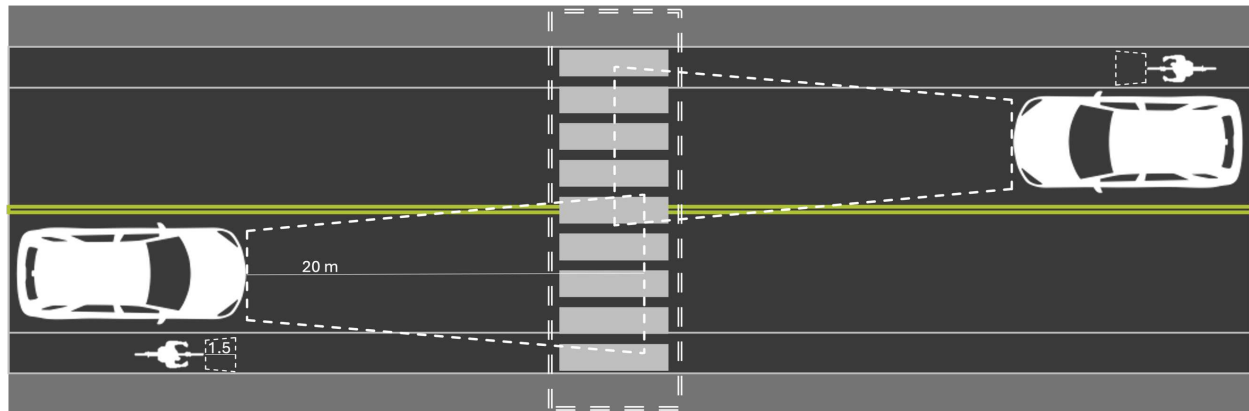
Vehicular and cycling traffic routes and volumes



Note. Routes are labeled with the number of motorists/cyclists along the route at any given time, which is also represented by linewidth. Dashed lines indicate a looped route.

Figure 5

Yielding behavior of virtual road users to VR user



Note. A virtual road user yields if the VR user is within their dashed tracked space or within the double-dashed crossing zone.

The intervention area contains one signaled intersection at the MAX Guideway, where public vehicular traffic travels east/west and only city-run buses travel north/south. Pedestrians and cyclists traveling north/south use a pedestrian signal. As reported by the City of Fort Collins, this signalized intersection operates in “free state” (J. Reed, personal communication, August 1, 2025). In essence, the signal’s default state is a green light for east/west vehicular traffic and red pedestrian signals. If the east/west pedestrian signal is triggered while the east/west vehicular signal is green, the pedestrian signal turns green. If it is triggered while the vehicular signal is red, the east/west pedestrian signal turns green with the vehicular signal at its next change. When the north/south pedestrian signal is triggered, the east/west vehicular signal turns to yellow for three seconds, then red. After four seconds with the vehicular signal on red, the north/south pedestrian signal is green for seven seconds. It then blinks red for 20 seconds before turning solid red. After a three second pause, the east/west vehicular signal turns green

again. An oncoming bus (north/south) interrupts this pattern approximately every 7-13 minutes (City of Fort Collins, n.d.).

I replicated this signal pattern, excluding the bus interruption, in VR through custom coding. The VR user triggered the pedestrian signal button via pointing at it with their dominant hand controller. When successfully triggered, the button visually depressed, the dominant hand controller vibrated, and a recording of a real-world pedestrian signal button played.

Interaction implementing

The XR Interaction Toolkit (Unity Technologies, Inc., 2025c) formed the foundation of VR interaction. The VR user's dominant hand [adapted from Stylized - Simple Hands package (sametsylmz3d, 2022)] and controller were modeled in VR. The hand had a transparent gray texture and moved its fingers appropriately when the trigger and/or grip buttons were pressed. The default Nvidia PhysX engine (n.d.) simulated realistic physics within the VR environment through rigidbodies. Rigidbodies are objects that can be subjected to gravity and other forces. Colliders are used to represent boundaries; a common application is denoting the edges of an object so that it can hit other colliders and rigidbodies. In the current simulation, the virtual element representing the VR user contained a rigidbody. The perspective of the user moved in response to forces placed onto this rigidbody as well as the user's physical movement via HMD tracking (e.g. VR user leaning forward, crouching down).

VR travel. Since the virtual space of the simulated environment (104,000 m²) was much larger than any physical space available for data collection, physical movement of the HMD (i.e., real walking) could not be used as the primary VR travel mode (LaViola et al., 2017). Instead, the VR user moved their location in the VR environment by stepping-in-place (Wilson et al., 2016).

As a partial gait VR travel technique (LaViola et al., 2017), stepping-in-place requires users to physically complete a walking-in-place movement in order to locomote their perspective in VR. To track the VR user's leg movement, their nondominant hand controller was placed on their thigh using a custom 3D-printed mount. This VR travel method was selected as it allowed data collection to be completed in a small physical space (3.33 m², known as the "playspace"). Furthermore, stepping-in-place is the third most researched VR locomotion technique (Martinez et al., 2022) and has been shown induce to more presence than many other VR travel techniques completed in similarly sized areas (i.e., flying) (Al Zayer et al., 2020). Also, it leads to better spatial orientation and more accurate distance estimations compared to arm-swinging, another travel technique for small spaces (Wilson et al., 2016). To reduce the likelihood of a user's perspective drifting due to incidental leg movement, the stepping-in-place protocol was supplemented with a continuous input requirement (e.g., holding a button) (LaViola et al., 2017).

The user's travel was executed via hand-directed steering, meaning that the direction of the dominant hand controller was used as the direction of travel. As compared to gaze-directed steering, hand-directed steering allows VR users to rotate their head while moving in a single direction (Al Zayer et al., 2020). This feature is paramount for a study investigating pedestrian behavior in environments with virtual road users as participants must be able to pivot their head to check for traffic while not interrupting their direction of travel. Torso-directed steering was considered but rejected in early testing phases as it did not fully divorce the direction of travel from head-pivoting behavior. Moreover, hand-directed steering is recommended for

applications in which the user is turning frequently (LaViola et al., 2017) as may occur in a pedestrian behavior study.

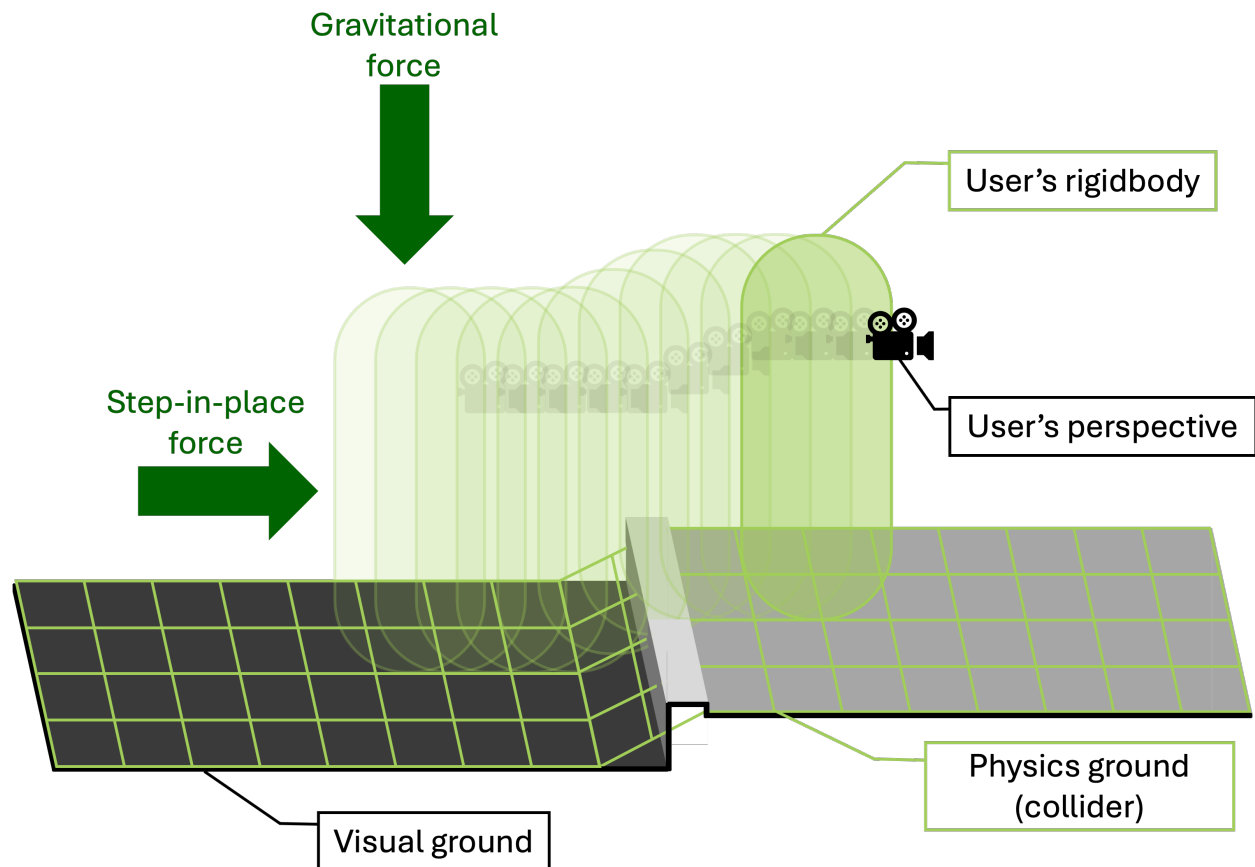
In sum, the VR user held their dominant hand controller forward from their body and physically rotated their body to face the direction they wished to travel. Then, they stepped-in-place and held the controller's grip button. When the simulation detected that the user was pressing the grip button and stepping-in-place via the hand controller mounted on their leg, a force was applied to the VR user's rigidbody. This force was in the direction the dominant hand controller pointed and at the magnitude required to move the VR user's rigidbody at a speed of 2.5 m/s. This speed balanced the realism of simulation interaction with time constraints of the study sessions as the user would travel over 2,000 m (1.25 mi) across 12 trials. Since the perspective of the user was tied to the position of the rigidbody, the movement of the rigidbody resulted in the perspective moving forward at an equivalent speed. In addition, the user's perspective also followed the physical bump and sway of their body as they stepped-in-place because the user's perspective was tied to both virtual movement of forces placed on the rigidbody and the physical movement of HMD tracking.

As mentioned, rigidbodies also have the ability to be stopped by colliders. Thus, placing a collider on the virtual ground and implementing a gravitational force on the VR user's rigidbody resulted in the user being able to move upon the ground's terrain (Figure 6). Unfortunately, large topographic variation results in higher cybersickness (Ang & Quarles, 2022), so I created a simplified ground geometry to structure the ground collider. I formed this "physics ground" geometry in Blender by projecting a high-polygon surface onto the original ground geometries via the "shrinkwrap" modifier. Micro-variations in the resulting mesh (e.g., bumps

on grass) were manually flattened. This process resulted in an invisible smooth ground surface upon which the participant's viewpoint stood, which was independent of the rough ground geometries that were viewed by the participant (named "visual ground" in Figure 6). The result was the VR user's perspective moving forward along the topography of the physics ground when a lateral force was applied to the user's rigidbody in response to them stepping-in-place. For instance, when the user moved from the street onto the sidewalk, their perspective smoothly transitioned as if they had stepped up onto the sidewalk.

Figure 6

Physics of travel in the simulation

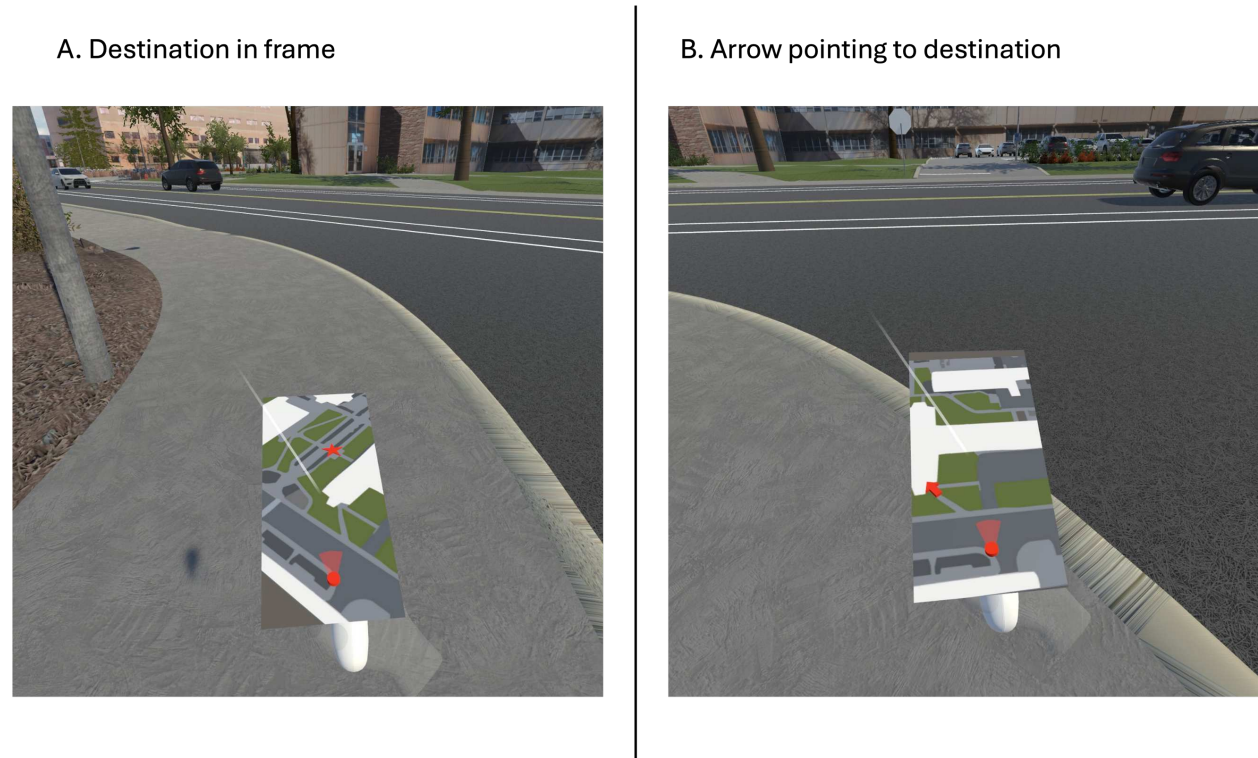


Other virtual road users contained rigidbodies and were subject to gravitational forces, so they too followed the topography of the “physics ground.” Colliders were added to virtual buildings and fences, meaning that VR users could not move through these elements by stepping-in-place. When they attempted to do so, their perspective did not move, and their dominant hand controller vibrated to notify them they had collided with an object. Street-scale objects that did not constrain routes through the VR environment (e.g., signs and trees) did not contain colliders as geometrically-complex colliders require significant processing power and can hurt simulation performance (Unity Technologies, Inc., 2026).

Study task. For each trial of the study, participants were asked to navigate to a specific destination (described in Study Trials section). When the VR user lifted their dominant hand’s palm like they were looking at a phone in VR, a map of the environment appeared (Figure 7) identifying their destination as recommended by LaViola et al. (2017). The handheld map interface was modeled after the Google Maps phone application. Using Adobe Illustrator (Version 24.1, 2020), I designed a simplified map of the virtual environment. The view of this map within VR was tilted 30 degrees. The VR user’s current location was illustrated as a dot with an angle facing forward, representing their perspective. When the user turned, the dot stayed stationary, and the background map rotated accordingly. Similarly, when the user moved their location in VR, the background map translated, such that the dot was fixed at the bottom center of the map at all times. The destination to which the VR user was navigating was presented as a red star (Figure 7 Panel A). When the destination was not within the boundaries of map, a red arrow appeared pointing to it (Figure 7 Panel B).

Figure 7

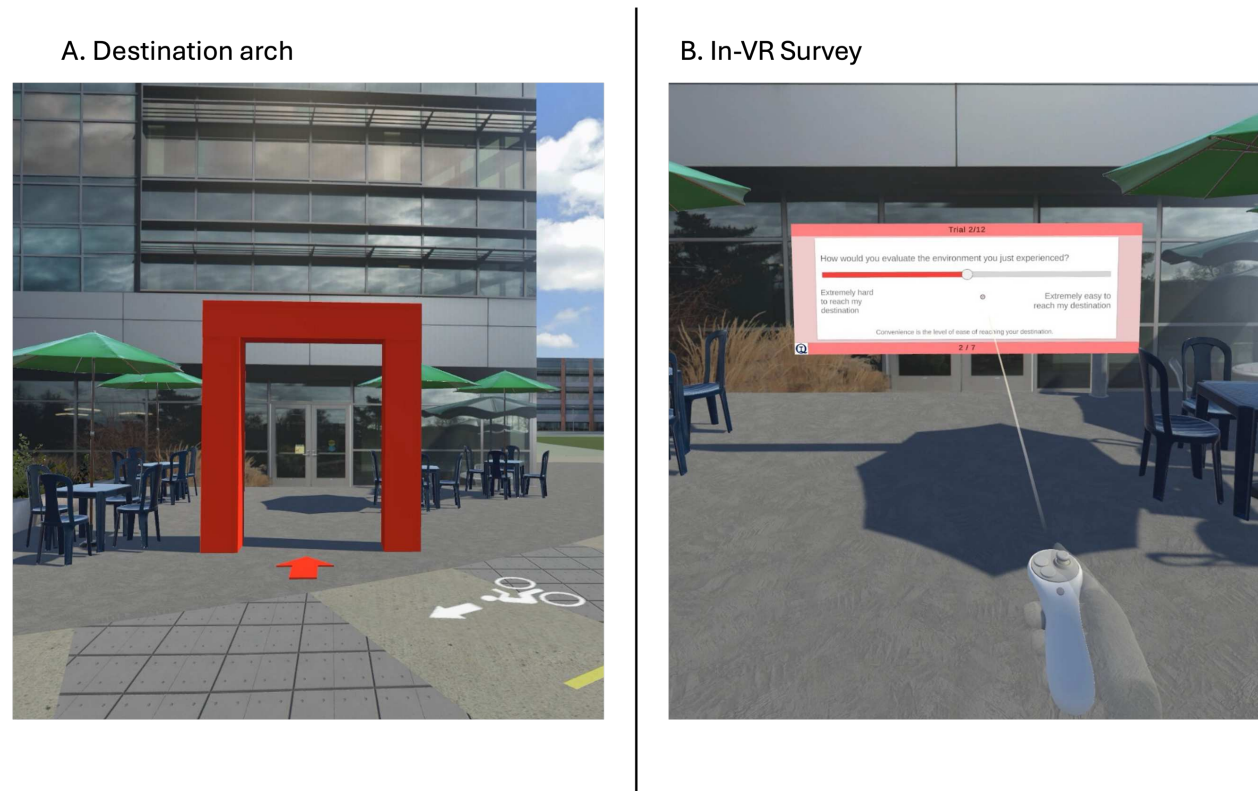
Handheld map interaction in VR



In the 3D virtual world, the destination was marked with a red arch (Figure 8 Panel A). When the VR user passed through this arch, a survey dialog box appeared (Panel B), and a celebratory melody played akin to the sound that accompanies an achievement in video games (Cyberwave Orchestra, 2024). The survey dialog boxes were implemented through the QuestionnaireToolkit package (Zefwih, 2023). VR users interacted with these screens by pointing their dominant hand controller at the buttons and pressing the trigger button. When the VR user clicked the “Next” or “Finish” buttons to progress the dialog page, the dominant hand controller vibrated.

Figure 8

Virtual view of destination and survey

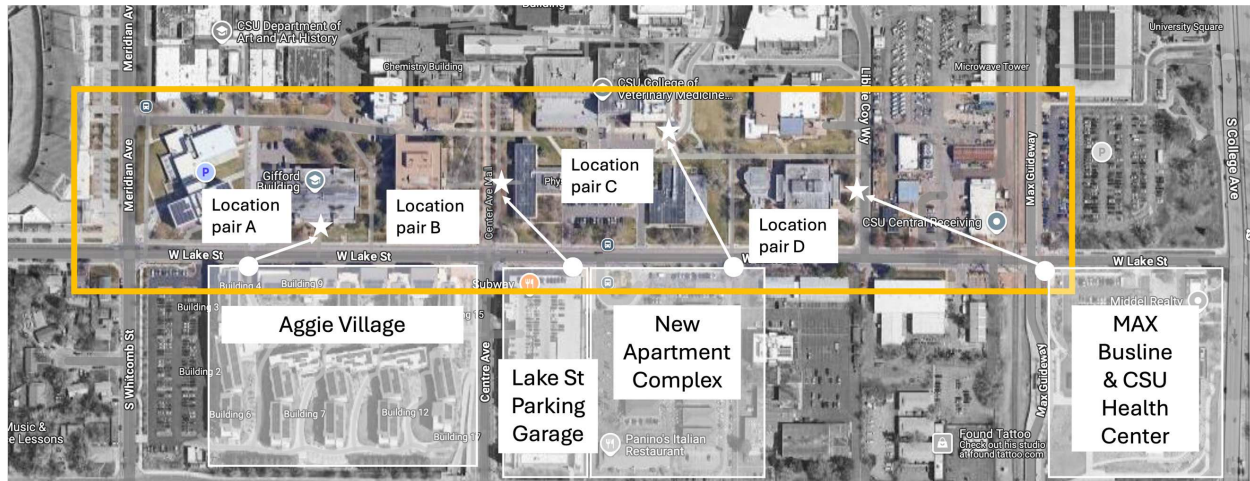


Game building

Study trials. Each study trial was created via a separate Unity Scene (12 scenes). To capture perceptions across the entire 750 m section of Lake St, trials spanned four regions of the area via “location pairs” (Figure 9). For each trial, participants began at a common location and moved to a corresponding destination, which required them to cross Lake St. Participants repeated the location pairs in 3 blocks (Table 1). I worked with CSU Transportation to ensure these location pairs reflected realistic pedestrian traffic patterns on campus.

Figure 9

Study 1 start and destination location pairs



Note. Gold rectangle represents VR simulation boundary.

Table 1

Order of location pairs and conditions

Block #	Trial #	Location Pair	Condition
Block 1	1	A	As-built
	2	C	Flexible delineators
	3	B	Concrete barriers
	4	D	As-built
Block 2	5	A	Flexible delineators
	6	C	Concrete barriers
	7	B	As-built
	8	D	Flexible delineators
Block 3	9	A	Concrete barriers
	10	C	As-built
	11	B	Flexible delineators
	12	D	Concrete barriers

In a fully-crossed design, one of three street designs was added to each Unity Scene: (1) as-built condition, (2) Two new crosswalks and flexible delineators between motor vehicle traffic and vulnerable road users, and (3) Two new crosswalks and contiguous concrete barriers between motor traffic and vulnerable road users. The order in which participants experienced these scenes was standardized to reduce complexity of the VR simulation (Table 1).

Respawning. Although virtual road users stopped when the VR user was in front of them, this system did not preclude all collisions between the VR user and virtual road users, such as if the VR user intentionally moves into the road user. If the VR user's rigidbody collided with that of a virtual road user, the VR user's perspective faded to black with a message reading "You collided with a car, cyclist, or other object. Let's restart the trial." After three seconds, their perspective faded back into the simulation at the starting point of the trial.

Environment boundaries. To deter VR users from diverting from the study tasks and finding the edge of the simulated environment, an invisible boundary was implemented. The limits of this boundary are presented in Figure 1. When a VR user was within 4 m of this boundary, a message appeared (Figure 10). If they continued to move toward the boundary, the VR user's rigidbody would be blocked by the collider of the boundary, meaning the VR user could not move outside of the boundary although they stepped-in-place.

Figure 10

Boundary message



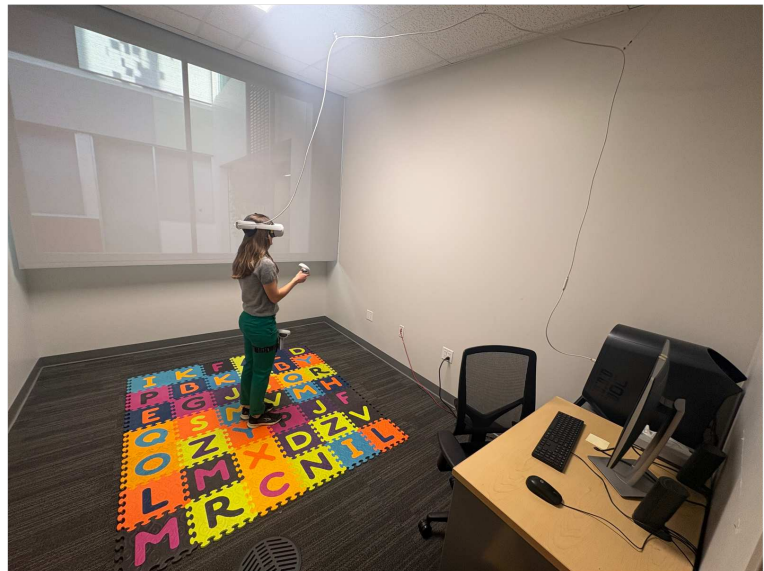
Final simulation applications and hardware setup

I used a Meta Quest 2 HMD (Model KW49CMEW4) wired to a Dell Alienware Aurora Ryzen Edition R14 (AMD Ryzen 9 5950X 16-Core Processor, 3401 Mhz, 32 Logical Processors, 32GB RAM) with Nvidia GeForce RTX 3060 Ti (8GB RAM) video card running Windows 11 as opposed to a standalone HMD setup as the wired setup allows simulation processing to occur on the much more powerful Alienware computer. This added processing power means that the simulation can be more detailed. Accordingly, two PC-based simulation apps were built from the Unity project, corresponding to left and right-handedness. Images of the final simulation can be found in Appendix B.

The study occurred in a small office-sized room (2.90 x 4.00 m). Figure 11 depicts the equipment setup for this project. The HMD wire was suspended over the VR user's head by retracting reels attached to the ceiling. This enabled the user to turn freely. Lastly, the VR user stood on a foam mat measuring 1.69 x 1.97 m, which provided tactile feedback when they strayed from the center of the playspace.

Figure 11

VR equipment and room setup



Participants

Traditional power analyses are inappropriate to determine sample sizes for feasibility trials (Eldridge, Chan, et al., 2016). Instead, Viechtbauer et al. (2015) provides a method of selecting feasibility sample size when the primary goal is “problem detection” such as the current investigation. This method uses the lowest likelihood of a problem worth detecting and

calculates the sample size necessary to estimate that the problem will occur at least once at a selected level of confidence (i.e., power). The lowest likelihood of a problem worth detecting was set at 7.5%, such that if a problem occurs less than 7.5% of the time in an efficacy study, it can be handled as needed. At a problem likelihood of 7.5% and the conventional 80% level of power, 21 participants are required. This number of participants was recruited from Colorado State University, a large university in the US Mountain West via flyers posted in the intervention area. Inclusion criteria were: (1) is ≥ 18 years old, (2) is not prone to motion sickness, (3) is not susceptible to dizziness, epilepsy, vertigo, or any other problems that would preclude them from using VR technology, and (4) is familiar with Lake St area as indicated by responding that they visit the area $\geq 1x/week$.

Of the 21 participants, only 18 completed the demographics survey as the study session duration elapsed before all study protocols were performed (discussed in Results Feasibility Criteria section). Most participants (52%) visited the intervention area $\geq 5x/week$, indicating strong familiarity. Though participants were primarily students at the university (71%), the mean age (25.39, SD = 6.94, Range = 20-48) was slightly above traditional college age (18-22). Research into the relationship between experience of cybersickness and age is mixed with evidence for both positive and inverse correlations (Chang et al., 2020). Regardless of directionality, the ages of the current sample are generally representative of the study's population. Compared to those assigned male (38%), more participants were assigned female at birth (48%), which is also linked to greater cybersickness symptoms (Stanney et al., 2020). Regarding VR experience, two-thirds of participants had previously experienced VR, most

commonly through gaming (48%). Additional characteristics of the study sample are available in Table 2.

Table 2

Study 1 participant characteristics

Note. Percentages may not sum to 100% as not all participants responded to all questions.

Characteristic	Response	Percentage
Affiliation	CSU student	71.4%
	CSU employee	14.3%
	Prefer not to answer / No response	14.3%
Gender	Woman	38.1%
	Man	38.1%
	Nonbinary or genderqueer	4.7%
	Prefer not to answer / No response	19.4%
Sex assigned at birth	Female	47.6%
	Male	38.1%
	Prefer not to answer / No response	14.3%
VR experience	No	14.3%
	Yes	66.7%
	1-5 x	47.6%
	6-20 x	14.3%
	21-50 x	0.0%
	>50 x	4.7%
	Prefer not to answer / No response	19.4%
Area familiarity	< 1x/week	4.7%
	1-2x/week	14.3%
	3-4x/week	14.3%
	5-6x/week	33.3%
	6x/week	19.4%
	Prefer not to answer / No response	14.3%

Although participants were screened for inclusion criteria before scheduling their study session, one participant responded that they visited the intervention area < 1x/week on the demographics survey administered during the study session. Analyses were run with and without this participant, and conclusions were robust against the exclusion. Results with all participants are presented in the text; results excluding this participant are reported in Appendix C.

Measures

In accordance with the acceptability criteria laid out above, induction of cybersickness was assessed with the VRISE domain of the VR Neuroscience Questionnaire (VRNQ, Kourtesis et al., 2019). This measure was specifically developed for researchers and clinicians to determine the usability of a VR simulation. The VRISE domain of the VRNQ asks respondents to report their experience of five symptoms associated with cybersickness (nausea, disorientation, dizziness, fatigue, & instability) on a 7-point labelled Likert scale, anchored at “1, Extreme intense feeling” and “7, Absent feeling” (Kourtesis et al., 2019). Higher scores are indicative of less cybersickness and better usability. This measure has demonstrated high internal consistency ($\alpha = 0.89$).

In order to monitor cybersickness at every trial, participants responded to the Fast Motion Sickness Questionnaire (FMS), a quick rating of sickness on a 1-20 scale (1 = “no sickness at all;” 20 = “frank sickness”) (Keshavarz & Hecht, 2011, p. 418). The dialog box at the end of each trial instructed participants to “please focus on nausea, general discomfort, and stomach problems. Please do not include any effects due to nervousness, boredom, or fatigue in this rating.” This dialog box also prompted participants to respond with their rating aloud, which was recorded by the researcher. Following Keshavarz and Hecht’s actions in their validation study of

the FMS (2011), ratings ≤ 15 prompted the researcher to confirm if the participant wanted to continue the study. Both the VRISE domain and FMS have been independently validated against a longer measure of simulator sickness (Somrak et al., 2021).

Presence was measured using the iGroup Presence Questionnaire (IPQ, Schubert et al., 2001), which has a 7-point Likert response scale with various labels. This survey measures three factors of presence: spatial presence ($\alpha = 0.77$), experienced realism ($\alpha = 0.70$), and involvement (degree of attention paid to VR simulation compared to the real-world environment, $\alpha = 0.76$) (Schubert et al., n.d.). Ratings of these factors synthesize into a single general score of presence which was assessed in the current study ($\alpha = 0.87$). Appendix D contains copies of all surveys completed in the current study.

Procedure

Participant sessions were completed individually. Upon arrival at the laboratory, the participant provided informed consent. After consent was obtained, I explained the FMS scale, noting what symptoms should be included and excluded in the rating, and asked the participant to verbally report their current experience of sickness. I measured the participant's interpupillary distance using a ruler and set the HMD to the appropriate interpupillary setting. If the participant was wearing glasses, the Quest 2 glasses spacer was added to the HMD. After inquiring about the participant's dominant hand, I placed the controller for their nondominant hand into the 3D-printed mount and helped the participant don the leg strap and mount on their chosen leg.

I taught the participant how to use (1) the trigger button to select options on VR dialog boxes and (2) the grip button and step-in-place procedure, mimicking the required movements.

I fit the wire suspension system to the participant's height and aided them in donning the remaining VR equipment. Necessary adjustments were made to ensure comfort and clarity. To minimize the participant's view of the laboratory, I turned off the room lights before launching the simulation app that corresponded with the participant's handedness.

Once in VR, the participant completed a tutorial period (mean duration = 6.37 min) in which they learned and practiced VR skills required for the study trials, including how (1) to interact with dialog boxes in VR, (2) to trigger crossing signals in VR, (3) to move in VR, (4) to use the handheld map, and (5) to report the FMS while in VR. In addition, this tutorial covered important study information: the study task (to move to a destination marked with a red arch), and a reminder that they could take a break or end the study session at any time.

When the tutorial ended, and the participant indicated they were ready to begin study trials, the simulation progressed to the first trial. The survey at the culmination of each trial consisted of five items: four regarding their judgements of the environment (the primary outcomes for an efficacy study) and the FMS. After verbally providing their cybersickness rating, the participant indicated they were ready to move onto the next trial, and the simulation progressed to the next Unity Scene.

The VR segment ended either when the participant wanted to leave VR or when they finished the 12 trials. Subsequently, I illuminated the laboratory lights and prompted the participant to complete a post-VR survey, including the VRNQ VRISE, IPQ, and demographics questions using a desktop computer. The last page of the survey debriefed the participant, and they received \$30 as compensation. Colorado State University's Institutional Review Board approved this study protocol (#7136).

STUDY 1 RESULTS

Following the extension of CONSORT's recommendations to feasibility trials (Eldridge, Chan, et al., 2016), no inferential statistics were completed. Instead, descriptive statistics were compared against prespecified feasibility and acceptability criteria outlined above. All analyses were completed in R Statistical Software (Version 4.3.3) using RStudio (Version 2023.12.1+402).

Feasibility criteria

Only 66.7% of sessions finished in 1 hour far below the prespecified completion threshold of > 90%. Three participants chose to stay beyond 1 hour to complete the post-VR survey. All primary outcome data (i.e., environmental judgements) were usable, surpassing both the target (< 10%) and lower (< 30%) thresholds for the missingness criterion.

Acceptability criteria

Aligning with the target threshold for cybersickness, the median VRNQ VRISE score was 30. The distribution of VRISE scores is presented in Figure 12. Regarding the FMS, only one participant provided a rating above 15 and elected to end the VR session early (Figure 13). Surpassing all prespecified thresholds (target: ≥ 3.86 , lower: ≥ 3.47), the mean IPQ score was 3.946 (SD = 0.551, Figure 14). Compared to over 200 studies using the IPQ reviewed by Tran et al. (2024), this score is roughly in the 84th percentile and is within the high presence class. Furthermore, the spatial presence (M = 4.600 [SD = 0.859]) and experienced realism (2.803 [0.860]) domains met the acceptable and marginally acceptable criteria set by Melo et al. (2023), respectively. Still, scores on involvement (3.329 [1.112]) were within the unacceptable

range (< 3.38). In the ranking scale presented by Tran et al. (2024), the observed spatial presence falls in the high rank, but experienced realism and involvement score as moderate.

Figure 12

Distribution of cybersickness VRNQ VRISE scores

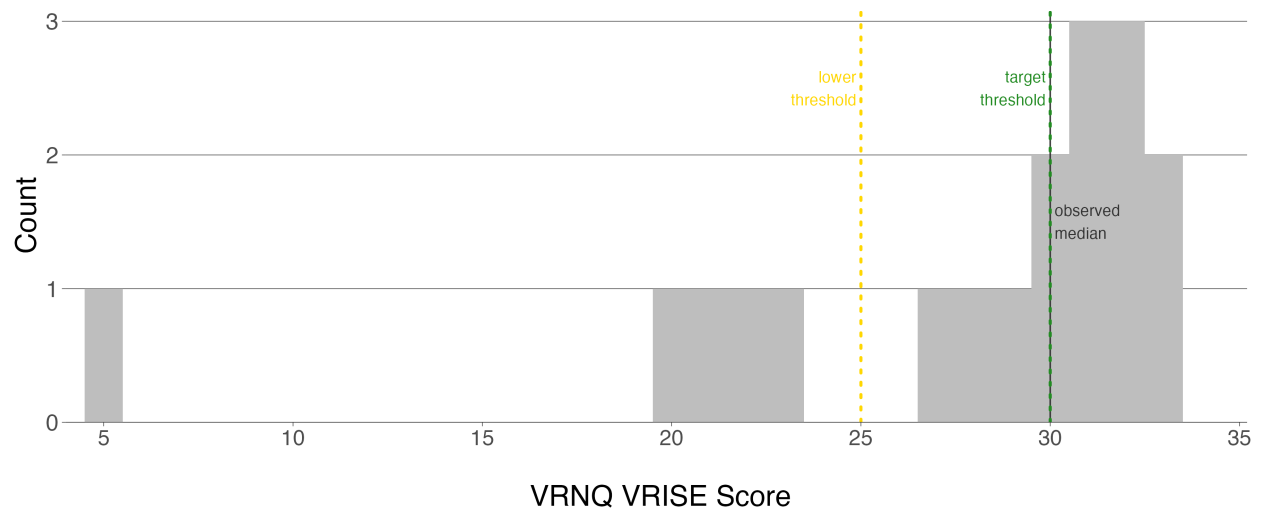
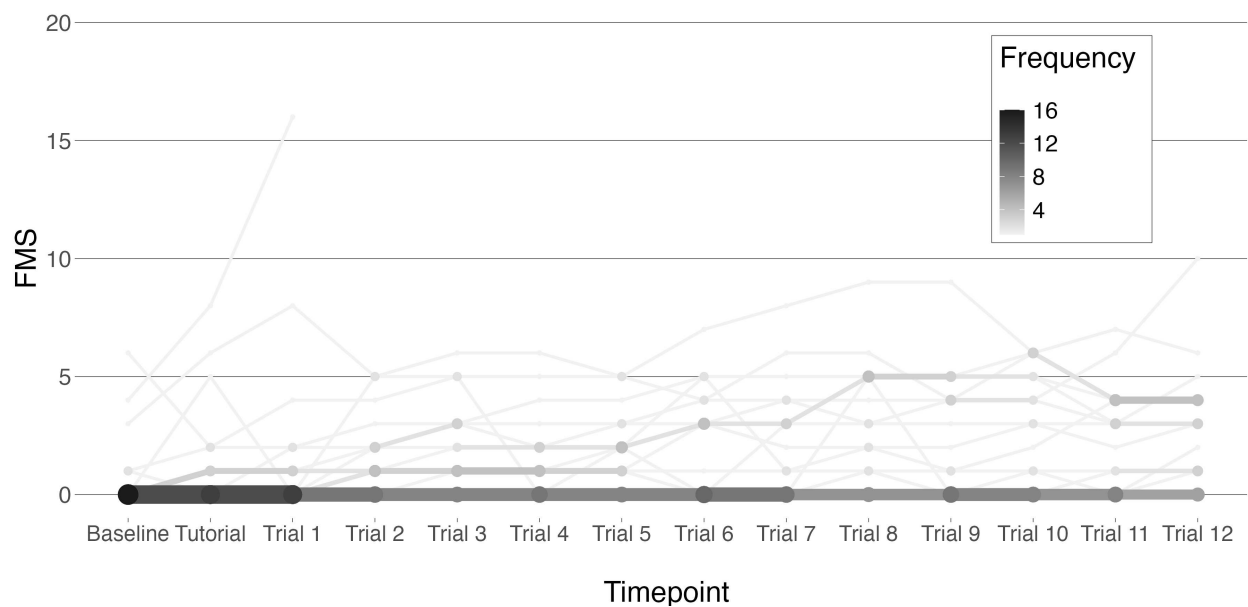


Figure 13

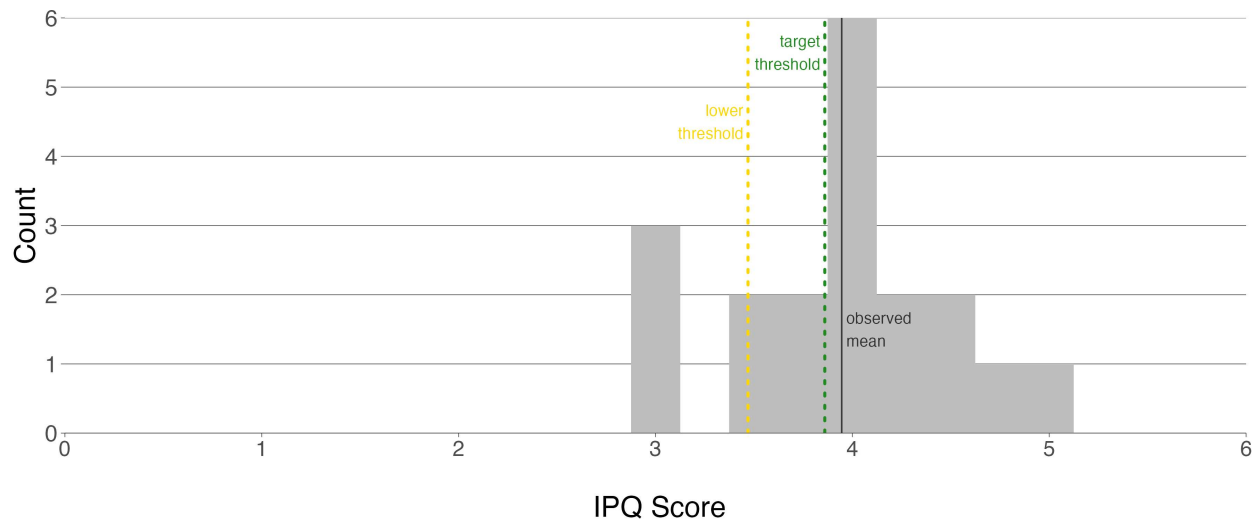
Cybersickness FMS scores across time in VR



Note. Frequency is reflected in shade, point size, and linewidth.

Figure 14

Distribution of presence IPQ score



In addition to the IPQ and VRNQ VRISE domain, participants answered several questions about their adjustment to the VR environment and the difficulty of simulation interaction. (Item language for the latter adopted from the VRNQ Game Mechanics domain (Kourtesis et al., 2019).) A large majority of participants found it easy to interact with objects and screens (16/18), to use the handheld map (15/18), and to move via stepping-in-place (14/18). The distributions of these responses are presented in Figure 15. Of those who completed the post-VR survey, all participants except two (88.9%) indicated that they adjusted to the VR environment as defined by feeling comfortable moving around without any disorientation (Figure 16); most participants did so within less than five minutes (83.3%), meaning they completed their adjustment within the average Tutorial period (6.37 min).

Figure 15

Perceived difficulty of simulation interaction

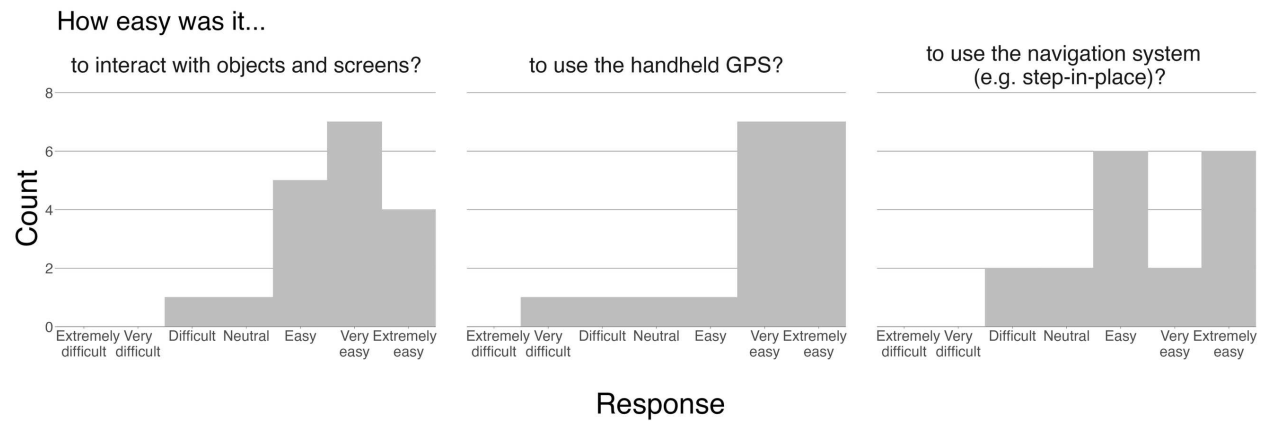
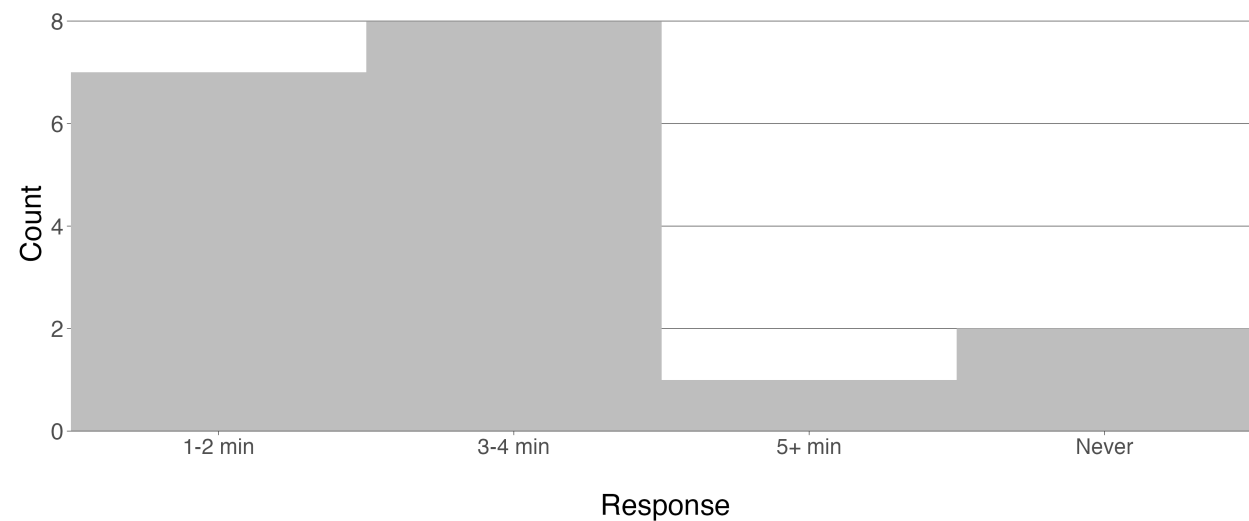


Figure 16

Distribution of self-reported VR adjustment duration



Crossing observations

Participants' use of marked crosswalks will be assessed in a subsequent efficacy study as a secondary outcome. Results from this current pilot study identified a potential issue with

measurement of this behavioral outcome. There was little variability in participants' actions: The proportion of virtual Lake St crossings completed within a marked crosswalk was 86.4%. Additionally, participants seemed to anticipate the locations of marked crosswalks when they repeated a location pair. Figure 17 illustrates this pattern: It depicts how participants' chosen routes changed across blocks. In location pair D (Figure 17 Panel D), a common pattern appeared (45.0% of participants): In the first block, many participants forwent the marked crossing at the MAX Guideway and traveled west initially on the south side of Lake St, but in the second block, they immediately crossed Lake St at the MAX Guideway, the first available marked crossing. These participants may have remembered that there was no marked crosswalk at Libbie Coy Way during the first block and anticipated that this would be the case in the second block although it was not. For other location pairs, participants tended to repeat the same route in subsequent blocks (Figure 17 Panels A-C).

Figure 17

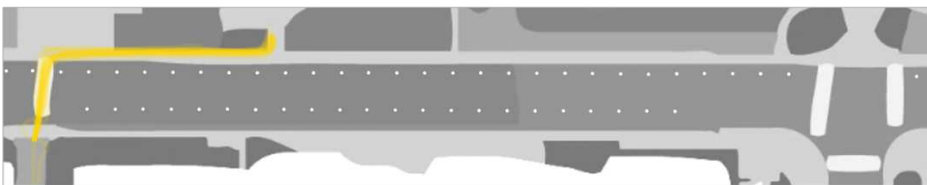
Lake street crossings stratified by location pair and block

A. Location pair A

I. Block 1: As-built



II. Block 2: Separated – Flexible delineators



III. Block 3: Separated – Contiguous concrete barriers



B. Location pair B

I. Block 1: Separated – Contiguous concrete barriers



II. Block 2: As-built



III. Block 3: Separated – Flexible delineators



C. Location pair C

I. Block 1: Separated – Flexible delineators



II. Block 2: Separated – Contiguous concrete barriers

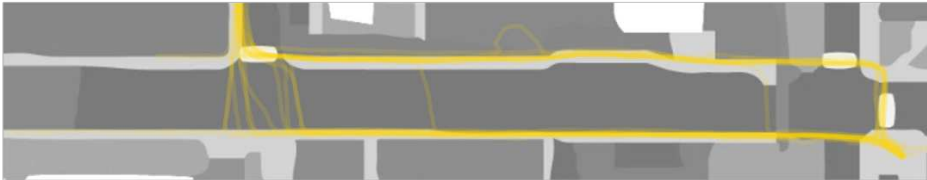


III. Block 3: As-built

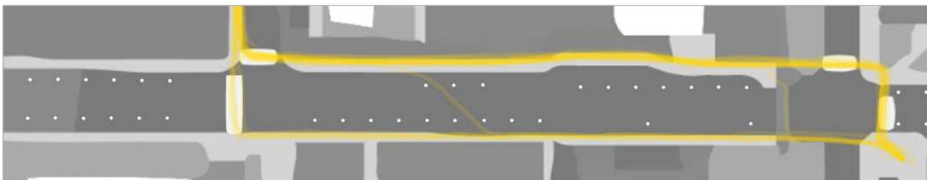


D. Location pair D

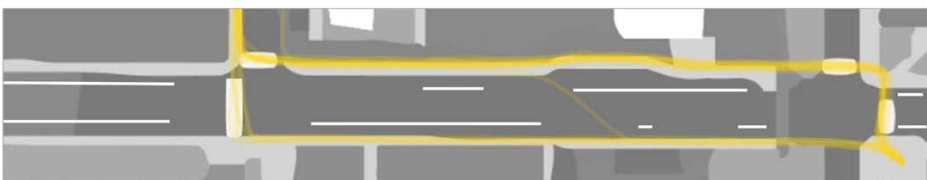
I. Block 1: As-built



II. Block 2: Separated – Flexible delineators



III. Block 3: Separated – Contiguous concrete barriers



Note. Each yellow line represents a single crossing attempt.

STUDY 1 DISCUSSION

The present pilot study assessed the feasibility and acceptability of a study protocol immersing participants into a VR replica of a portion of a college campus. Specifically, it compared session duration, data missingness, participant cybersickness, and presence to prespecified thresholds. Observed data met the upper thresholds for all criteria except study duration: Only about two-thirds of participants completed all study protocols within the allotted hour. The predetermined pathway in the case that this criterion was not met was to extend participants' sessions to 1.5 hours in the efficacy study.

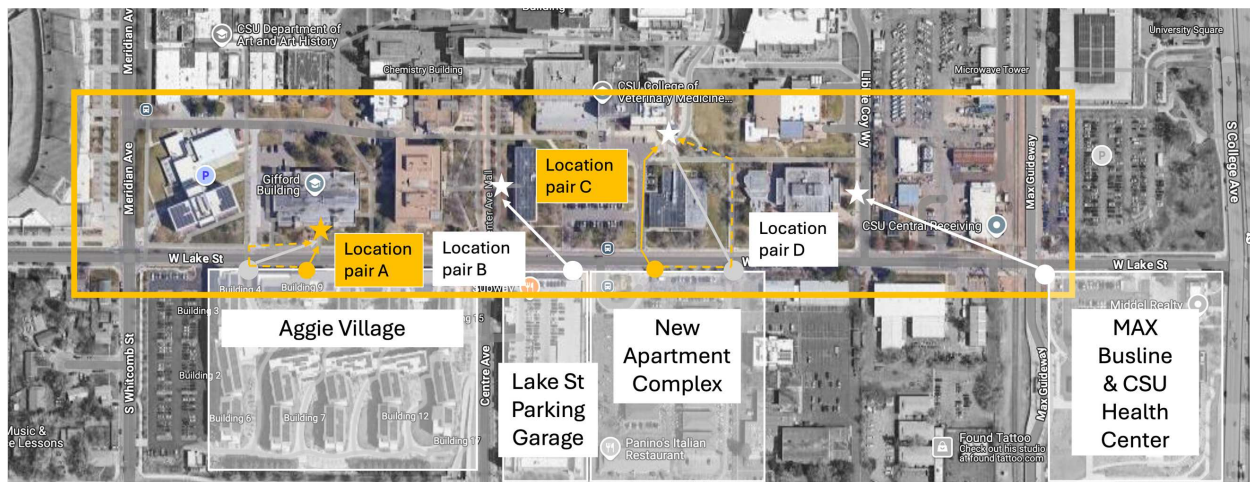
In addition to comparison against prespecified criteria, this study aimed to detect unexpected issues with the study simulation or protocol. The present investigation revealed a possibility of participants adjusting their route based on learning. This possibility of differential carryover effects is a concern because the order of conditions and location pairs was standardized, meaning that the effects of the interventions were confounded with those of learning. For the subsequent efficacy study, counterbalancing intervention order should be prioritized over coding complexity.

Another concern was the lack of variability regarding the use of marked crosswalks, essentially indicating inappropriate item difficulty. In two of the four location pairs (A and C), the starting point was directly in front of a marked crosswalk. Use of the marked crosswalk was convenient: Its location was known, salient, and along the shortest route provided participants attempted to spend the least amount of time within the limits of the street. While these starting locations align with real-world pedestrian volumes anticipated by CSU Transportation, the lack

of variability in crossing decisions poses a challenge to answering the consequential question: “Do the tested interventions result in fewer unmarked crossings?” To better address this question in an efficacy study, the starting points of location pairs A and C were shifted. Based on discussions with CSU Transportation, location pairs B and D were not altered as the examination of pedestrian navigation through the high-traffic intersection at Centre Ave (B) and from the highly-used bus stop on the MAX Guideway (D) were priorities. For location pairs A and C, the current pilot study prompted the movement of the starting locations such that the most direct route to the destination involved making an unmarked crossing. This adjustment increases the difficulty of using a marked crosswalk because participants would need to search for one and take a less direct path in order to use it. Figure 18 shows the adjusted location pairs.

Figure 18

Adjusted location pairs



Note. Gold rectangle represents VR simulation boundary.

Limitations

Like all research methods, the approach using immersive simulation to study transportation behavior has inherent limitations. Perceptions of environments judged in VR replicas are known to be more similar to judgements made in the real environment than those made in response to 2D stimuli (Higuera-Trujillo et al., 2017). Still, the absolute validity of these perceptions to the real world varies (Nishio & Ito, 2020; Shi et al., 2020; Spitzer et al., 2025). Furthermore, some studies have shown more cautious walking kinematics in VR compared with real-world walking (Mason et al., 2023). To minimize the likelihood of experiencing cybersickness due to terrain variability (Ang & Quarles, 2022), participants were instructed not to move onto large areas of grass. Because of this instruction and/or differences between real-world and VR behavior, participants may have selected an alternative route and crossed Lake St at a different location than they would have otherwise.

Relatedly, participants in this study protocol were not walking naturally. Real walking is generally regarded as the optimal VR travel method but is difficult to implement when the virtual space is larger than the available physical space (LaViola et al., 2017). As noted by LaViola et al. (2017), walking-in-place protocols address this space issue and expend energy; thus, choosing a longer route in VR carried both a time and energy cost like in the real world. Still, it is possible that participants' behavior and/or perceptions of the environment were altered by the use of this alternative VR travel mode. The selection of stepping-in-place also limited the behaviors that could be measured as outcome variables (e.g., measuring walking speed was not appropriate) (Spitzer & Graham, 2025).

The results of this pilot study should not be interpreted as evidence of the simulation's acceptability among the general public. The sample was selected from a specific university-based population. Sample characteristics are not representative of other populations; notably, participants were relatively young. This young sample is appropriate for the current application of the VR simulation to study a university-based population. Individual characteristics are linked to experience of cybersickness (Chang et al., 2020), so another pilot study would be necessary for the simulation to be used with a different population.

Guidelines for collaborative walkability research utilizing VR

An aim of the current project is to promote the wider application of behavioral science to pretest built environmental interventions. Existing guidelines for the adoption of VR into environmental research programs either do not detail the interdependent relationship between VR simulation development and study design (Birenboim et al., 2021) or do not address active transportation infrastructure (Joseph et al., 2020; Vasser & Aru, 2020). Furthermore, these recommendations do not identify how to integrate the expertise of local decisionmakers and design practitioners. Thus, I find it useful to define specific guidelines for the use of VR in walkability research conducted in collaboration with local transportation planners which links study design decisions to VR development choices. The presented approach to collaborative study design for VR environmental research is only one of many and is far from being exhaustive. It incorporates lessons learned from the current study and specifies the bidirectional relationship between study objectives and VR development.

Match study outcomes with VR travel mode, wayfinding system, and study task with consideration to available resources. As noted, certain study outcomes call for VR travel

techniques with particular characteristics. This is most evident with behavioral outcomes, such as the measurement of cadence requiring a travel mode incorporating steps. Still, VR travel modes can be resource-demanding. Some require large amounts of space (LaViola et al., 2017) or complex algorithms (Nilsson et al., 2018). Before choosing a VR travel mode, VR research teams should index the resources and expertise available to them. Relatedly, the target variables of a study may require participants to independently wayfind within the virtual environment. The current study would not have been able to address local transportation planners' inquiry about where individuals cross Lake St if participants were directed where to walk. Thus, a wayfinding system had to be designed. To do so, it may be useful to examine how the target population usually wayfinds (e.g., by phone application) and what landmarks and/or signage will assist them in orienting themselves within the virtual environment. Both the VR travel mode and wayfinding system have a bidirectional relationship with development of the study tasks participants will complete. Vassar and Aru (2020) recommend goal-directed behavior in virtual environments rather than passive experience. In designing the study tasks, VR travel, and wayfinding, consider what realistic contextual features and real-world behavioral characteristics should be present in VR in order to address the study goals.

Be flexible with tested interventions. In a VR simulation created via 3D modeling as described in Figure 2, the implementation and alteration of individual built environmental elements is relatively simple compared to the previously-mentioned simulation systems (i.e., travel, wayfinding, traffic, tasks). Thus, it may be useful to allow a degree of flexibility in the selection of which interventions to test as funding availability and local priorities change. The ability to align research outcomes with the goals of local decisionmakers is a benefit of

collaboration between behavioral scientists and transportation planners in conducting rigorous applied research. Designing simulations and studies with a focus on outcomes may lead to future opportunities to reuse the protocol. For example, reduction of unmarked mid-block crossings on Lake St is a goal of CSU Transportation; thus, the current study's design prioritized measurement of this consequential outcome. In the subsequent efficacy study, the effects of newly introduced crosswalks and bike lane treatments on pedestrian perceptions and crossings will be tested. However, by developing this protocol and simulation around CSU Transportation's target behaviors and outcomes, it can be easily tailored for future research investigating the effects of other street design options, such as curb extensions or bulb-outs.

Minimize area of simulated boundaries. This guideline has been specified after those addressing VR travel, wayfinding, study tasks, and simulation reuse as I recommend teams finalize simulation boundaries only after previously-mentioned guidelines have been discussed. I discourage research teams from taking a top-down approach to this decision as completed in the current study. A priori selection of a rectangular area for virtual replication resulted in the unnecessary development of an entire 25,000 m² section northwest of the virtual area participants experienced. Instead, I suggest teams work together to map out the minimum areas that must be included in the simulation to achieve study goals with respect to study tasks, wayfinding system, and future use. If participants will only experience several corridors, surrounding areas do not need to be replicated realistically in VR. If participants are permitted to independently wayfind, they may stray from these corridors, and more realistic context may be required. If future use of the simulation may immerse participants in areas of the simulation not experienced by participants in the current study, it may be appropriate to invest in the VR

development of a larger area. Selecting simulation boundaries based on these study features ensures that resources are not allocated to the development of unnecessary sections of the simulation.

Harness real-world data to enhance ecological validity. Researcher-decisionmaker collaborations benefit from the sharing of resources, such as real-world data. Although not used in the current study, our team created a broad recruitment plan for the efficacy study that reaches potential participants through utilizing data from the campus transportation system. This collaboration will enable the efficacy study to recruit from publics who may not regularly participate in behavioral science research. In another example of sharing of real-world data, traffic volume data provided by municipal transportation planners resulted in high-fidelity simulation of traffic in the VR environment.

Simplify virtual traffic as much as possible. The implementation of realistic motor vehicle and cyclist traffic that was responsive to other road users, traffic laws, and the VR user was by far the most challenging portion of the simulation development for the current study. Thus, teams of behavioral scientists and transportation planners should work together to determine what degree of realistic traffic is necessary for the specific goals of the research.

Test the protocol with entire team. Once key study decisions have been made and VR development has commenced, we suggest working iteratively and meeting with the entire team regularly to receive feedback. Transportation planners can provide expertise regarding the visualization of the area within the simulation and the virtual implementation of the interventions. Behavioral scientists can offer skills related to measurement and study design validity. Important insight into the clarity of participant instructions and simulation usability can

be gained by having diverse team members experience the protocol. If resources are available, a pilot study like the current one can be extremely informative.

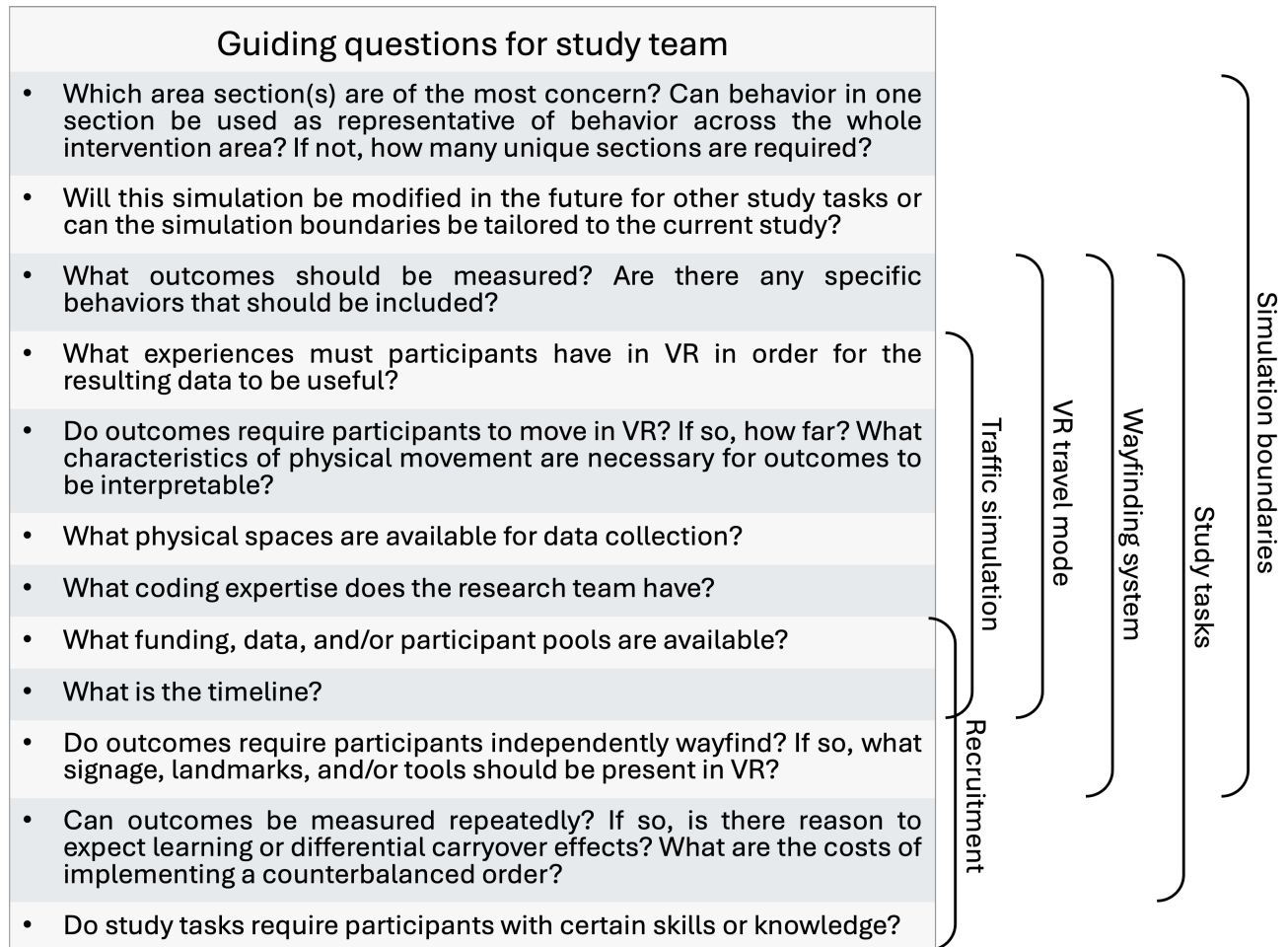
Using these guidelines. To aid readers in considering these guidelines for the development of VR simulations and study designs, Figure 19 provides a compilation of questions that a study team with both behavioral scientists and transportation planners may find useful to discuss. It outlines how these questions may inform various simulation and study decisions. Additionally, an actionable workflow describing VR development for built environmental research is presented in Figure 2. Indeed, there are many approaches to VR development for research (Joseph et al., 2020; Spitzer & Graham, 2025), and this is simply the one that this study has adopted.

Conclusion and future directions

Informed by the acceptability and feasibility of the current simulation and by the lessons learned of this pilot study, an efficacy study can be commenced while continuing to work collaboratively with municipal transportation planners. Other universities and municipalities may find the information presented in the current study useful to begin similar research programs investigating how to alter their specific built environments to boost safe active transportation.

Figure 19

Considerations for VR simulation and study design



STUDY 2: EXAMINING THE EFFECTS OF CAMPUS STREET DESIGN ON PEDESTRIANS THROUGH VIRTUAL REALITY WITH APPLICATION TO A REAL-WORLD INTERVENTION

The US is facing dual public health and climate crises. Roughly three-quarters of Americans are insufficiently active (Elgaddal et al., 2022) despite overwhelming evidence that physical activity reduces incidence of all-cause mortality (Zhao et al., 2020) and cardiovascular disease (Arnett et al., 2019; Tian & Meng, 2019), the top cause of death in the US (Murphy et al., 2024). The mechanisms by which physical activity reduces risk of cardiovascular disease as well as many other chronic diseases (Cleven et al., 2020; Friedenreich et al., 2021; Mctiernan et al., 2019; Rezende et al., 2018) are numerous, including but not limited to lowering lipid levels, increasing insulin sensitivity, improving blood pressure, and decreasing stress (Moyers & Hagger, 2023; Tian & Meng, 2019). At the same time, over six billion metric tons of greenhouse gases are emitted in the US each year, contributing to climate change (U.S. Environmental Protection Agency, 2024), a serious health hazard (Rocque et al., 2021). Through a greater frequency of extreme weather events, climate change is estimated to result in 417 million lost years of life and nearly 1.6 trillion years of life with a disability globally by 2050 (World Economic Forum, 2024). Thus, powerful approaches to physical activity promotion and climate action are crucial.

One high-impact approach to addressing these dual crises is boosting active transportation, especially among young adults. The most frequently used mode of transportation in the US is decidedly driving a personal vehicle (U.S. Department of Transportation Bureau of Transportation Statistics, 2026, Chapter 2). Indeed, light-duty vehicles (e.g., passenger cars, light trucks) make up 16% of the US's total greenhouse gas emissions (U.S.

Environmental Protection Agency Office of Transportation and Air Quality, 2024). Furthermore, active transportation can help individuals meet recommended physical activity levels, and walking for transport is specifically linked to lower cardiovascular disease risk when adjusting for other forms of physical activity (i.e., leisure-time and work-related) (Celis-Morales et al., 2017). Among college students, many of whom also drive as their primary transport mode (Nash & Mitra, 2019), adoption of walking for transport can lead to health impacts across the lifetime because college active transportation practices predict later patterns (Bopp et al., 2019). Therefore, establishing walking for transport practices on college campuses is vital.

Literature review

To promote walking for transport with the college community, universities can harness the influence of the built environment (i.e., the design and organization of the physical surroundings inclusive of transportation infrastructure, buildings, and land use) (Saelens & Handy, 2008; Z. Zhang et al., 2025). There are many models specifying relationships between the built environment and walking behavior [e.g., Ewing & Handy (2009), 5Ds (Ewing & Cervero, 2010), Gehl (2010)]. Alfonzo's walking needs (2005), a prominent model in the field, bridges design and behavioral science perspectives: It was developed as an integration of walkability research from urban design, psychology, public health, and transportation disciplines. As a result of this multidisciplinary synthesis, the model centers pedestrian perceptions and specifies how they relate to variables meaningful to design practitioners. Specifically, this model posits that the built environment can promote walking by fulfilling four needs: accessibility, safety, comfort, and pleasurability. Alfonzo (2005) clarifies that it is the *perception* of an environment meeting these needs that influences an individual's decision to walk. Much of the walkability

research and measurement tools utilized in the last decade addresses one or more of these walking needs (Tabatabaee et al., 2021); see Wang et al. (2022) for a recent review. These needs also map onto self-reported influences on the decision to walk (Distefano et al., 2023). Importantly, designers consider how these concepts facilitate walking in their practice (Bozovic et al., 2021).

For the current study, walking needs definitions were adapted from Xu et al. (2025) because of brevity and lack of jargon as these needs were defined to participants. Accessibility refers to the presence of desirable walking destinations and the ease of accessing them. Safety concerns the absence of risk for conflict between pedestrians and cyclists/motorized traffic.¹ Comfort is the “level of physical ease and reduction of distress experienced” during walking (L. Xu et al., 2025, p. 4). Lastly, pleasurability captures “aesthetic enjoyment and positive emotional responses elicited during” walking (L. Xu et al., 2025, p. 4).

Virtual reality walkability research

Emerging research examining how built environments alter walking does so in experimental paradigms via virtual reality (VR) technology (Ghanbari et al., 2024; Spitzer & Graham, 2025), which can simulate pedestrian perceptions and behavior comparable though not identical to the real world. For example, individuals judge risk equivalently (Bhagavathula et al., 2020), but they may show more cautious behavior (Angulo et al., 2023; Schneider et al., 2022) when crossing a VR street compared to a real-world one. Ratings of walking motivation

¹ The walking need of safety has been conceptualized as safety from crime (Beenackers et al., 2014; Koo et al., 2022; Sapawi & Said, 2012; Van Cauwenberg et al., 2014), from traffic (Gill et al., 2022), and from both (Lindelöw et al., 2014; Mehta, 2008; Rhodes et al., 2018; Vo & Kim, 2024; Wedyan et al., 2025; L. Xu et al., 2025). Research has established a link between the interventions investigated in the current study on traffic safety (Hu et al., 2024; Van Petegem et al., 2021) but not crime. Thus, I define safety in the context of traffic.

and environmental pleasantness provided in VR and the real-world are alike (Spitzer et al., 2025), but those of spaciousness are not (Nishio & Ito, 2020; Spitzer et al., 2025). Perhaps most importantly, affective, psychological, and physiological responses to VR environments are more similar to real-world environments than responses to photographed and video-graphed environments (Higuera-Trujillo et al., 2017; Newman et al., 2022).

Some walkability researchers have employed VR technology as an immersive representation technique in which participants passively experience a 360-degree photograph or video and report judgements after viewing street designs (Fang et al., 2024; Huang et al., 2023; H. Lee & Kim, 2021; Nakamura, 2021; Park & Kwon, 2023; Vo & Kim, 2024). This approach is also increasingly common to solicit community feedback in transportation design practice (Alan M. Voorhees Transportation Center, 2020; U.S. Department of Transportation Federal Highway Administration, 2022; Zimmermann & Dillé, 2019). Utilizing this approach, Nakamura and others (2021) evaluated perceptions of walking needs in response to 360-degree videos of existing streets with varying levels of pedestrian infrastructure (e.g., sidewalk width). In similar studies, Fang and colleagues (2024) and Vo and Kim (2024) quantified the effect of specific street elements on walking needs. Fang et al. (2024) primarily focused on the influence of individual street objects such as billboards, parked cars, and fences. These authors concluded that visual attention only partially mediated the effect. Conversely, Vo and Kim (2024) assessed the impact of walking infrastructure, finding that the presence of sidewalks as well as the complete absence of motor traffic (i.e., pedestrian-only avenues) improved perceptions of walkability measured through walking needs.

In addition to these entire applications of Alfonzo's (2005) walking needs model, VR technology has been adopted to assess walking needs separately. Hori and colleagues (2024) examined the effect of sidewalk width on perceived safety and comfort from different pedestrian perspectives. Lee and Kim (2021) found that VR streets with pedestrian zones, regardless of level of designation were perceived to be safer than fully shared streets, in which all traffic is on one plane with no delineation between modes of transport. Also studying shared streets via VR, Xu and others (2022) observed that streets with clearly-delineated pedestrian zones are judged as safer and more enjoyable; however, a modified shared street with loosely-defined walking zones was most comfortable from a pedestrian's perspective. A couple of these studies (Hori et al., 2024; L. Xu et al., 2022) as well as many other VR research protocols concerning walkability (Batistatou et al., 2022; Birenboim et al., 2021; Oselinsky et al., 2023; Silvennoinen et al., 2022; Spitzer et al., 2025, 2026) utilized an approach in which participants interact with the virtual world through movement, enabling the collection of behavioral data (Spitzer & Graham, 2025).

This interactive VR research approach has also been applied to examine how street design influences perceived safety and behavior of crossing pedestrians in a safe and controlled manner. Studies have identified perceived safety benefits to adding systems that notify motor vehicles of crossing pedestrians (Angulo et al., 2024; Guo, Angulo, et al., 2023) and to decreasing motor traffic lanes (Llinares et al., 2020). Virtual streets with fewer lanes lead to pedestrians crossing slower and choosing shorter intervals between cars in which to cross (Figuerola-Medina et al., 2023). Pedestrians also cross slower when virtual streets have sidewalk pedestrian zones than when virtual streets are shared (Kwon et al., 2022; Luu et al., 2022). This

behavioral difference was interpreted as shared streets leading to more cautious behavior, which was confirmed by pedestrian perceptions of less danger on virtual streets with sidewalks. Adding to the accumulating evidence for the importance of designated pedestrian areas to safety perceptions and behavior, Argota Sánchez-Vaquerizo et al. (2024) found that pedestrians report crossing a virtual street with a permanent marked crosswalk as safer than when no pedestrian zones (i.e., no crossings, sidewalks) or when on-demand temporary pedestrian zones are present. Moreover, the effects of virtual street design on crossing behaviors occurs indirectly through perceived risk (Kwon et al., 2022). Lee and colleagues (2025) harnessed VR technology to test the effects of alternative pedestrian crossing designs, such as public art within intersections. Not only was the art installation perceived to be less safe, but it also led to the highest rate of crossing the virtual street without a marked crossing (i.e., “jaywalking”).

Separated bike lanes

The reviewed VR walkability research primarily tests interventions specifically targeting pedestrians; however, transportation planning decisions affect all modes of transport (Marshall & Ferencak, 2019; Von Stülpnagel & Rintelen, 2024). An increasing trend within street design is the implementation of separated bike lanes (U.S. Department of Transportation Federal Highway Administration, 2024). Primarily considered a bikeability intervention, the separated bike lane involves the installation of some separating physical elements between motor traffic and vulnerable road users, which include pedestrians (National Association of City Transportation Officials, 2025). In a study using 2D videos of a cyclist’s perspective traveling through existing streets, Lim and colleagues (2025) observed higher ratings of safety, comfort, and pleasantness for streets with separated bike lanes compared to traditional bike lanes.

(Accessibility was not assessed.) The positive effect of separated bike lanes on perceived safety is echoed by the VR findings of Bialkova et al. (2022), Nazemi et al. (2021) and Friel et al. (2023). In these studies, participants rode a stationary bike along streets with various bike lane treatments through a VR head-mounted display (HMD) (Bialkova et al., 2022; Nazemi et al., 2021) or a CAVE VR simulator (Friel et al., 2023). Separated bike lanes were consistently perceived to be safer than no bike lanes (Bialkova et al., 2022; Nazemi et al., 2021) and traditional bike lanes (Friel et al., 2023; Nazemi et al., 2021).

Regarding objective safety, separated bike lanes are associated with lower crash rates than conventional bike lanes according to ambulance records (Van Petegem et al., 2021). The implementation of new separated bike lanes has led to fewer crashes per cyclist among streets that previously did not have bike lanes, but no fewer among those that formerly had conventional bike lanes (Ling et al., 2020). Still, individuals report a preference for cycling along routes with separated over conventional bike lanes (Hardinghaus & Papantoniou, 2020). In observational studies, the implementation of separated bike lanes has been linked to higher usage of bike lanes (Ling et al., 2020; Pellicer-Chenoll et al., 2025) and shared bike services (Chahine et al., 2025).

Separated bike lanes can be implemented with a number of different separating elements (National Association of City Transportation Officials, 2025), including flexible delineators, short curbs, concrete barriers, and planters. The method by which a separated bike lane is established can alter its effects on perceived safety (Friel et al., 2023). One categorization of these variations regards their contiguousness: Some barriers are discrete elements placed at intervals (e.g., flexible delineators, planters); others are implemented as continuous lines of

separation (e.g., contiguous concrete barriers, curbs). Analyzing visits to emergency departments in three cities, Cicchino and colleagues (2020) concluded that the odds of a bicycle crash leading to an emergency department visit were lower on roads with a heavily separated bike lane (e.g., contiguous concrete barrier) than a road with no bike lane, but not any different between a lightly separated bike lane (e.g., flexible delineators) and no bike lane. In a pre-post assessment of ten bike lane improvements, Van Veghel and Scott (2024) observed an increase in bicycling traffic for half of the interventions implementing a separated bike lane created with concrete barriers (3/6) but none of the interventions implementing a separated bike lane created with flexible delineators (0/2). Based on VR methodology, Saglio et al. (2023) reported that separated bike lanes with flexible delineators were rated as safer than sharing the road with motor vehicles but not any safer than traditional bike lanes. Still, the separated bike lane was most frequently ranked as the safest of the three options when elicited by a forced choice prompt.

Bike lane treatments, in particular, influence road users other than cyclists (Burke & Scott, 2018). Separated bike lanes are linked to fewer serious crashes among all road users (Marshall & Ferencak, 2019). Regarding perceived safety, von Stülpnagel and Rintelen (2024) created 2D images of manipulated street environments from driver, cyclist, or pedestrian perspectives and collected expected safety ratings. Conditions with separated bike lanes were all created with discrete elements (e.g., bollards). Separated bike lane environments were not examined from a pedestrian's point of view, but they were expected to be safer than bike lanes without any separating elements from both drivers' (Von Stülpnagel & Rintelen, 2024) and cyclists' perspectives (Von Stülpnagel & Binnig, 2022; Von Stülpnagel & Rintelen, 2024). The

effect of separated bike lanes on pedestrians remains a gap in the literature despite their implementation of a partition between pedestrians and motor traffic. In fact, a nationally representative survey revealed that Americans perceive pedestrian-traffic separation as a method of creating safer streets and inducing more walking (Soto et al., 2022).

The current study

The present study expands the growing research area using VR to investigate walkability by assessing the effect of separated bike lanes on perceived walking needs. Through collaboration with local transportation planners and decisionmakers, it also provides site-specific causal evidence concerning the effects of two potential interventions along a real university street (Colorado State University's Lake St). As the effects of built environmental factors interact with local factors such as existing environmental conditions (Sallis et al., 2008), the ability to test interventions in the specific context that will be modified is powerful.

In a within-subjects design, participants experienced three variants of a Lake St VR simulation depicting the as-built conditions and the two potential interventions. After moving through each variant, participants rated the environment on Alfonzo's four walking needs related to the built environment: accessibility, safety, comfort, and pleasurability. The investigated interventions matched those under consideration by local decisionmakers, namely the City of Fort Collins and the Transportation Department of Colorado State University (CSU), where the intervention is proposed. These interventions consisted of a separated bike lane either with flexible delineators or contiguous concrete barriers. Both intervention environments also introduced two new pedestrian zebra crosswalks in locations under consideration by campus transportation. Dense crosswalk networks are associated with lower risk of a crash

involving a pedestrian, possibly by reducing unmarked pedestrian crossings (Hu et al., 2024). In fact, the National Association of City Transportation Officials recommend placing marked crosswalks no more than 200 m apart due to the increased likelihood of crossings outside of a marked crosswalk (Global Designing Cities Initiative & National Association of City Transportation Officials, 2016). Young adults, in particular, identify crosswalks as a useful safety countermeasure promoting walking (Soto et al., 2022).

Hypotheses

Based on the reviewed research that (1) separated bike lanes increase cyclists' perceptions of safety (Friel et al., 2023; Lim et al., 2025; Nazemi et al., 2021; Von Stülpnagel & Binnig, 2022; Von Stülpnagel & Rintelen, 2024), comfort (Lim et al., 2025), and pleasantness (Lim et al., 2025), and (2) heavily separated bike lanes are associated with better objective safety outcomes (Cicchino et al., 2020; Van Veghel & Scott, 2024); the following two hypotheses were proposed.

- H1) Participants will perceive that both potential interventions meet their walking needs of safety, comfort, and pleasurability better than the as-built condition.
- H2) Participants will perceive that the separated bike lane with contiguous concrete barriers condition meets their walking needs of safety, comfort, and pleasurability better than the condition with flexible delineators.

Based on evidence that crosswalks increase pedestrian connectivity (Verma & Ukkusuri, 2023) and safety (Hu et al., 2024) but an acknowledgement that contiguous concrete barriers may pose an obstacle to pedestrian routes, accessibility hypotheses were proposed:

- H3) Participants will perceive that the potential intervention with flexible delineators meets their walking need of accessibility better than the as-built condition.
- H4) Participant will perceive that the potential intervention with contiguous concrete barriers meets their walking need of accessibility worse than the as-built condition.

STUDY 2 METHOD

Participants

Sample size was driven primarily by feasibility (i.e., time and funding resources), resulting in 75 participants. According to Arend and Schäfer's (2019) simulation-based power recommendations for multilevel models, a study with 70 participants each completing 12 trials and a large ICC (as indicated by present data) is appropriately powered (power ≥ 0.80 , $\alpha = 0.05$) to detect a moderately-small ($\beta = 0.15$) within-subjects direct effect. Similar studies examining perceptual and affective responses to various VR environments report effect sizes in this range (Batistatou et al., 2022; L. Xu et al., 2022). Indeed, models based on pilot data estimated standardized direct effects of interventions on perceptions of walking needs that are well within the detectable range with 70 participants ($\beta_{\text{Range}} = 0.175\text{-}0.282$).

These 75 participants were recruited via email and flyers. With aid from CSU Transportation, patrons of parking structures near the intervention area received a recruitment email. Flyers were displayed in university buildings near the area and shared with undergraduate courses and organizations. Interested individuals completed a screening questionnaire, which confirmed that they met inclusion criteria: (1) ≥ 18 years old, (2) not prone to motion sickness, (3) not susceptible to dizziness, epilepsy, vertigo, or any other problems that would preclude them from using VR technology, and (4) familiar with Lake St area (as indicated by responding that they visit the area $\geq 1x$ per week). A couple of participants (2) indicated that they met this fourth criterion in the screening questionnaire but replied that they visited the area $< 1x/\text{week}$ during the study survey. Sensitivity analyses excluding these participants

revealed identical conclusions and negligible changes to effect size for all quantitative analyses. Thus, the analyses with all participants are presented within the text. The results of sensitivity analyses are reported in Appendix C.

Participant characteristics are outlined in Table 3. Participants were very familiar with the intervention area. (79% visited the area ≥ 3 x/week.) All were students (89%) and/or employees of the university (15%). The most frequent mode of transport among participants was to drive (38%) though this group was underrepresented compared to university data (72%) (Colorado State University, n.d.-a). In contrast, pedestrians (31% v. 7%) and cyclists (22% v. 11%) were overrepresented. The proportion of the sample that most frequently bus to school/work (9%) was consistent with university data (8%). About half of participants were women (51%), slightly less were men (45%), and several were nonbinary or genderqueer (4%). A slim majority were assigned female at birth (55%). Although this sample was primarily White (67%) and not Hispanic or Latino/a/x (72%), it was more ethnically and racially diverse than the CSU population according to university-wide employee (Colorado State University Institutional Research, Planning and Effectiveness, n.d.) and student data (Colorado State University, n.d.-b). Almost half of participants had previously experienced VR a handful of times or fewer (43%) while nearly a third had never experienced VR. Only a small portion were very experienced with VR (21+ times: 15%).

Table 3*Study 2 participant characteristics*

Note. Percentages may not sum to 100% as not all participants responded to all questions.

^aOne participant indicated they were both a student and employee. ^bRespondents were permitted to select one or more categories. ^cIncludes participant who indicated they skateboard.

Characteristic	Response	Percentage
Affiliation ^a	CSU student	89.3%
	CSU employee	14.7%
	Prefer not to answer / No response	0.0%
Gender	Woman	50.7%
	Man	44.0%
	Nonbinary or genderqueer	4.0%
	Prefer not to answer / No response	1.3%
Sex assigned at birth	Female	54.7%
	Male	45.3%
	Prefer not to answer / No response	0.0%
Ethnicity	Hispanic or Latino/a/x	20.0%
	Not Hispanic or Latino/a/x	72.0%
	Prefer not to answer / No response	8.0%
Race ^b	African American / Black	4.0%
	Asian / Asian American / Pacific Islander	9.3%
	Native American	1.3%
	White	66.7%
	Other / Self-identified another race	11.6%
	Prefer not to answer / No response	10.7%
VR experience	No	29.3%
	Yes	69.3%
	1-5 x	42.7%
	6-20 x	12.0%
	21-50 x	8.0%
	>50 x	6.7%
	Prefer not to answer / No response	1.3%

Characteristic	Response	Percentage
Visits to intervention area	< 1x/week	2.6%
	1-2x/week	18.7%
	3-4x/week	25.3%
	5-6x/week	34.7%
	> 6x/week	18.7%
	Prefer not to answer / No response	0.0%
Most frequent travel mode	Drive alone	33.3%
	Walk	30.7%
	Bicycle ^c	21.3%
	Take bus	9.3%
	Drive with another person	4.0%
	Telecommute / Work from home	0.0%
	Prefer not to answer / No response	1.3%
Age	Mean = 24.16, SD = 7.77, Range = 18-55	

VR set-up

A Dell Alienware Aurora Ryzen Edition R14 (AMD Ryzen 9 5950X 16-Core Processor, 3401 Mhz, 32 Logical Processors, 32GB RAM with Nvidia GeForce RTX 3060 Ti (8GB RAM) video card) ran a VR simulation to a wired Meta Quest 2 VR HMD (Model KW49CMEW4). A system of pulleys suspended the connecting wire above a “playspace” comprised of a 1.69 x 1.97 m foam mat. This pulley system ensured the participant could move and turn unencumbered within the playspace. This mat also notified participants when they moved out of the playspace by providing tactile feedback via a change in ground texture.

I developed a custom VR simulation for the current study, including 3D modeling in Autodesk InfraWorks (Version 24.1.3.129, 2024) and Blender (Version 4.4.0, Blender Online Community, 2025); texture-mapping in Blender; and interaction/game building in Unity Game Engine (Version 6000.2 Unity Technologies, Inc., 2025b). Briefly, the simulation was a virtual

replica of the 104,000 m² Lake St area. The simulation featured streets, sidewalks, and walking paths built to the dimensions of the real environment. Virtual buildings displayed photographs of the real-world buildings. The simulation also contained greenery and street furniture in locations consistent with the real world. Signage was customized, including street and building signage to facilitate wayfinding. The virtual weather was a sunny day as is common for the area (Doesken et al., 2003). Spatial audio increased the immersive nature of this simulation with ambient bird song and virtual road users emitting appropriate engine or cycling spoke sounds.

Real-world traffic data (Kimley-Horn and Associates, Inc., 2024) provided a guide for the development of realistic virtual motor vehicular and cycling traffic. Namely, traffic routes and volumes were comparable to the real world. Virtual road users obeyed traffic laws and yielded to the participant if the participant was in the pathway of the virtual road user. Furthermore, they stopped for the participant when the participant was at a marked crosswalk landing.

In the VR environment, participants were tasked with navigating to specific destinations marked with red arches (Figure 20). They held the VR hand controller matching their dominant hand and used it to view a map of the environment modeled after the Google Maps phone application. To move in VR, they stepped-in-place with their nondominant hand controller mounted to their thigh to track leg movement. Once participants walked through the destination arch, they answered survey questions on a text dialog screen using their hand controller. A detailed description of VR simulation development is available in Study 1.

Figure 20

VR destination and handheld map



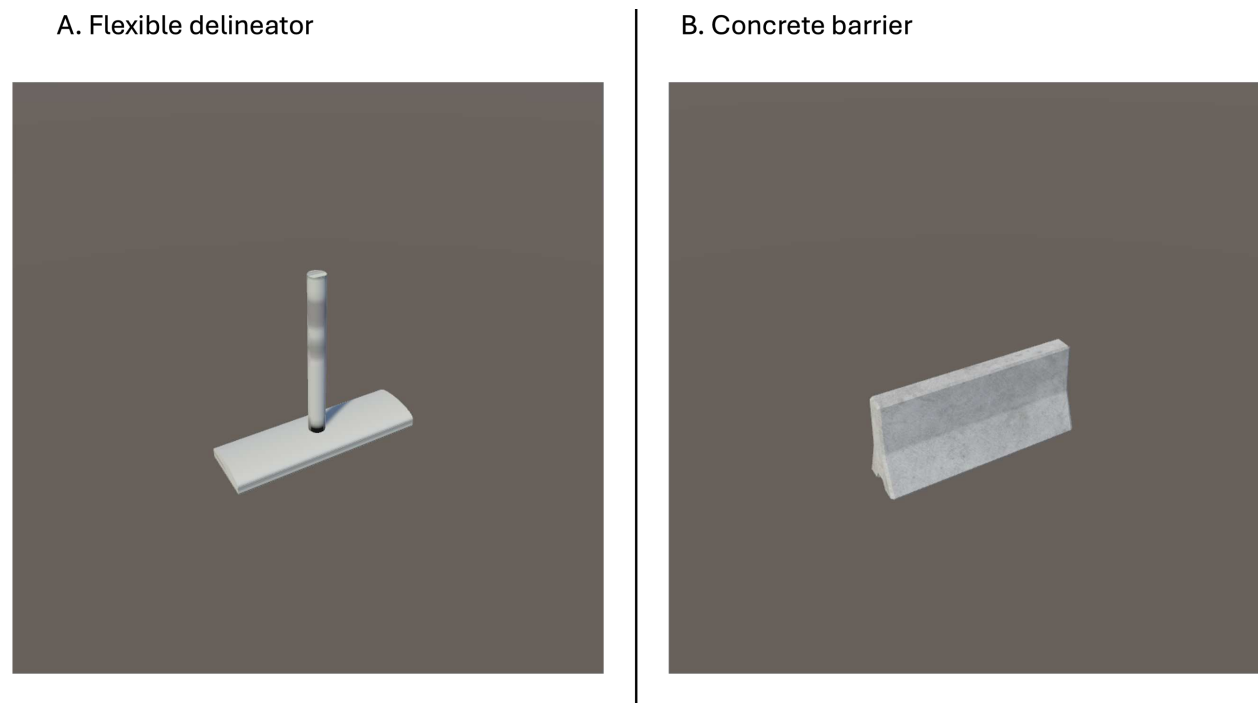
Study conditions

Participants experienced three study conditions: the flexible delineator intervention, the concrete barrier intervention, and the as-built condition. For the condition with a separated bike lane created with flexible delineators, the delineators were placed 6.1 m (20') on center with gaps to allow for turning cyclists/vehicles and marked crosswalks. Each flexible delineator (Figure 21 Panel A) was comprised of a small, raised base (1 x 0.3 x 0.08 m) holding a 0.87 m tall

delineator post 0.08 m in radius (total barrier height = 0.95 m). Approximate locations of the separating delineators are illustrated in Figure 22 Panel A. The material of both the base and the delineator was white plastic. Additionally, this study condition introduced two new zebra crosswalks at locations proposed by CSU Transportation (Figure 22 Panel A).

Figure 21

Virtual delineators and barriers



The study condition with concrete barriers also added these same new zebra crosswalks (Figure 22 Panel B). However, the separated bike lane was delineated with contiguous concrete barriers, each 1 m long and 0.46 m (18") tall (Figure 21 Panel B). These were textured with a white concrete material and placed continuously between motor traffic and bike lanes, interrupted only to allow for zebra crosswalks and turning cyclists/motor vehicles (Figure 22 Panel B). These two intervention study conditions were compared against the as-built condition. Images of the three study conditions are displayed in Figure 23.

Figure 22

Approximate locations of virtual separating elements and marked crossings

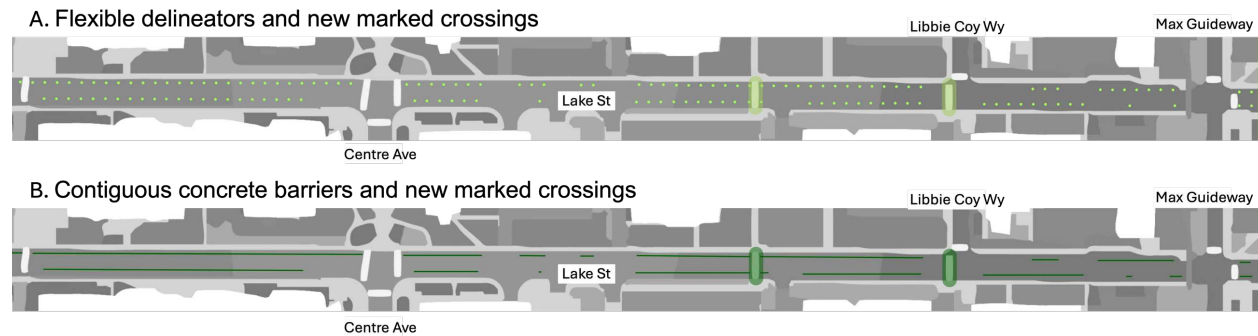


Figure 23

VR simulation depicting tested environmental modifications and as-built condition



The order in which participants experienced these conditions was assigned based on a balanced set of two Latin squares as presented by Williams (1949) to account for learning effects and differential carryover effects. Within the extension of paired Latin squares illustrated in Table 4, each unique order of the three conditions is represented. Every condition is presented first twice and follows every other condition thrice. Participants were randomly assigned to one of the six possible order groups.

Table 4*Balanced Latin square for condition order*

Trial # (Location Pair)	Order Group					
	U	V	W	X	Y	Z
1 (A)	As-built	Flexible delineators	Concrete barriers	Flexible delineators	Concrete barriers	As-built
2 (C)	Concrete barriers	As-built	Flexible delineators	Concrete barriers	As-built	Flexible delineators
3 (B)	Flexible delineators	Concrete barriers	As-built	As-built	Flexible delineators	Concrete barriers
4 (D)	As-built	Flexible delineators	Concrete barriers	Flexible delineators	Concrete barriers	As-built
5 (A)	Concrete barriers	As-built	Flexible delineators	Concrete barriers	As-built	Flexible delineators
6 (C)	Flexible delineators	Concrete barriers	As-built	As-built	Flexible delineators	Concrete barriers
7 (B)	As-built	Flexible delineators	Concrete barriers	Flexible delineators	Concrete barriers	As-built
8 (D)	Concrete barriers	As-built	Flexible delineators	Concrete barriers	As-built	Flexible delineators
9 (A)	Flexible delineators	Concrete barriers	As-built	As-built	Flexible delineators	Concrete barriers
10 (C)	As-built	Flexible delineators	Concrete barriers	Flexible delineators	Concrete barriers	As-built
11 (B)	Concrete barriers	As-built	Flexible delineators	Concrete barriers	As-built	Flexible delineators
12 (D)	Flexible delineators	Concrete barriers	As-built	As-built	Flexible delineators	Concrete barriers

Measures

Perceptions regarding fulfillment of each walking need were self-reported via a single item reading, “How would you evaluate the environment you just experienced?” The language of this question was adopted from Nishio and Ito (2020), wherein participants reported their perceptions of differing VR environments on numerous domains, including pleasantness. The

need for brevity and minimization of survey fatigue primarily drove the decision to use a single item: Participants assessed each walking need in 12 trials. Participants responded to this single item on a sliding scale from extremely hard to reach my destination / extremely unsafe / extremely uncomfortable / extremely unpleasant to extremely easy to reach my destination / extremely safe / extremely comfortable / extremely pleasant. This scale was not anchored by numbers but was scored 0-100. For clarity, these concepts were defined for participants during the tutorial period. Definitions provided to participants are available in Appendix D.

Cybersickness was monitored in real time via the Fast Motion Sickness Questionnaire (FMS, Keshavarz & Hecht, 2011). This measure asks participants to verbally rate their experience of sickness on a scale from 0-20, where 0 represents “no sickness at all” and 20 represents “frank sickness” (Keshavarz & Hecht, 2011, p. 418). Respondents are asked to “focus on nausea, general discomfort, and stomach problems” and ignore “nervousness, boredom and fatigue” (Keshavarz & Hecht, 2011, p. 418). FMS ratings correlate highly with scores on the 16-item Simulator Sickness Questionnaire (Somrak et al., 2021). When the FMS was administered in VR, a dialog box presented these instructions, and the participant provided their rating aloud. If, at any point, the participant’s rating was 15 or greater, I asked if the participant would like to continue as performed by the measure’s authors in validation of the FMS (Keshavarz & Hecht, 2011). If the participant responded negatively, the VR session of the study promptly ended. Additionally, cybersickness was assessed after VR exposure via the more thorough VRISE domain of the VR Neuroscience Questionnaire (VRNQ, $\alpha = 0.89$) (Kourtesis et al., 2019), which asks participants to rate the experienced intensity of nausea, disorientation, dizziness, fatigue, and instability using a 7-point Likert-scale, in which higher scores indicate less intense

symptoms. The VRNQ VRISE domain has also been validated against the Simulator Sickness Questionnaire (Somrak et al., 2021).

In the same survey after exiting VR, participants responded to the iGroup Presence Questionnaire (IPQ, $\alpha = 0.87$) (Schubert et al., 2001) to quantify presence, the feeling of “being there” (Heeter, 1992). This measure consists of 14 items querying realism, general presence, physical presence, and attention to the virtual environment relative to the outside environment. Respondents answer on a 7-point anchored Likert scale.

This post-VR survey also debriefed participants on the three street designs they experienced in VR. They were asked to identify which of the three was their top preference and their lowest preference. Subsequently, free response survey items prompted them to explain the reasons behind their choices. The presentation of these preference items is shown in Figure 24. Appendix D lists the complete surveys utilized in the present study.

Figure 24

Survey items regarding preference

A. Ranking items

Today, you experienced three different street designs shown below:

A: Plastic barrier between cars and pedestrians



B: Concrete barrier between cars and pedestrians



C: No barrier between cars and pedestrians



Which street design is your top preference?

A: Plastic barrier between cars and pedestrians

B: Concrete barrier between cars and pedestrians

C: No barrier

Which street design is your least preferred option?

A: Plastic barrier between cars and pedestrians

B: Concrete barrier between cars and pedestrians

C: No barrier

>>

B. Explanation items

Please share why you ranked A: **Plastic barrier between cars and pedestrians** as your top preference.

Please share why you ranked B: **Concrete barrier between cars and pedestrians** as your least preferred option.

>>

Procedures

Participants individually reported to a small laboratory space on CSU's campus (2.90 x 4.00 m) for their study session and provided informed consent. They also reported a baseline FMS score. I fit the Quest 2 HMD's lens distance using a mm ruler to estimate the participant's interocular distance. The Quest 2 glasses spacer was installed as appropriate. The participant put on a leg strap, which held the VR hand controller corresponding to their nondominant hand.

This equipment allowed the simulation to detect when the participant was stepping-in-place, the method by which they would move in VR.

Modeling with the controller of the participant's dominant hand, I instructed the participant on how to interact with virtual text screens and how to use the stepping-in-place locomotion technique. Subsequently, the participant entered VR, and I adjusted the fit of the HMD, ensuring that the set-up was comfortable and the virtual image was clear. The Qualtrics built-in randomizer assigned the participant to an order group. I began the version of the simulation that matched this order group and the participant's handedness.

During a brief tutorial (mean length = 5.52 min), the participant acclimated to VR as recommended by guidelines for the use of VR in human subjects research (Birenboim et al., 2021; Joseph et al., 2020). The participant was introduced to key terms (i.e., convenience, safety, comfort, pleasurability) and the study task (i.e., to navigate to the destination). This tutorial reviewed interaction with text screens and stepping-in-place. The participant also practiced navigating with the handheld map and using a sliding scale to respond to survey questions. At the culmination of this tutorial, the participant answered the FMS and was reminded that they could leave VR for a break or end the VR session whenever they wanted.

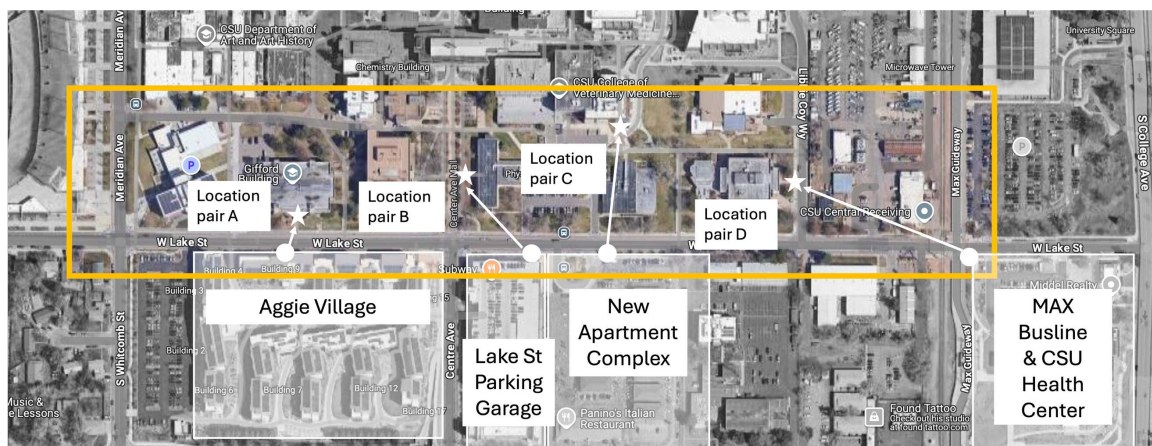
After the tutorial, the participant completed 12 trials, four in each study condition according to their randomized order group. (See Table 4.) Each trial proceeded as follows:

1. The participant's viewport faded into one of four common points of interest on the south sidewalk of Lake St (labelled with circles in Figure 25). The four starting locations were individually paired with common destinations north of Lake St (stars in Figure 25) in collaboration with CSU Transportation to reflect routine walking

- routes on campus. Henceforth, these are named “location pairs” and have been labeled A-D. The participant completed each location pair three times, meaning study conditions were fully-crossed with location pairs. For simplicity of VR coding, the order of location pairs was constant across participants (Table 4).
2. As previously mentioned, the participant’s task was to use stepping-in-place to move to the destination via a self-selected route. The simulation barred them from taking shortcuts though buildings or jumping fences. Notably, the participant was able to move through the virtual concrete barriers, representing stepping over them.
 3. After arriving at their destination, the participant completed a brief survey inside the VR simulation assessing environmental perceptions and verbally reported the FMS.
 4. When the survey was complete, the participant’s view faded to black, and they progressed to the next trial.

Figure 25

Study 2 start and destination location pairs



Note. Gold rectangle represents VR simulation boundary.

When all 12 trials were complete or when the participant chose to end the VR period, I helped the participant remove the VR equipment. The participant responded to the post-VR survey on a desktop computer. This survey queried cybersickness, presence, preference, and demographics. Participants were debriefed and received \$40 for their participation. This study was approved by Colorado State University's Institutional Review Board (Protocol #7136).

Analyses

Data cleaning was performed in R Statistical Software (Version 4.3.3) with RStudio (Version 2023.12.1+402). Table 5 details missing data stratified by each outcome variable. Overall, this study contained a very low percentage of missing data (Range = 0.0-1.3%). Six participants had missing data from trials – two due to early termination of the VR session (after trials 8 and 10) and four due to missing data from a single trial that occurred because of errors saving the data. One participant did not finish the post-experience survey due to time limitations, resulting in a single missing preference observation. All predictors were manipulated variables (i.e., condition, trial number, location pair); thus, these values were only missing when a participant did not complete a trial. For all analyses, treatment of missing data involved listwise deletion, the default in the utilized statistical packages and software.

Table 5*Missing data by outcome*

Outcome variable	% Missing observations	Reason for missingness [# of participants (# missing observations/participant)]
Perception of walking needs	0.9%	Early VR termination [1(2), 1(4)] Error saving data [2(1)]
FMS	0.1%	Proceeded through the FMS prompt in the VR tutorial without responding [1(1)]
Crossing data	0.9%	Early VR termination [1(2), 1(4)] Error saving data [2(1)]
Preferences	1.3%	Session duration elapsed before survey was complete [1]
Presence	0.0%	NA
Cybersickness	0.0%	NA

Perception of walking needs

Within-subjects data of perceptions of walking needs were highly clustered [$ICC_{\text{Range}} = 0.35\text{--}0.57$, Kish's design effect $_{\text{Range}} = 4.81\text{--}7.21$], indicating violation of the assumption of uncorrelated error terms. Accordingly, analyses for these data were completed using the multilevel structural equation modeling (MSEM) framework using Mplus (Version 8.10, L. K. Muthén & Muthén, 1998). These data were slightly negatively skewed (Skewness $_{\text{Range}} = -0.69$ - - 0.3), indicating ceiling effects. Thus, perceptions of walking needs were treated as censored variables. Additionally, perceptions of walking needs were highly correlated. (See Table 6.) With the current limitations of the Mplus software, this shared covariance cannot be estimated among censored variables. Consequently, I selected a two-step approach to analyzing these walking needs data.

Table 6*Correlation matrix of walking needs*

Note. [LL, UL] indicates a 95% CI.

Variable	1	2	3
1. Accessibility			
2. Safety	0.653 [0.614, 0.689]		
3. Comfort	0.692 [0.656, 0.725]	0.707 [0.673, 0.738]	
4. Pleasurability	0.576 [0.531, 0.619]	0.626 [0.585, 0.665]	0.663 [0.624, 0.698]

First, separate analyses were completed for each walking need, treating it as a censored variable. These models used the Maximum Likelihood with Robust Standard Errors (MLR) estimator, which provides identical point estimates to the maximum likelihood estimator but employs sandwich standard errors, supplying robustness against nonnormality observed in the data (L. K. Muthén & Muthén, 1998; Rosseel, 2017). Built environmental modifications were captured using two level-1 nominal variable indicators (i.e., dummy codes) with the as-built condition as the reference. A direct path was estimated between these environmental modification variables and each walking need on level 1. Location pair (level-1 variable) was included as a categorical control represented by 3 indicator variables (reference: location pair D). Trial number (continuous level-1 variable) controlled for practice effects. Following a model building approach, four models for each walking need were compared: (1) Fixed intercept and slopes; (2) Random intercept, fixed slopes; (3) Fixed intercept, random slopes for environmental

modification indicator variables; (4) Random intercept and slopes. Fit criteria included sample size adjusted Bayesian Information criterion (saBIC; Sclove, 1987): These values represent relative fit, such that among nested models, an saBIC of a more complex model is interpreted as evidence for a better fit to the data if it is closer to 0 than the saBIC of a simpler model (B. Muthén & Muthén, 2000).

Second, a model was fit in which all walking needs served as indicators of two latent variables [(1) level-1, (2) level-2]. The Bayes estimator with non-informative priors was employed for this model as it is known to handle nonnormality well (B. Muthén, 2010). Similar to the separate walking needs models, two level-1 indicator variables represented environmental modifications and were used to predict the level-1 latent variable. For this approach, model comparison selected both control variables and random slopes as the model with all control variables fit poorly (PPP = 0.00). Regarding controls, model fit criteria included Deviance Information Criterion (DIC; Spiegelhalter et al., 2002), predictive p-value (PPP; Meng, 1994), and potential scale reduction (PSR) of the last iteration (Gelman & Rubin, 1992). DIC can be interpreted similarly to saBIC with evidence for better fit of a more complex model if its DIC is closer to 0 than a simpler nested model. The magnitude of the evidence increases with the size of the margin; Cain and Zhang (2019) recommend a DIC margin of at least 7 to justify the selection of a more complex model. Additionally, a well-fitting model reports a PPP of approximately 0.5 and a PSR of 1.0; however, PPPs ranging 0.05 to 0.95 are acceptable (Gelman, 2014). PPP is not available for models with random effects; thus, only DIC and PSR were examined for these models.

Midblock crossings

Exploratory analyses queried if the introduced interventions reduced unmarked midblock crossings. To do so, the coordinates of the participant within virtual space were recorded at a frequency of 2 Hz. Coordinate points for a single route were filtered to only those ≥ 1 m from the previous point. These data were used for visualization.

For crossings analyses, the coordinate data were further reduced to only those points at least two meters into Lake St defined as the southernmost and northernmost coordinates of the virtual street ± 2 m. Each street crossing was categorized as within five meters of a marked crosswalk ($Y = 1$, $N = 0$) using the same method with the eastmost and westmost coordinates of each virtual crosswalk ± 5 m. This method resulted in only two undefined categorizations, in which only a portion of the crossing was within five meters of a crosswalk. These two observations were manually categorized based on a visual map. Sensitivity analyses excluding these manual categorizations did not alter conclusions and can be found in Appendix C. If a participant collided with another road user and restarted the trial, both street crossings were retained and treated individually. Using the lme4 package (Version 1.1-35.1, Bates et al., 2015) in R Statistical Software, multilevel logistic regression modeled the log odds of crossing within five meters of a crosswalk as a function of environmental modification indicator variables (reference: as-built condition) and a random intercept for participant, accounting for variability in participants' tendencies to cross within a marked crosswalk.

Preferences

In R Statistical Software, two exploratory chi-square goodness of fit tests examined whether the distributions of top preference and lowest preference quantitative data differed

from uniform distributions. Observed deviations from uniform distributions were probed via pairwise comparisons using odds ratios. Descriptive responses regarding preference reasoning were analyzed using Miles and colleagues' (2020) thematic analysis approach in Microsoft Excel.

Route distance

Distance analyses were added to explore free response findings related to free movement and accessibility of the environmental modifications. These analyses employed the same coordinate data as the visualization of crossing behavior. Only trials in which the participant successfully reached their destination were retained. For example, if a participant restarted a trial for any reason, only their final successful attempt was included in distance analyses. For each of these trials, the distance between every coordinate point from trial initiation to destination arrival was calculated and summed. Using the MSEM framework, the total distance of each route was regressed on two environmental modification indicator variables (reference: as-built condition) as well as location pair controls (reference: D) and trial number at level 1 using the Bayes estimator with noninformative priors.

The intervention conditions introduced new zebra crosswalks near location pairs C and D but not location pairs A and B. For this reason, models in which location pair moderates the level-1 path between condition and route distance were explored. Preacher (2016) recommends the latent moderated structural equation approach (LMS) to model level-1 moderation [1x(1->1)] in order to address the conflation of multilevel moderation effects. However, this approach does not apply to moderation between within-only exogenous variables since no conflation is present. Asparouhov and Muthén (2012) propose multilevel mixture modeling as an alternative approach to moderation with at least one categorical exogenous variable. Again,

this approach centers around between-level variance of the categorical variable (i.e., known latent class). In the current study, location pair and condition were manipulated within-subjects in a fully-crossed design; consequently, they contain only level-1 variability and share no covariance. Thus, the above approaches are not applicable, and moderation in the current study was modeled via the product of the indicator variables of location pair and condition.

Individual differences in tendency to cross without a marked crosswalk may influence heterogeneity regarding the effects of the introduction of new zebra crosswalks and location pairs (which varied in their proximity to marked crosswalks) on route distance. Therefore, model comparison contrasted models with fixed and random intercepts and fixed and random slopes for environmental modifications, for location pairs, and for the interaction. Model fit criteria were identical to the previously described latent variable models with the Bayes estimator and non-informative priors ($0.05 \leq \text{PPP} \leq 0.95$, $\text{PSR} \approx 1.0$, $\Delta\text{DIC} \geq 7$).

STUDY 2 RESULTS

Description of presence and cybersickness

The level of presence participants of this study experienced [$M = 3.535$ ($SD = 0.974$)] falls within the marginally-acceptable grade outlined by Melo et al. (2023). This overall presence score is approximately in the 61st percentile among over 200 studies reviewed by Tran et al. (2024), placing it in Tran et al.'s moderate rank. Participants in the current study reported little experience of the involvement [3.070 (1.206)] and realism [2.597 (1.060)] domains of the IPQ. Experience of spatial presence [4.165 (1.123)] was slightly better. Ratings of cybersickness (median = 29) met the minimum cutoff (25) and neared the “parsimonious cutoff” (30) of the VRNQ VRISE domain (Kourtesis et al., 2019). Additionally, the median FMS scores before entering VR, before the first trial, and after the last trial were 0 ($SD = 1.116$), 0 (1.272), and 2 (3.777), indicating low intensity of cybersickness. Indeed, only one participant intentionally provided a rating at or above 15 and chose to leave the VR simulation early.²

Perception of walking needs

Model fit indices for separate walking needs are presented in Table 7. For each outcome, the best fitting model estimated a random intercept and fixed slopes, indicating meaningful individual differences in participants' rating tendencies [$SD(\text{intercept})_{\text{Accessibility}} = 16.428$, $SD(\text{intercept})_{\text{Safety}} = 17.889$, $SD(\text{intercept})_{\text{Comfort}} = 19.379$, $SD(\text{intercept})_{\text{Pleasurability}} = 19.263$], but

² One participant rated a 20 on trial 10 after providing zeros for all previous FMS ratings, and they responded that they did not wish to continue. After the participant left VR, I confirmed their rating of 20, and they clarified that they meant zero. They did not provide any additional explanation for wanting to leave VR but verified that they were not cybersick and meant to report zeros throughout the entire exposure.

not in their responses to environmental conditions. In the following interpretation, b and β are used to refer to unstandardized and standardized path coefficients, respectively.

Table 7

Model fit indices for separate walking needs

Note. Bold indicates the best fitting model for each outcome.

Outcome	Fixed effects	Random effects	saBIC
Accessibility	Intercepts Condition slopes Control slopes	NA	7462.112
	Condition slopes Control slopes	Intercepts	7150.701
	Intercepts Control slopes	Condition slopes	7368.345
	Control slopes	Intercepts Condition slopes	7157.952
Safety	Intercepts Condition slopes Control slopes	NA	7825.999
	Condition slopes Control slopes	Intercepts	7407.790
	Intercepts Control slopes	Condition slopes	7697.311
	Control slopes	Intercepts Condition slopes	7415.070
Comfort	Intercepts Condition slopes Control slopes	NA	7586.156
	Condition slopes Control slopes	Intercepts	6986.225

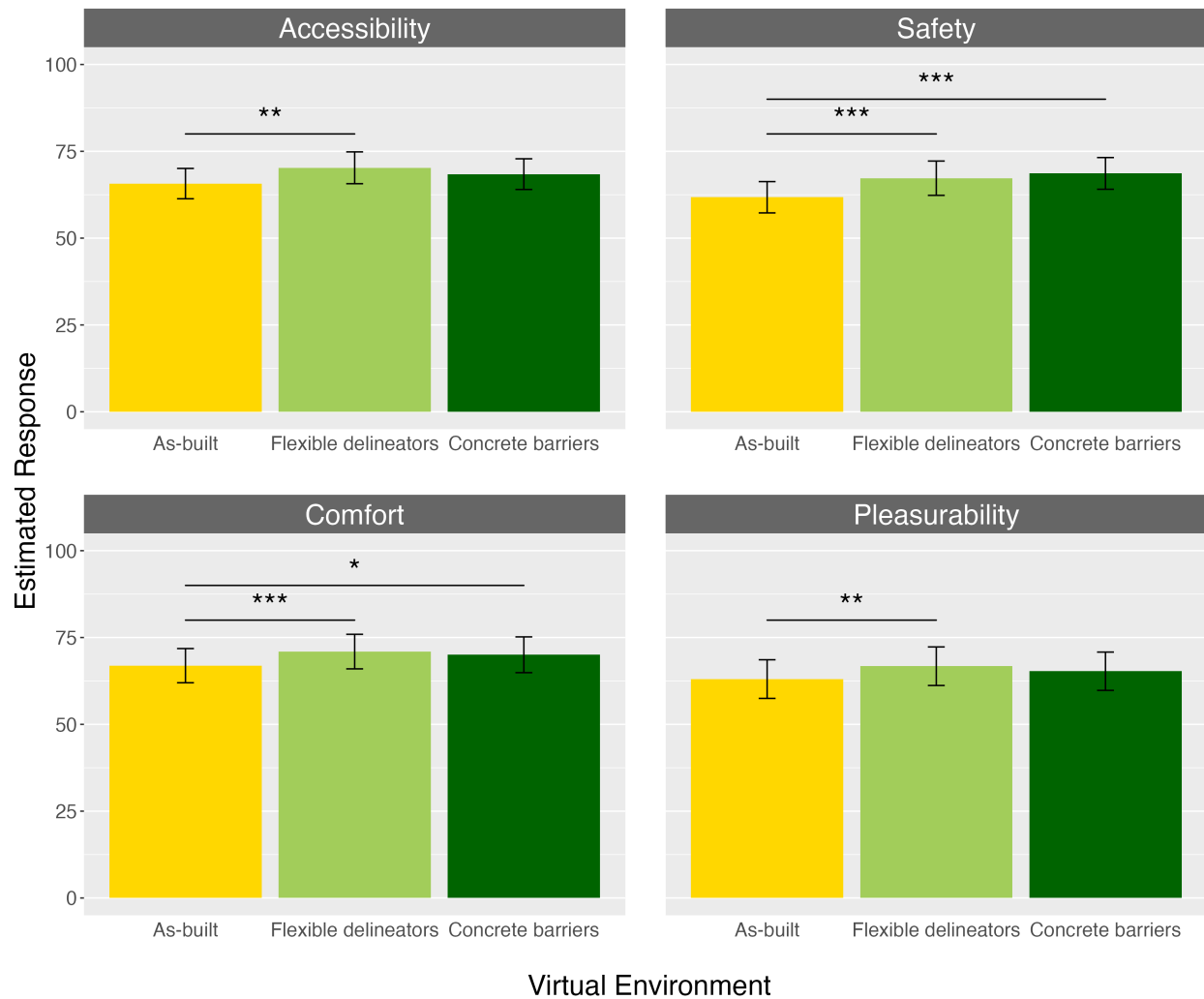
Outcome	Fixed effects	Random effects	saBIC
	Intercepts Control slopes	Condition slopes	7407.394
	Control slopes	Intercepts Condition slopes	6993.382
Pleasurability	Intercepts Condition slopes Control slopes	NA	7567.328
	Condition slopes Control slopes	Intercepts	7034.433
	Intercepts Control slopes	Condition slopes	7399.260
	Control slopes	Intercepts Condition slopes	7041.898

Accessibility

There was evidence for a small difference between perceptions of accessibility in response to the environment with the flexible delineators compared to the as-built environment, when controlling for location pair and trial number ($\beta = 0.106$, 95% confidence interval (CI) [0.045, 0.166], SE = 0.031, $p = 0.001$). The model estimated that participants responded about 4.6 units higher on the 100 pt scale for accessibility in the flexible delineator intervention condition than the as-built condition when accounting for controls ($b = 4.556$, 95%CI[1.919, 7.194]). The difference in accessibility ratings between the environment with contiguous concrete barriers and the as-built condition ($\beta = 0.063$, 95%CI[-0.014, 0.141], SE = 0.040, $p = 0.110$) as well as between both intervention conditions ($\beta = -0.042$, 95%CI[-0.102, 0.017], SE = 0.030, $p = 0.166$) were clinically and statistically insignificant. This pattern is illustrated in Figure 26, and a standardized path diagram is presented in Figure 27.

Figure 26

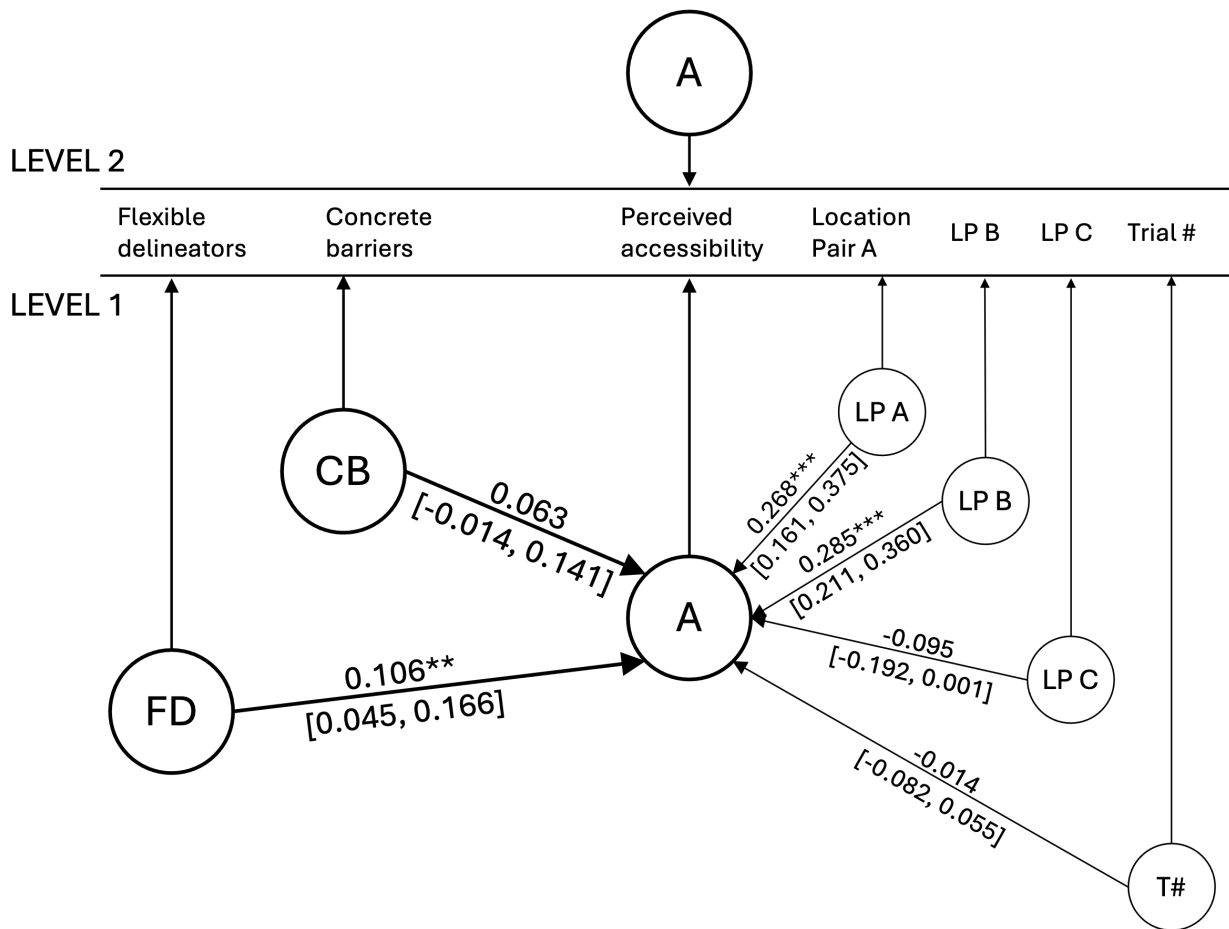
Estimated perceptions of countermeasures against as-built condition



Note. * indicates $p < 0.05$, ** indicates $p < 0.01$, *** indicates $p < 0.001$. Estimated values were calculated at the control levels of trial number 1 and location pair D.

Figure 27

Standardized path diagram for perceived accessibility



Note. [LL, UL] indicates a 95% CI. Reference categories are as follows: Condition: as-built; Location pair: D. * indicates $p < 0.05$, ** indicates $p < 0.01$, *** indicates $p < 0.001$.

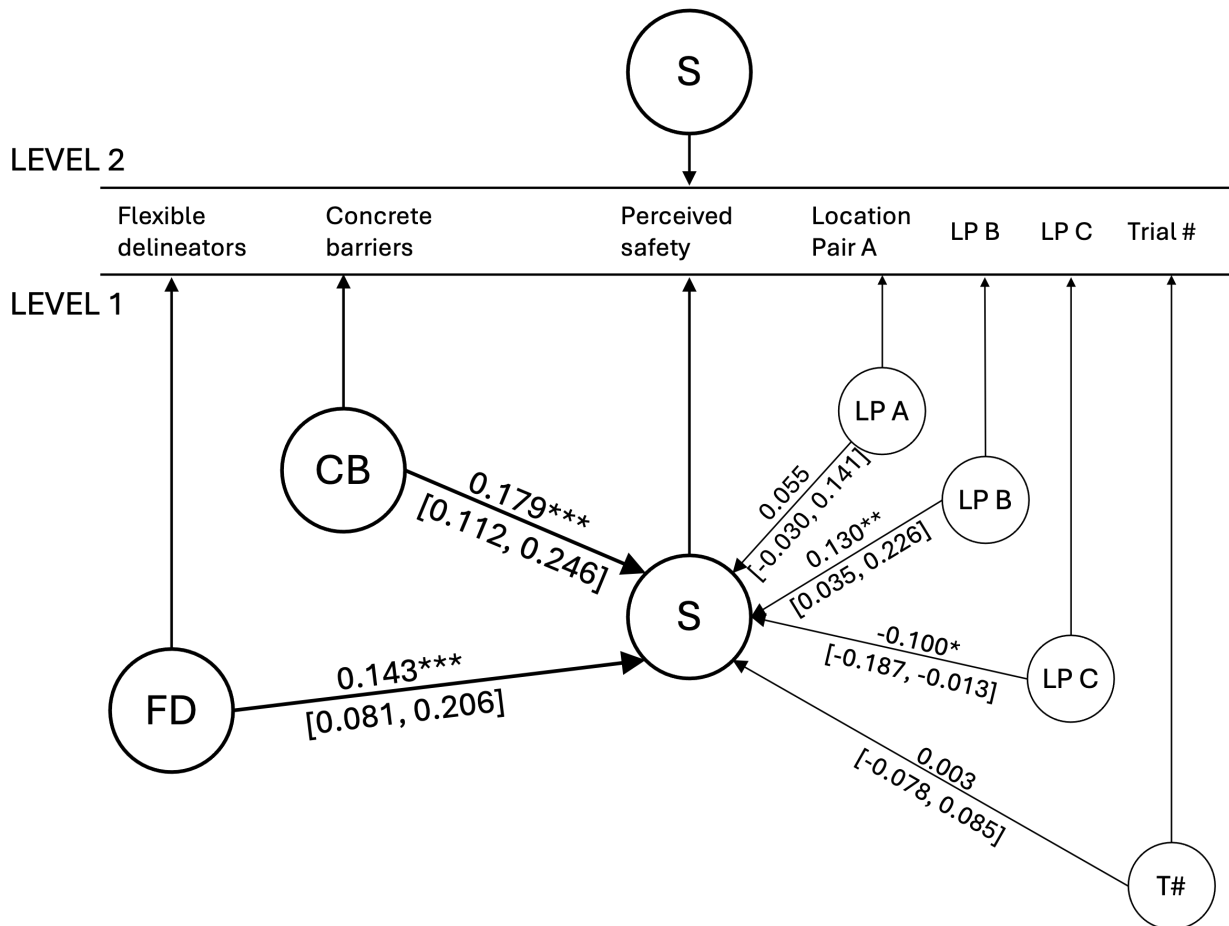
Safety

There was strong evidence for increased perceptions of safety in response to both the intervention conditions with flexible delineators ($\beta = 0.143$, 95%CI[0.081, 0.206], SE = 0.032, $p < 0.001$) and with contiguous concrete barriers ($\beta = 0.179$, 95%CI[0.112, 0.246], SE = 0.034, $p < 0.001$) compared to the as-built condition and accounting for location pair and trial number. See Figures 26 and 28. The best fitting model estimated that safety responses to the flexible

delineator condition were about 5.5 units higher than the as-built condition ($b = 5.483$, $95\%CI[3.091, 7.875]$) while those to the contiguous concrete barrier intervention were 6.9 units higher than the as-built condition ($b = 6.862$, $95\%CI[4.145, 9.579]$). Again, the difference between the two intervention conditions was negligible ($\beta = 0.036$, $95\%CI[-0.024, 0.095]$, $SE = 0.030$, $p = 0.236$).

Figure 28

Standardized path diagram for perceived safety



Note. [LL, UL] indicates a 95% CI. Reference categories are as follows: Condition: as-built; Location pair: D. * indicates $p < 0.05$, ** indicates $p < 0.01$, *** indicates $p < 0.001$.

Comfort

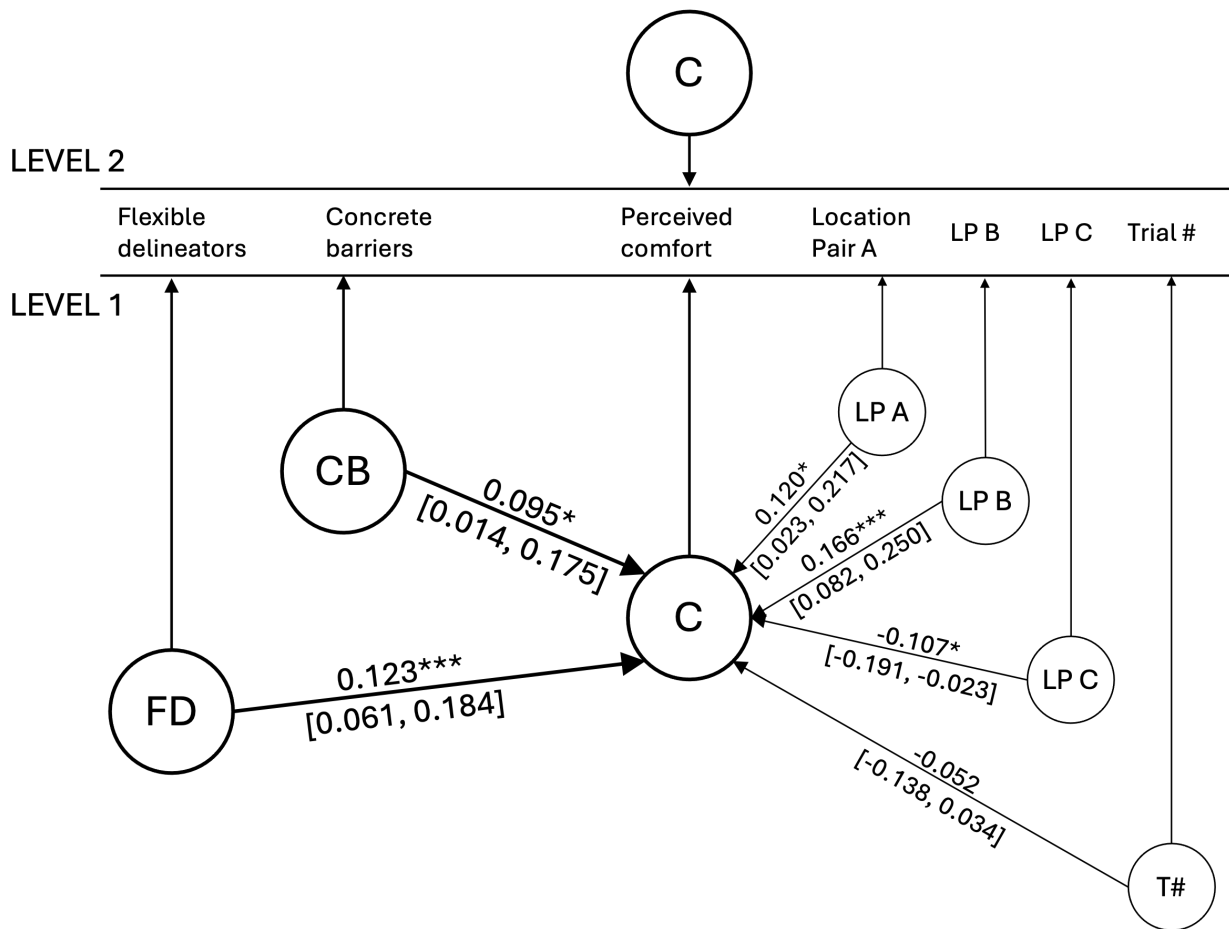
Similar to perceptions of safety, both the flexible delineator intervention ($\beta = 0.123$, 95%CI[0.061, 0.184], SE = 0.031, $p < 0.001$) and the contiguous concrete barrier intervention ($\beta = 0.095$, 95%CI[0.014, 0.175], SE = 0.041, $p = 0.021$) resulted in higher judgements of comfort than the as-built condition when controlling for trial number and location pair (Figures 26 and 29). The difference in ratings between each intervention condition and the as-built condition were each small ($b_{\text{Flexible}} = 4.058$, 95%CI_{Flexible}[2.062, 6.054]; $b_{\text{Concrete}} = 3.138$, 95% CI_{Concrete}[0.408, 5.868]), and there was no evidence that the intervention conditions differed from one another ($\beta = -0.028$, 95%CI[-0.094, 0.038], SE = 0.034, $p = 0.410$).

Pleasurability

There was only evidence for a small difference in perceptions of pleasurability for the environment with a separated bike lane created by flexible delineators compared to the as-built environment ($\beta = 0.103$, 95%CI[0.030, 0.176], SE = 0.037, $p = 0.006$) when accounting for controls (Figures 26 and 30). Based on the best-fitting model estimates and adjusting for trial number and location pair, participants responded with pleasurability ratings of 3.7 units higher in the flexible delineator condition than the as-built condition ($b = 3.704$, 95%CI[1.111, 6.297]). There was no evidence for a difference between the contiguous concrete separated bike lane condition and the as-built condition ($\beta = 0.063$, 95%CI[-0.011, 0.136], SE = 0.038, $p = 0.096$) nor between the contiguous concrete and flexible delineator intervention conditions ($\beta = -0.040$, 95%CI[-0.100, 0.020], SE = 0.031, $p = 0.191$).

Figure 29

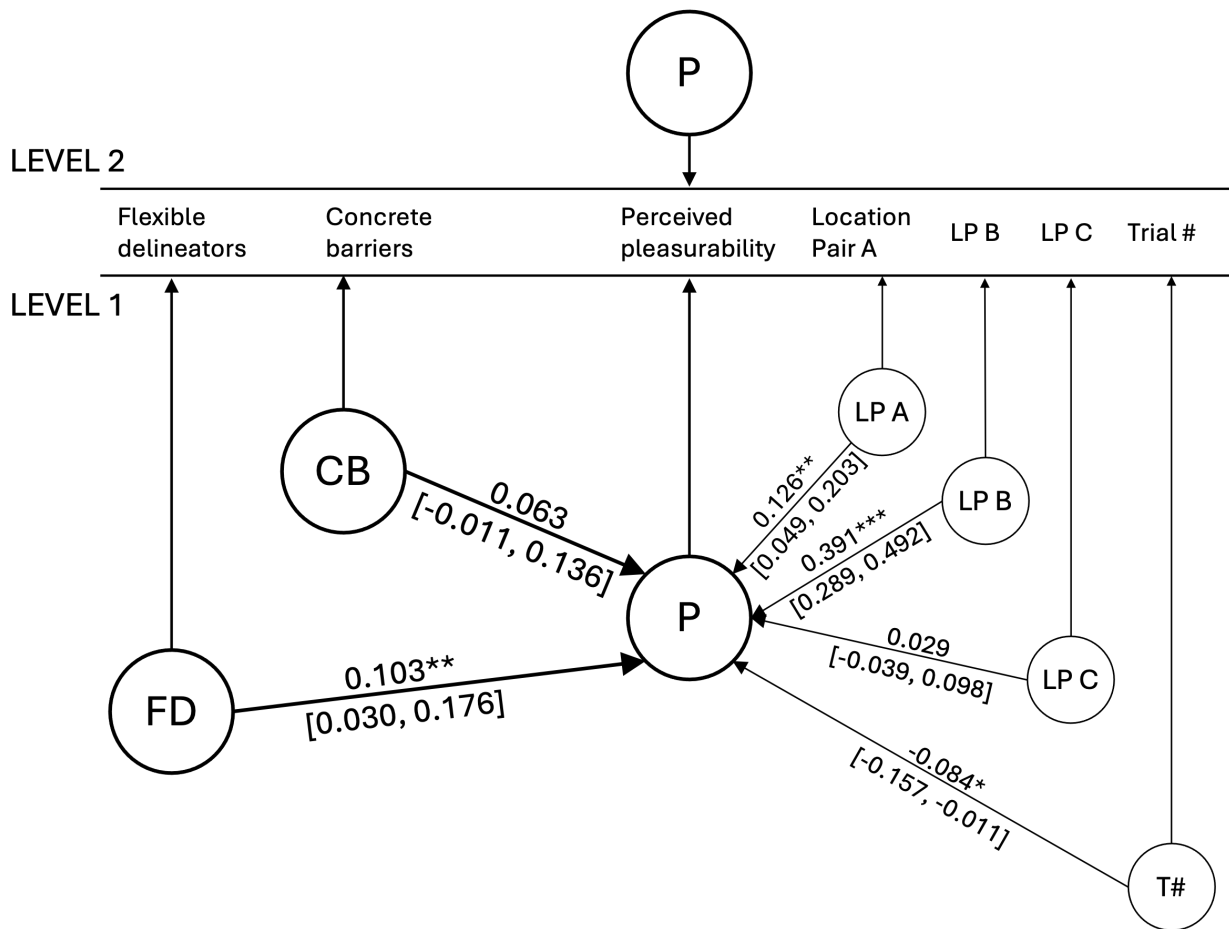
Standardized path diagram for perceived comfort



Note. [LL, UL] indicates a 95% CI. Reference categories are as follows: Condition: as-built; Location pair: D. * indicates $p < 0.05$, ** indicates $p < 0.01$, *** indicates $p < 0.001$.

Figure 30

Standardized path diagram for perceived pleasurability



Note. [LL, UL] indicates a 95% CI. Reference categories are as follows: Condition: as-built; Location pair: D. * indicates $p < 0.05$, ** indicates $p < 0.01$, *** indicates $p < 0.001$.

Latent variables

The measurement model specifying level-1 and level-2 latent variables with perception of walking needs indicators fit well (PPP = 0.548, PSR = 1.042). The standardized loadings for each indicator were appropriately high (Range = 0.616 – 0.904). These latent variables have been named versions of “audiovisual walkability perceptions.” Recent research investigating walking needs based on VR exposures have referred to the needs collectively as “perceived

walkability” (Fang et al., 2024; Vo & Kim, 2024). However, others have named similar constructs “visual walkability perceptions” to emphasize the sensory factors influencing walking behavior that are not present in these exposures (Huang et al., 2023). As the VR simulation employed in the present study contained both auditory and visual stimuli, I have selected the term “audiovisual walkability perceptions.”

The level-2 latent variable represents individual differences in audiovisual walkability rating tendencies. This aligns with research indicating individual factors of perceived walkability [e.g., education level (De Vos et al., 2023), attitudes toward walking (Van Der Vlugt et al., 2025)] as well as Alfonzo’s (2005) theory, which specifies individual differences in judgements of walking needs. Thus, the level-2 latent variable has been named “Person-level audiovisual walkability perceptions.” It explained 92% of level-2 variability in accessibility ($R^2 = 0.915$), 86% of that in safety ($R^2 = 0.858$), 77% of that in comfort ($R^2 = 0.769$), and 77% of that in pleasurability ($R^2 = 0.769$). Moreover, the latent variable results indicated that individuals who tended to provide high ratings for one indicator did so for others.

Conversely, the level-1 latent variable represents variability in ratings of audiovisual walkability from trial to trial; therefore, it has been named “exposure-based audiovisual walkability perceptions.” This latent variable explained 46% of level-1 variability in accessibility ($R^2 = 0.460$), 52% of that in safety ($R^2 = 0.518$), 75% of that in comfort ($R^2 = 0.747$), and 38% of that in pleasurability ($R^2 = 0.379$). Similar to the level-2 latent variable results, high levels of exposure-based audiovisual walkability perceptions were linked to high ratings of all walking needs.

Fit indices for comparison of structural models are presented in Table 8. As shown in this table, the best fitting model included fixed slopes and no control variables, and it fit acceptably (PPP = 0.274, PSR = 1.002). Thus, location pair and trial number did not explain substantial variance in exposure-based audiovisual walkability perceptions above and beyond condition alone. Also, there were not meaningful individual differences in the effect of condition on exposure-based audiovisual walkability perceptions.

Table 8

Latent variable structural model fit indices

Note. Bold indicates the best fitting model.

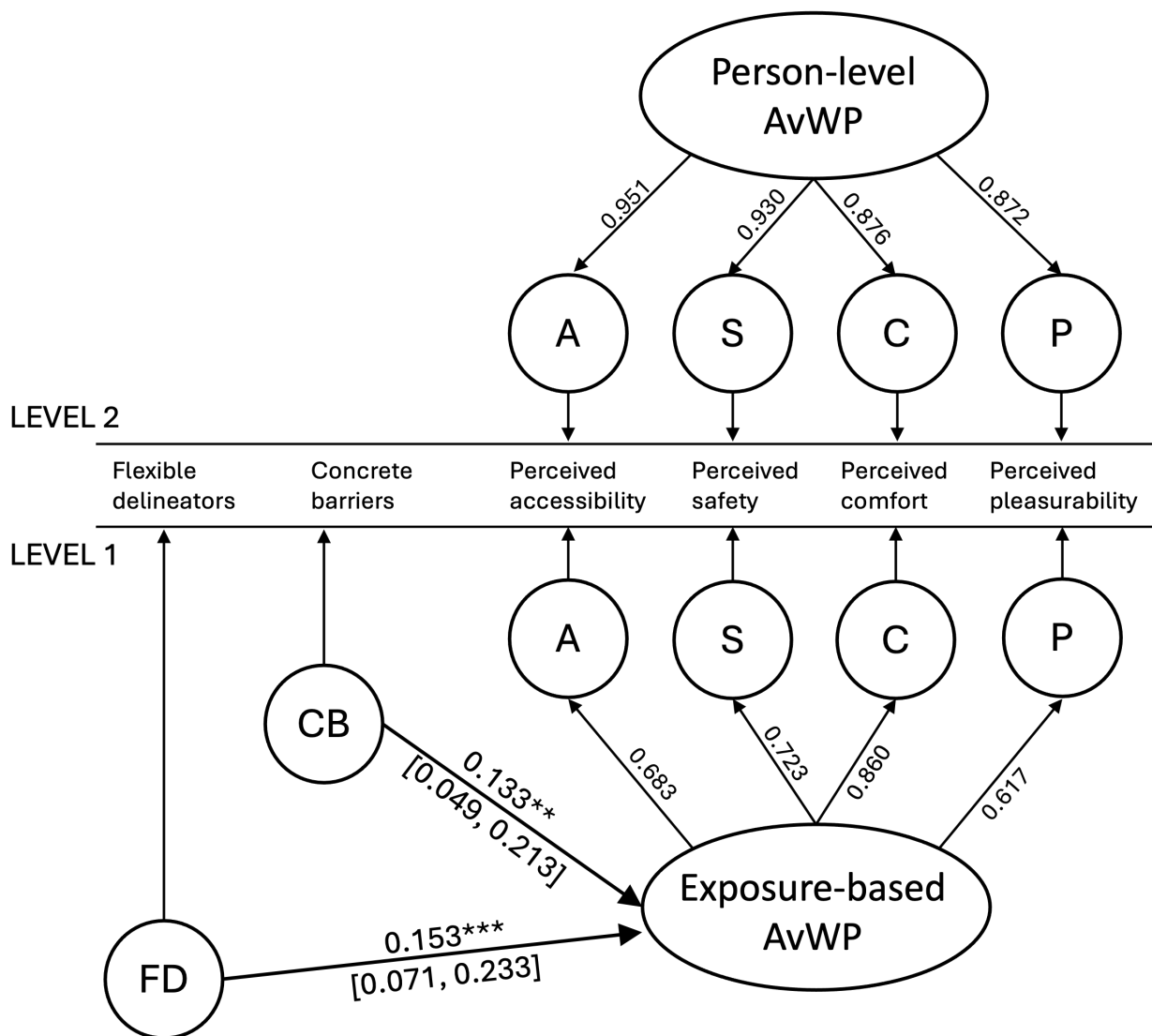
Random effects	Fixed effects	PPP	DIC	PSR
Intercept	Condition	0.274	29213.204	1.002
Intercept Condition	NA	NA	29220.461	1.001
Intercept	Condition Location Pair	0.000	29112.422	1.001
Intercept	Condition Trial number	0.152	29211.526	1.001
Intercept	Condition Location Pair Trial number	0.000	29114.917	1.001

Aligned with patterns observed in discrete walking need models, there was evidence for moderately-small differences in exposure-based audiovisual walkability perceptions between the flexible delineator and the as-built condition ($\beta = 0.153$, 95% Credible Interval (CrI) [0.071, 0.233], Posterior SD = 0.041, $p < 0.001$) as well as between the contiguous concrete barrier and

the as-built condition ($\beta = 0.133$, 95%CrI[0.049, 0.213], Posterior SD = 0.042, $p = 0.001$). See Figure 31. Furthermore, there was no evidence for a difference in exposure-based audiovisual walkability perceptions between the two types of separated bike lane ($\beta = -0.020$, 95%CrI[-0.103, 0.062], Posterior SD = 0.042, $p = 0.314$).

Figure 31

Standardized path diagram for latent variable model



Note. [LL, UL] indicates a 95% CrI. Condition reference: as-built. AvWP refers to audiovisual walkability perceptions. * indicates $p < 0.05$, ** indicates $p < 0.01$, *** indicates $p < 0.001$.

Midblock crossings

According to multilevel logistic regression models, there was evidence that the odds of crossing the street within five meters of a marked crosswalk differed based on condition ($\chi^2 = 43.867$, $p < 0.0001$, Table 9). For the typical participant, the interventions with flexible delineators and contiguous concrete barriers were associated with 116.0% higher (95%CI[45.9%, 219.6%], $\chi^2 = 3.850$, $p = 0.0001$) and 297.6% higher (95%CI[160.7%, 506.5%], $\chi^2 = 6.408$, $p < 0.0001$) estimated odds of crossing the street within five meters of a marked crosswalk than the as-built condition, respectively. Between the two types of interventions, the estimated odds of crossing within five meters of a marked crosswalk were 84.1% higher in environments with the concrete barriers compared to the flexible delineators (95%CI[20.0%, 182.6%], $\chi^2 = 2.792$, $p = 0.005$). Figure 32 illustrates virtual street crossings in each environmental condition.

Table 9

Frequency table of incidence of marked crossings by condition

Condition	Marked	Unmarked	Total
Flexible delineators	218	80	298
Concrete barriers	247	56	303
As-built	183	120	303
Total	648	256	904

Figure 32

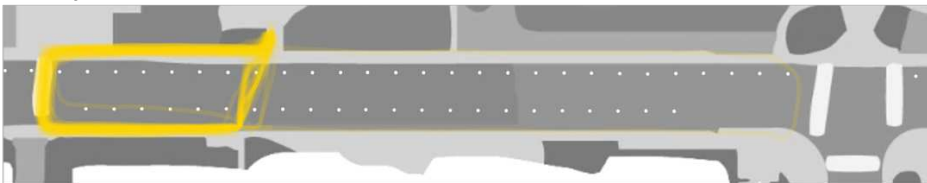
Crossing routes stratified by condition

A. Location pair A

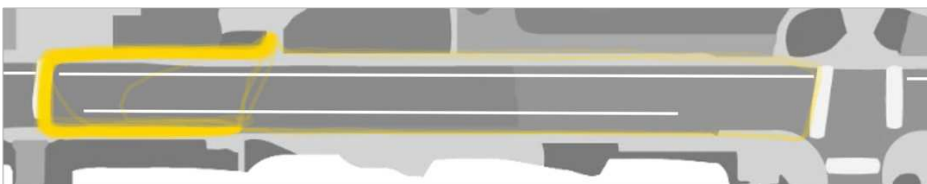
I. As-built



II. Separated – Flexible delineators

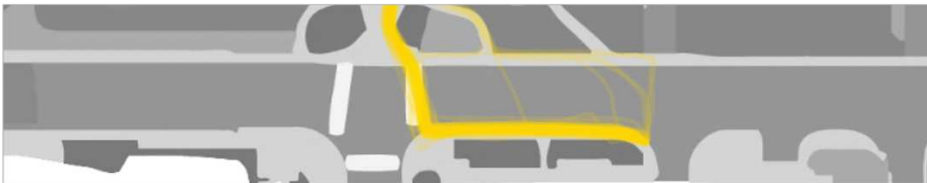


III. Separated – Contiguous concrete barriers



B. Location pair B

I. As-built



II. Separated – Flexible delineators



III. Separated – Contiguous concrete barriers

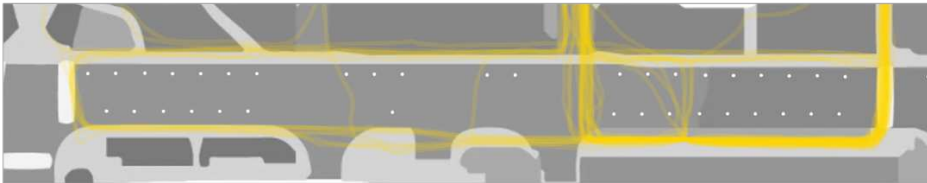


C. Location pair C

I. As-built



II. Separated – Flexible delineators

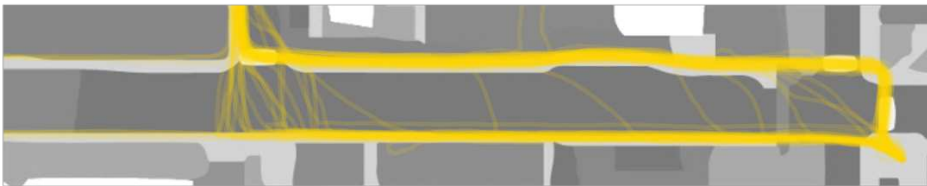


III. Separated – Contiguous concrete barriers

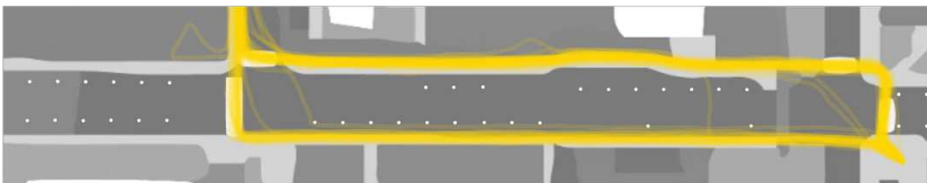


D. Location pair D

I. As-built



II. Separated – Flexible delineators



III. Separated – Contiguous concrete barriers



Note. Each yellow line represents a single crossing attempt.

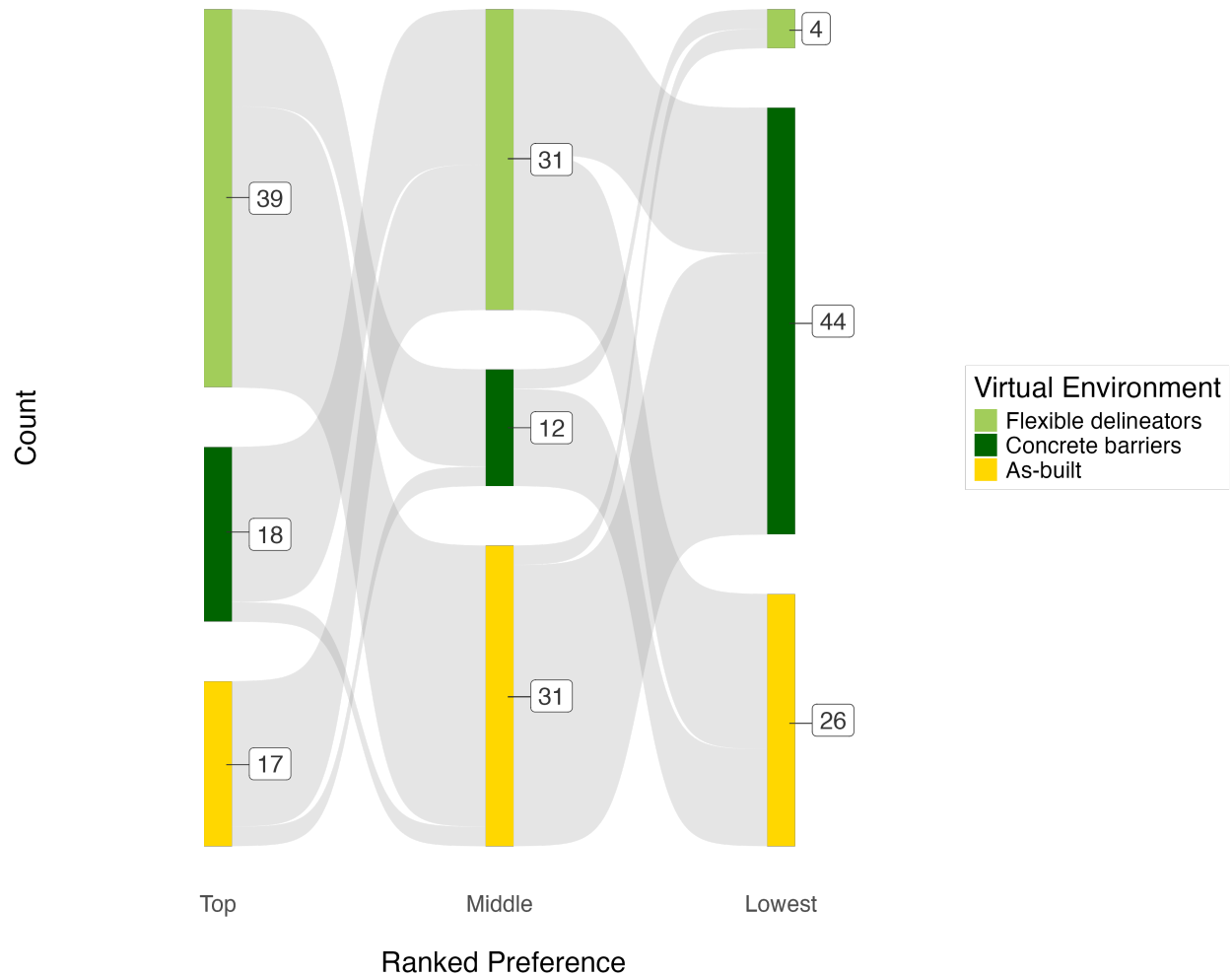
Preferences

A chi-square goodness of fit test indicated that the distribution of top preferences was not consistent with a uniform distribution ($\chi^2 = 12.514$, $p = 0.002$). See Figure 33. Based on residual analysis, more participants preferred the flexible delineator condition than expected under a uniform distribution. Moreover, the estimated odds of favoring the flexible delineator intervention were 242.3% higher than the odds of favoring the contiguous concrete barrier intervention (95%CI[72.3%, 596.7%], $p = 0.0004$) and 268.6% higher than those of favoring the as-built condition (95%CI[84.2%, 656.9%], $p = 0.0002$). The estimated odds of favoring the contiguous concrete barrier intervention did not differ from those of the as-built condition (OR=1.077, 95%CI[0.508, 2.288], $p = 0.850$).

Conversely, the distribution of lowest preferences was also not consistent with a uniform distribution ($\chi^2 = 32.541$, $p < 0.0001$). Residual analysis indicated fewer participants disliked the flexible delineator condition and more participants disliked the contiguous concrete barrier condition than expected under a uniform distribution. In fact, the estimated odds of disliking the flexible delineator intervention were 95.9% lower than the odds of disliking the contiguous concrete barrier intervention (95%CI[88.5%, 98.7%], $p < 0.0001$) and 89.0% lower than those of disliking the as-built condition (95%CI[68.9%, 96.4%], $p < 0.0001$). The estimated odds of disliking the contiguous concrete barrier intervention were 168.3% higher than those of the as-built condition (95%CI[39.2%, 426.5%], $p = 0.003$).

Figure 33

Preferences for street design conditions



Thematic analysis of descriptive explanations for preferences developed three themes:

1. *Separated bike lanes affect perceptions of safety,*
2. *Type of separated bike lane influences perceptions of amenities in the environment,*
- and 3. *A street's safety and amenities are independent forces that should be balanced.*

Theme 1 - Separated bike lanes affect perceptions of safety.

Most participants mentioned safety issues (63/74 participants). They discussed safety in both general terms (e.g., “seems safer”) and by specifically referencing the “separation between the cars and pedestrians” (34). This separation increased perceptions of safety as it “help[ed] keep people in the area they need to be; i.e., bikes in the bike area, pedestrians on sidewalks.” A sizable number of participants even discussed protection from impact (13): “It was a physical deterrent that will deflect or slow down a car careening into the bike lane or sidewalk.”

Positive descriptions of safety were most common in the context of flexible delineators (34) and contiguous concrete barriers (27), while lack of safety was most prevalent in responses about the as-built condition (26). In fact, safety was mentioned by every participant who most preferred the concrete barrier intervention (18) and every participant who least preferred the as-built condition (26). Among those who favored it, the concrete barrier condition was viewed as “the safest option” because “the concrete barrier [was] going to provide more protection in the event of a collision” (5). Conversely, in the as-built condition, “If a car or bike were to swerve or crash into the sidewalk, there would be nothing preventing it from hitting a person” (8), leading to statements such as “No barrier [did] not make me feel safe.” A handful of participants praised the concrete barriers because they “force[d] the pedestrian to go to the crosswalk, which is great” (5) and criticized the as-built condition for “making it easier for people to go wherever they want” (5), a dissenting opinion as described below in Theme 2.

Still, several participants voiced concerns that the contiguous concrete barriers posed a “potential hazard” (7) or “obscured the view of the other side” (3). The flexible delineators were

seen as a solution to this issue as they “allow[ed] good vision” of the road and other road users (5).

Theme 2 - Type of separated bike lane influences perceptions of amenities in the environment.

Amenities “[help] to provide comfort, convenience, or enjoyment” (Merriam-Webster, n.d.), complementary to Alfonzo’s walking needs of comfort, accessibility, and pleasurability. Participants regularly referenced these three concepts in their reasoning for preferences. Regarding accessibility, they discussed free movement of road users. They specifically noted how some street designs, namely the flexible delineator (15) and as-built (9) conditions, made it “easier to cross the street” than others and allowed them to “[take] the most optimal route.” Furthermore, participants discussed crossing the street without a marked crosswalk as their prerogative: “In this volume of traffic, I’m perfectly comfortable jaywalking in order to reach my destination quicker.” Numerous participants (20) disliked the “annoying” and “very aggressive” contiguous concrete barriers because they believed that this condition “force[d] you to walk a specific way,” and the crosswalks “sometimes [could] be pretty far away from the destination and inconvenient for walking.”

Perceiving concrete barriers as restrictive was emphasized by descriptions of “feel[ing] very cornered,” “congested,” and “trapped” (12). In contrast, flexible delineator (6) and as-built (5) environments were described as “open,” “free,” and “cleaner.” As demonstrated by this spectrum of openness and constraint, participants regularly discussed the comfort and pleasurability (i.e., enjoyment) of a space conjointly: “I prefer this from a comfort perspective. I just think the open street looked and felt nicer to walk by.” Aligned with descriptions of openness, several participants believed the as-built (5) and flexible delineator (5) conditions had

“better aesthetic[s]” while the contiguous concrete barriers were “very ugly” and “just look[ed] terrible” (17).

Theme 3 - A street’s safety and amenities are independent forces that should be balanced.

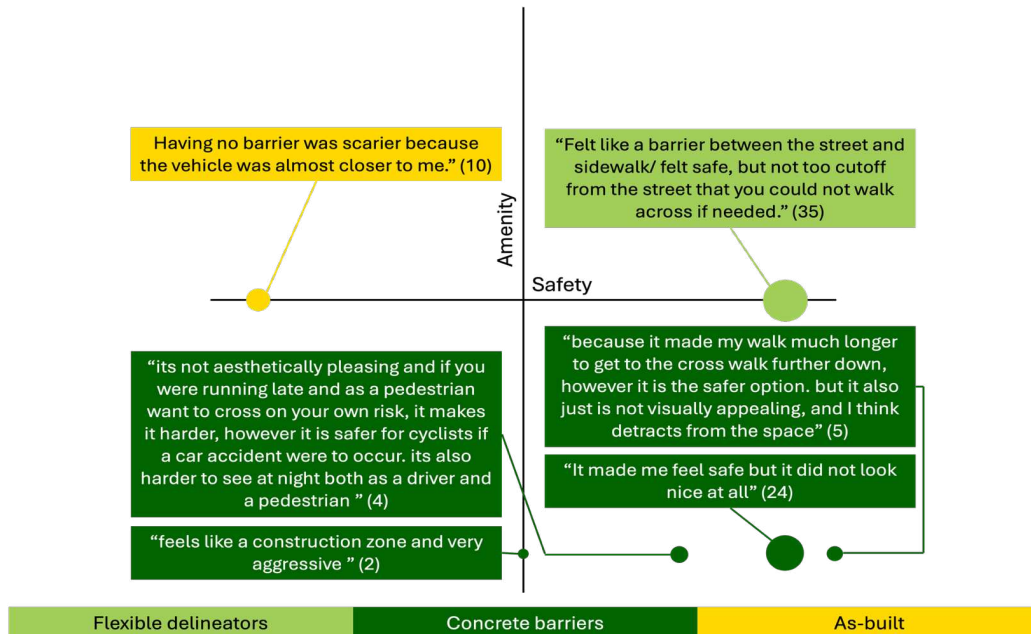
Nearly half of participants described a desire for balance in street design (34), most clearly through the explicit phrases “a good middle ground” and “a good in between,” which were used to describe the flexible delineator condition (2). More frequently, participants described a balance of safety and amenities through oppositional conjunctions and adverbs (27), such as “while” (e.g., “The plastic barrier enforced the space designated for cars and bikes the most while not being a major obstacle or unpleasant to look at.”), “still,” and “but” (e.g., “There [was] some separation and protection, but [the option with flexible delineators] also still allow[ed] for easy movement.”).

Patterns in descriptions of street design conditions with respect to safety and amenities are presented in Figure 34. As demonstrated, contrasting safety and amenities occurred most commonly when respondents explained why they favored the flexible delineator condition (Figure 34 Panel A). In contrast, those who favored the concrete barrier condition more frequently discussed only safety (Figure 34 Panel B) as those who favored the as-built condition did with amenities (Panel C).

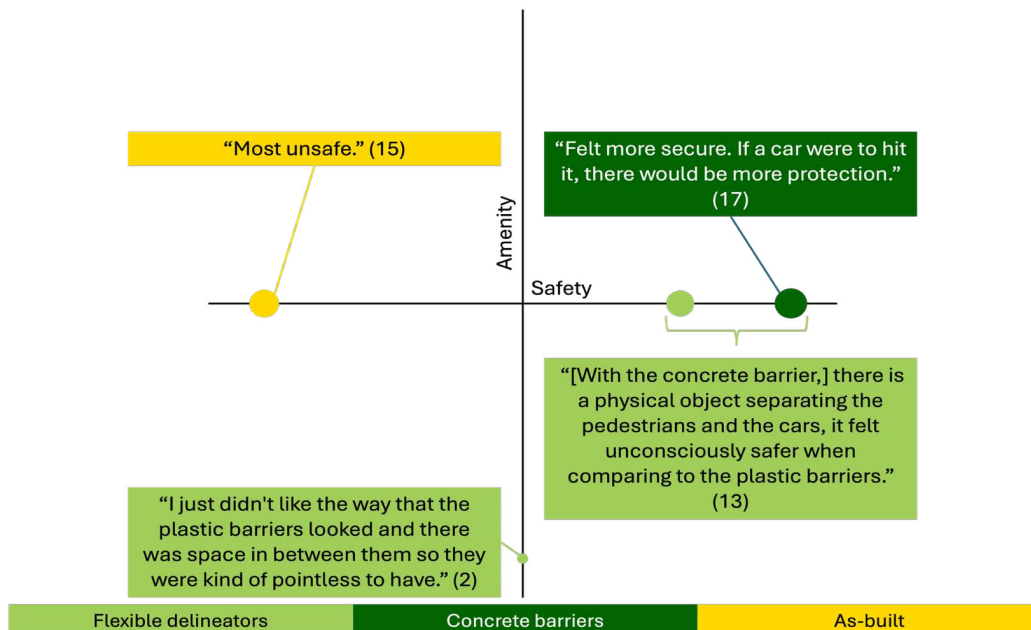
Figure 34

Descriptions of amenities and safety balance stratified by top preference

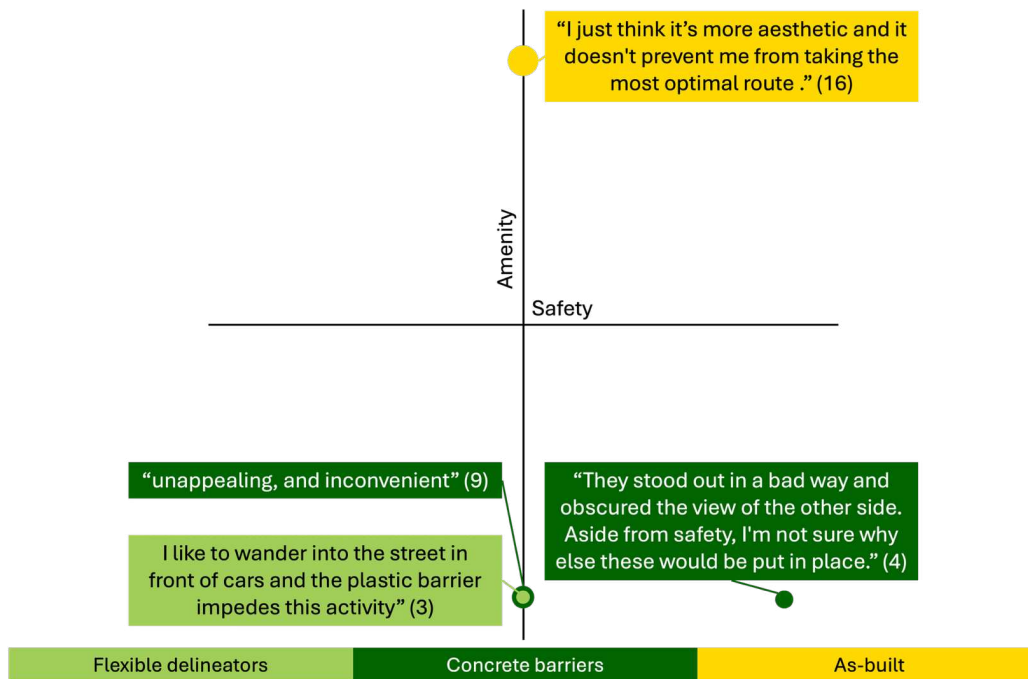
A. Preference for flexible delineator condition



B. Preference for concrete barrier condition



C. Preference for as-built condition



Note. Frequency is reflected in point size.

Still, an imbalance was detailed as reason for disliking both types of separated bike lanes. Indeed, three of the four participants who least preferred the flexible delineator condition described an imbalance between little to no improvement in safety that could offset their negative effects on amenities (e.g., "It didn't really do a whole lot other than be less pleasing," Figure 34 Panel B). This concept was echoed by participants (7) who regarded the concrete barriers as "overkill" and "unnecessary given that it's not a very high-speed road" (Figure 34 Panels A & C). Backing the need for a balance, several participants (8) explicitly rejected the idea that the safest option was the best. One participant who disliked the concrete barrier condition reasoned, "It made my walk much longer to get to the crosswalk further

down; however, it is the safer option, but it also just [was] not visually appealing, and I think detracts from the space.”

Route distance

To investigate the accuracy of statements claiming the continuous concrete barrier condition prompted longer routes, an exploratory MSEM analysis was conducted. The most complex model, which predicted route distance with a random interaction effect between condition and location pair, fit the data best. See Table 10. In other words, the effect of condition on route distance differed across location pairs, and there were meaningful individual differences in the magnitude of these effects. Complete model results are available in Table 11. The interaction was probed via pairwise comparisons between conditions stratified by location pair. These results are described in the text below, visualized in Figure 35, and listed in Table 12.

Table 10*Route distance model fit indices*

Note. Bold indicates the best fitting model.

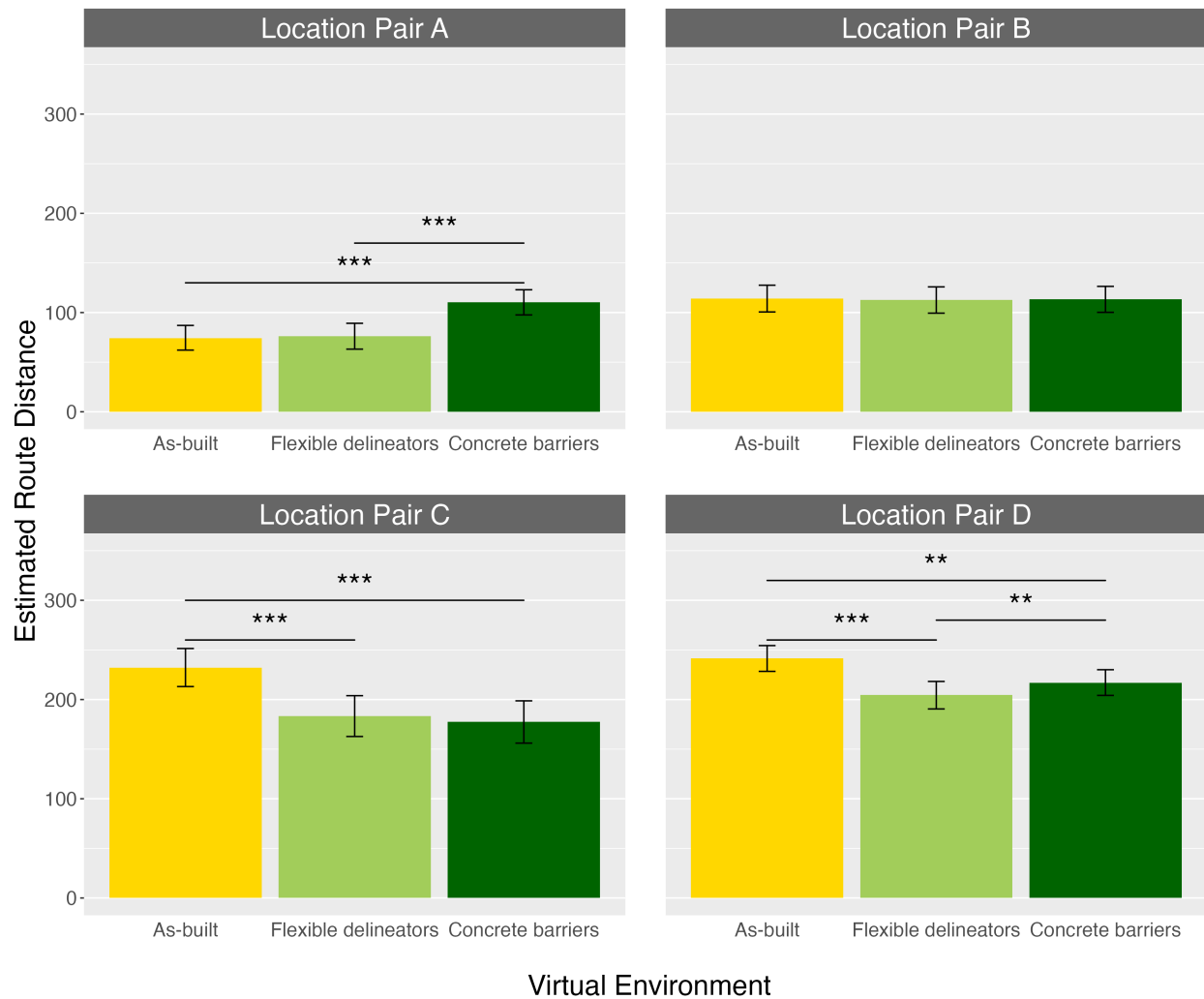
Random effects	Fixed effects	PPP	DIC	PSR
NA	Intercept Condition Location pair Trial number	0.511	9873.361	1.000
Intercept	Condition Location pair Trial number	0.494	9803.427	1.002
Intercept Condition	Location pair Trial number	NA	9809.889	1.003
Intercept Location pair	Condition Trial number	NA	9690.301	1.001
Intercept Location pair Condition	Trial number	NA	9697.843	1.005
Intercept	Condition Location pair Condition * Location pair Trial number	0.495	9754.811	1.000
Intercept Condition Location pair Condition * Location pair	Trial number	NA	9626.789	1.025

Table 11*Results of best fitting model for route distance**Note.* * indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$.

Fixed effects	b [95%CrI]	posterior SD	p
Trial number	-0.150 [-1.176, 0.853]	0.520	0.386
Random effects	Mean (b) [95%CrI]	posterior SD	p
Flexible delineators	-37.012 [-52.706, -21.200]	8.165	< 0.001***
Concrete barriers	-24.641 [-38.483, -9.343]	7.478	0.001**
Location Pair A	-167.226 [-182.271, -151.130]	7.915	< 0.001***
Location Pair B	-127.669 [-142.226, -111.182]	8.075	< 0.001***
Location Pair C	-9.208 [-30.388, 12.028]	10.850	0.197
Flexible delineators*A	38.920 [15.815, 61.550]	11.476	0.003**
Flexible delineators*B	35.524 [12.719, 58.102]	11.541	0.001**
Flexible delineators*C	-11.880 [-35.513, 11.848]	12.047	0.163
Concrete barriers*A	60.235 [39.341, 82.058]	10.846	< 0.001***
Concrete barriers*B	23.736 [1.456, 45.580]	11.406	0.019*
Concrete barriers*C	-30.311 [-53.832, -7.698]	11.857	0.004**

Figure 35

Estimated route distance by condition stratified by location pair



Note. Estimated values are in meters and were calculated at the control level of trial number 1 using mean(b) parameters. * indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$.

Table 12

Unstandardized pairwise comparisons between conditions by location pair

Note. Units for estimates are in meters. * indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$.

Location pair	Condition	1 Mean(b) [95%CrI]	2 Mean(b) [95%CrI]
A	1. Flexible delineators		
	2. Concrete barriers	-34.399 95%CrI[-45.109, -23.574]; $p < 0.001^{***}$	
	3. As-built	2.024 95%CrI[-14.469, 17.434]; $p = 0.402$	36.063 95%CrI[20.282, 51.061]; $p < 0.001^{***}$
B	1. Flexible delineators		
	2. Concrete barriers	-0.799 95%CrI[-9.138, 7.626]; $p = 0.426$	
	3. As-built	-1.359 95%CrI[-17.611, 14.929]; $p = 0.434$	-0.754 95%CrI[-16.775, 16.100]; $p = 0.463$
C	1. Flexible delineators		
	2. Concrete barriers	5.885 95%CrI[-8.376, 19.964]; $p = 0.208$	

Location pair	Condition	1 Mean(b) [95%CrI]	2 Mean(b) [95%CrI]
	3. As-built	-48.946 95%CrI[-66.129, -31.620]; $p < 0.001^{***}$	-54.832 95%CrI[-72.894, -36.745]; $p < 0.001^{***}$
D	1. Flexible delineators		
	2. Concrete barriers	-12.280 95%CrI[-20.412, -4.712]; $p = 0.001^{**}$	
	3. As-built	-37.012 95%CrI[-52.706, -21.200]; $p < 0.001^{***}$	-24.641 95%CrI[-38.483, -9.343]; $p = 0.001^{**}$

Among trials in which participants completed location pair A, they tended to take routes about 35 m longer in the concrete barrier condition than the flexible delineator condition (mean(b) = 34.399 m, 95%CrI[23.574, 45.109], $p < 0.001$) and as-built condition (mean(b) = 36.063 m, 95%CrI[20.282, 51.061], $p < 0.001$), when controlling for trial number. This is consistent with crossing data, which visualizes that some participants selected the most direct route for location pair A through Lake St without a marked crossing in the as-built (Figure 32 Panel A.I) and flexible delineator (Panel A.II) conditions but walked around the concrete barriers to the marked crosswalk in the concrete condition (Panel A.III). This also aligns with participants' claims that the concrete barriers blocked them from taking the shortest route.

In contrast, while completing location pair B, participants generally chose a similar distance route regardless of condition, controlling for trial number (Table 12). As shown in Figure 32 Panel B, participants generally used the marked crosswalk in location pair B,

potentially because the crossing was relatively near to the most direct route and/or the nearby intersection is known to have a high volume and be unsafe (Kimley-Horn and Associates, Inc., 2024).

Location pairs C and D are unique in that both intervention conditions introduced a nearby zebra crosswalk. In these trials, participants tended to select shorter routes in the flexible delineator ($\text{mean}(b_c) = -48.946$, $95\%CrI_c[-66.129, -31.620]$, $p_c < 0.001$; $\text{mean}(b_d) = -37.012$, $95\%CrI_d[-52.706, -21.200]$, $p_d < 0.001$) and concrete barrier ($\text{mean}(b_c) = -54.832$, $95\%CrI_c[-72.894, -36.745]$; $p_c < 0.001$; $\text{mean}(b_d) = -24.641$, $95\%CrI_d[-38.483, -9.343]$; $p_d = 0.001$) conditions than the as-built condition when accounting for trial number. On average, location pair C routes in separated bike lane conditions were 50 m shorter than those in the as-built condition, conflicting with participants' statements that their routes felt longer in the concrete barrier condition. In location pair D, routes for the flexible delineator separated bike lane condition were on average 37 m shorter than routes in the as-built condition while those in the concrete barrier condition were only 25 m shorter, a difference which partially supports participants' descriptive statements ($\text{mean}(b) = 12.280$, $95\%CrI[-20.412, -4.712]$; $p = 0.001$). Integrating the distance results for location pairs C and D with crossing visualization in Figure 33 Panels C and D, the separated bike lane conditions may have shortened route distance through the introduction of new zebra crosswalk that provided a closer alternative to participants that opted for indirect routes in the as-built condition in order to use a marked crosswalk.

STUDY 2 DISCUSSION

The current study applied VR technology to assess the effects of two potential street design interventions on pedestrian environmental perceptions, walking decisions, and preferences. In a within-subjects design, individuals experienced, from a pedestrian's perspective, a virtual replica of a university's campus as it currently stands and with two modifications under consideration for implementation. While experiencing the environments with separated bike lanes and zebra crosswalk interventions, participants judged their surroundings as safer and more comfortable than when experiencing the unmodified environment. These findings add to existing research indicating crosswalks are important factors of pedestrians' safety perceptions (Argota Sánchez-Vaquerizo et al., 2024; Soto et al., 2022) and builds upon cycling literature linking separation to perceived safety (Bialkova et al., 2022; Friel et al., 2023; Nazemi et al., 2021) and comfort (Lim et al., 2025). In addition, the environment with additional pedestrian crosswalks and a separated bike lane created with flexible delineators was judged in real time to be more accessible and pleasurable from a pedestrian's perspective than the environment depicting the as-built conditions. Interestingly, differences between in-VR perceptions of the two intervention conditions were minimal.

Real-time judgements of these four walking needs (accessibility, safety, comfort, & pleasurability) loaded onto two latent variables, representing person-level and exposure-based audiovisual walkability perceptions. The acceptable fit of these latent variables provides support for Alfonzo's (2005) model as underlying walkability perceptions explained observed judgements of walking needs. Furthermore, both environmental interventions predicted small

boosts to exposure-based audiovisual walkability perceptions compared to the as-built condition. Again, there was a negligible difference between the two investigated countermeasures. In context of the numerous factors that correlate with perceptions of walking needs [e.g., street connectivity, land use (Tabatabaee et al., 2021)], observing differences between identical environments save for bike lane separation and the introduction of new zebra crosswalks is notable. Moreover, the investigated interventions were successful in enhancing exposure-based audiovisual walkability perceptions despite their low expense and small scale relative to city-scale walkability influences, such as land use.

The current study also provided evidence for the tested interventions' effectiveness altering perceptions of exposure-based audiovisual walkability independent of the interventions' effects on other road users' behaviors. One explanation for the lower incidence of serious crashes in bikeable cities is that infrastructure, such as separated bike lanes, reduces motor vehicle speeds (Marshall & Ferencak, 2019). VR research has also indicated that separated bike lanes reduce cyclists' speeds (Guo, Tavakoli, et al., 2023). In the current study, the speed of other road users was controlled across environmental conditions, meaning that the observed changes to exposure-based audiovisual walkability perceptions were caused by the environmental interventions directly. It is expected that if a separated bike lane and new zebra crosswalks are implemented in the investigated context, effects on exposure-based audiovisual walkability perceptions of magnitudes larger than those reported in the current study may be observed. Direct effects of the intervention may be compounded by any indirect effects through other road users' safety behaviors, although additional research would be needed to confirm.

In addition to perceptions of walking needs, the current study measured preferences for the investigated street designs after VR exposure. Most participants preferred the environment with the flexible delineators. Although about a quarter of participants most preferred the concrete barrier intervention, nearly 60% of participants ranked it as their least preferred, indicating polarization concerning this condition. The most common reason provided for ranking the concrete barrier intervention low was that these barriers reduced perceptions of amenities in the environment, namely the space's openness and pleasantness and the ease of reaching destinations. In other words, participants described negative effects on accessibility, comfort, and pleasurability. This contrasts with the quantitative walking needs findings, in which participants did not judge the environment with the concrete barriers as less accessible or less pleasurable and even judged it to be more comfortable than the as-built condition.

The observed discrepancies between ratings provided in VR and preferences provided after exposures may be explained by recall bias. Retrospective reports can be influenced by information salient at the time of recall while real-time data (i.e., momentary assessment) curtails this bias (Shiffman et al., 2008). As pictured in Figure 24, the survey item addressing preference presented images of nearly identical environments with separating elements depicted in the foreground. This survey item named the intervention conditions by separation type and material, and it did not mention the new crosswalks. Thus, the presentation of this survey item enhanced the salience of the separating elements. For example, when participants were within the virtual environment, their pleasurability judgements may have been based on numerous environmental factors, including building design, lack of litter, and greenery, all of which are related to environment pleasantness (Brunner et al., 2025). However, when

completing the post-VR survey these factors were not salient, and participants overestimated the effect of the concrete barriers on overall pleasurability. In fact, research indicates humans make systematic errors in predicting transportation experiences, including overestimating the enjoyableness of motor vehicle trips (Comerford, 2011).

In another conflict with ratings provided in VR, participants' feedback suggested a conceptualization of safety as independent of free movement, openness, and pleasantness. The balance between safety and the amenities of the environment was provided as a key reason for preference of the flexible delineator condition. Although participants recounted these forces as independent after the VR experience, they did not report them as such in real time: The current study's latent variable findings indicated that a singular construct of exposure-based audiovisual walkability perceptions underlay walking needs ratings. While making judgements of walking needs in VR, participants may have considered the audiovisual walkability of the overall environment, and the experience of safety was linked to experiences of accessibility, comfort, and pleasurability. However, when asked directly about the flexible delineators and concrete barriers, participants may have considered how these separating elements specifically influenced free movement, safety, openness, and pleasantness. Additional research similar to the current study, in which participants rate environments in place following a think-aloud protocol could clarify how participants weigh various factors in these different self-report paradigms.

A benefit of using this simulation-based approach to pre-test potential environmental interventions is the ability to collect behavioral data in a controlled setting. This enabled behavioral exploration into discrepancies between judgements of accessibility from ratings

completed in VR and preferences provided later. In the current study, route analysis demonstrated that participants crossed the street in different locations depending on condition. Both types of interventions shortened the average route distance in two of the four location pairs. These conditions also resulted in much higher odds of using a marked crosswalk than the as-built condition. In contrast, individuals only rated the environment with flexible delineators as more accessible than the as-built condition. As noted, a common criticism of the concrete barrier condition was that it prohibited participants from taking a shorter route. The odds of an unmarked midblock crossing were much lower in the environment with continuous concrete barriers than those with flexible delineators, meaning the concrete barriers were more effective at guiding pedestrians to marked crosswalks. Objective measurement of route distance partially supported participants' claim that the concrete barriers resulted in longer routes: The routes were longer on average than the as-built and flexible delineator conditions in one and two of the four location pairs, respectively. As mentioned, the routes in the concrete barrier condition were shorter than the as-built conditions in two location pairs. Thus, the concrete barrier condition was far from unilaterally lengthening routes as participants described in their written feedback. Again, salience may help resolve this difference between walking behavior and retrospectively-reported experience. The preference survey item centered the barriers; thus, participants may have provided their preferences regarding only the barriers and not the entire intervention condition, including the new crosswalks.

Limitations

The described findings are site-specific and must be contextualized within the limitations of the study. This study compared the as-built conditions with two multifaceted interventions as

they would be implemented. While this decision improves the direct applicability of these findings to CSU's intervention decision, it means that the effects of any specific feature in each intervention cannot be identified. It is possible that the condition with flexible delineators led to more pleasurable ratings than the as-built condition simply because they were simulated with a plastic material. If the delineators were depicted as concrete bollards, perceptions of this condition may have been more akin to those observed in response to the concrete barriers. Indeed, research has indicated that individuals perceive concrete environments as cold and unpleasant (He et al., 2025). Similarly, the barrier condition may have been preferred more if the virtual barriers were mapped with a plastic or metal texture rather than concrete. In addition to materiality, the effects of the delineators and barriers cannot be untangled from those of the added zebra crosswalks. It is likely that a negative effect of barriers on accessibility, which was described in written feedback, was obscured by a positive effect of the new marked crosswalks. Still, the prioritization of studying complete interventions as they would be implemented aligns with the primary goal of the current applied research: to provide site-specific pedestrian-focused recommendations to campus decisionmakers.

As participants were not naturally walking and instead were stepping-in-place, their physical limitations may have been unclear, namely participants may not have known that they could step over concrete barriers. Although participants could and some did move over the concrete barriers, one described in their writing that "I had no way of getting over them in the simulation." Furthermore, the current findings may have been influenced by social desirability effects, in which participants elected to more closely follow traffic laws (i.e., use marked crosswalks) in the study session than they would in the real world. To minimize these effects,

participants were explicitly asked to “behave as [they] would in the real world” during the tutorial and reminded of this instruction if they asked the researcher whether they had to follow traffic laws. The concern for social desirability effects is also assuaged by the written responses of many participants that explicitly discussed their preference for a street design which enables unmarked crossings (33 participants). Another limitation of virtual locomotion in the current study stems from the instruction to participants to avoid moving through large areas of grass. This instruction was necessary to ensure the safety of participants as topographic variability, which exists in the intervention area’s grassy lawns, is known to induce higher intensities of cybersickness (Ang & Quarles, 2022). Still participants may have navigated along different routes had they not received this directive.

It is common to use repeated measures studies in VR research for their high statistical power (Birenboim et al., 2021; Spitzer & Graham, 2025); however, this research design bears the limitation of learning effects. The current study originally intended to quantify these learning effects via test-retest reliability calculations. However, this tertiary analysis could not be completed due to the decision to counterbalance the order of conditions. Pilot data suggested that a study design with a standardized location pair and condition order would have enabled test-retest reliability analyses but likely would not have clearly addressed the main inquiry: how the tested environmental modifications influence perceptions of walking needs. These pilot data demonstrated a nontrivial possibility of differential carryover effects, interfering with the study’s ability to detect effects of the manipulation. Therefore, counterbalancing order through Williams’ (1949) paired Latin square approach was prioritized over the ability to conduct test-retest reliability calculations. Learning effects regarding environmental judgements, walking

behavior, and wayfinding remain an open inquiry within the research area (Birenboim et al., 2021). Future VR applications to transportation planning behavioral research would benefit from additional basic research quantifying these learning effects.

Strengths

In addition to these limitations, this study also has several strengths, starting with its true experimental design. True experiments are historically uncommon in environmental research, but the rise of VR technology equips researchers to conduct these studies due to VR's ability to manipulate environments (Spitzer & Graham, 2025). By holding extraneous factors constant, this research design permits causal conclusions, which are atypical in this research area. Thus, this project is unique in that it equips decisionmakers with evidence as to which interventions *modify* rather than simply correlate with perceptions of walkability. Moreover, this research does so with high ecological validity, supporting its direct applicability to a real-world environment. Using real-world GIS data, traffic data, and photographs improved the realism of the VR simulation. Partnership with CSU Transportation and the City of Fort Collins ensured that the tested interventions represented those considered for real-world implementation. This collaboration bridges the gap between transportation research and practice and ensures that the resulting intervention is based on rigorous context-specific science.

The observed discrepancies between judgements made in real time and in later surveys highlights the value of simulation-based research to collect in-place judgements as well as behavioral measures. As participants were recruited from the specific area under investigation, the current project serves as a type of community outreach. Community opinions are indubitably an important source of information in decision-making concerning street design;

however, they may not necessarily reflect those same individuals' perceptions of the intervention when it is in place. As previously noted, VR simulations induce environmental responses more similar to the real world than 2D representation techniques (Higuera-Trujillo et al., 2017; Newman et al., 2022). The current research suggests that judgements of environments based on 2D images of recently-experienced VR simulations may not even match judgements made in that same VR simulation. The value of applying VR technology in street design goes beyond the ability to represent potential interventions and is magnified by collecting behavioral and momentary assessment data from community members within controlled but realistic environments. The current research gathered in-place data regarding an environment after the trial was completed. Future VR simulation studies could further reduce the delay between a contextual exposure and data collection, such as prompting a survey after participants cross a virtual street or after a motor vehicle passes. This type of work could shed insight into how individual design elements influence audiovisual walkability perceptions across the pedestrian experience.

Conclusions, recommendations, and implications

The described study was conducted to address the gap in the literature regarding the influence of separated bike lanes on pedestrians and to aid local decisionmakers in identifying which of two potential separated bike lane and crosswalk interventions will have the maximum positive impact on pedestrians. Contributing to research into the effects of cycling infrastructure on other road users, the findings indicated more evidence that separated bike lanes with flexible delineators will increase safe walking in the investigated area. Both tested separated bike lane and crosswalk interventions improved exposure-based audiovisual walkability

perceptions, comfort, and safety. Still, this study found stronger support for the flexible delineator intervention in enhancing pedestrian accessibility and pleasurability. In real time, participants perceived it to be easier to reach their destination in the condition with the flexible delineators even though on average, the distance of their selected route to the destination was shorter in only two of the four location pairs. Because *perceptions* of fulfillment of walking needs, rather than *objective measures* of fulfillment influence the decision to walk (Alfonzo, 2005), these findings support the idea that the flexible delineator intervention will lead to more walking in this campus region.

Although the contiguous concrete barrier intervention resulted in a marginal benefit to the safe walking behavior of using a marked crosswalk, the evidence that the flexible delineator intervention resulted in higher perceptions of fulfilled walking needs compared to the as-built condition was stronger. These findings support the implementation of an intervention with a separated bike lane via flexible delineators and two new zebra crosswalks on Lake St to promote safe walking. This recommendation was presented to the City of Fort Collins and CSU Transportation; therefore, this project will result in promoting the safe walking behavior of potentially thousands of current and future students and employees that inhabit Lake St daily.

More broadly, these findings reinforce the influence of relatively low-cost street-scale interventions on perceptions of walkability and provide support for a popular walkability theory. The observed discrepancies between stated community preference and in-VR data regarding walking needs and behavior advances the field of walkability by underscoring the importance of real-time data capture. In addition to local benefits to a campus community, the current study progresses the field through the implementation of VR technology to collect causal evidence

sensitive to local context and the direct application of research to street design via cross-sector partnership.

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FUNDING INFORMATION

Funding for VR equipment and participant compensation was provided by Colorado State University's Department of Psychology. The Department of Psychology and Colorado State University Transportation funded protected time for VR simulation development and testing.

APPENDIX A. UTILIZED UNITY ASSETS

Greenery

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APPENDIX B. PHOTOGRAPHS OF VR SIMULATION

Figure B.1

View from Lake St Parking Garage W toward Centre St intersection in concrete barrier condition



Figure B.2

View from Centre Ave intersection N toward pedestrian mall in concrete barrier condition



Figure B.3

View from Molecular and Radiological Biosciences Building W toward Gifford Building in flexible delineator condition



Figure B.4

View from new crosswalk NE toward Pathology Building in flexible delineator condition



Figure B.5

View from new crosswalk NW toward Environmental Health Building in flexible delineator condition



Figure B.6

View from Pathology Building NE toward Painter Center



Figure B.7

View from Environmental Health Building W toward Veterinary Medicine Parking Lot



Figure B.8

View from Veterinary Medicine Parking W toward Physiology Building



Figure B.9

View from Physiology Building W toward pedestrian mall



Figure B.10

View from Physiology Building NW toward Yates Hall



Figure B.11

Physiology Building and sign



Figure B.12

Eastward view of MAX Guideway and pedestrian crossing signal in as-built condition



Figure B.13

View from Libbie Coy Way SW toward National Forest Service Library in as-built condition



Figure B.14

View from Libbie Coy Way intersection NW toward Pathology Building



Figure B.15

View from Aggie Village NW toward Nancy Richardson Design Center in as-built condition



Figure B.16

Eastward view from Nancy Richardson Design Center



Figure B.17

View from Nancy Richardson Design Center SE toward Gifford Building



Figure B.18

View from Nancy Richardson Design Center W toward Canvas Stadium



APPENDIX C. MODEL OUTPUT FOR ROBUSTNESS ANALYSES

Study 1

Feasibility criteria

% of study sessions completed within 1 hr excluding participant visiting area < 1x/week = 70.0%

Acceptability criteria

Table C.1

Descriptive statistics of presence excluding participant visiting area < 1x/week

	Mean	SD
IPQ Total	3.949	0.567
Involvement	3.347	1.141
Spatial presence	4.589	0.882
Experienced realism	2.721	0.833

VRNQ VRISE median excluding participant visiting area < 1x/week = 30

Number of FMS ratings ≥ 15 excluding participant visiting area < 1x/week = 1

Table C.2

FMS scores by timepoint excluding participant visiting area < 1x/week

Timepoint	FMS Mean	SD
Before VR	0.750	1.650
Before Trial 1	1.250	2.337
After Trial 12	2.632	2.650

Study 2

Perception of walking needs

Table C.3

Correlation matrix of walking needs excluding 2 participants visiting area < 1x/week

Note. [LL, UL] indicates a 95% CI.

Variable	1	2	3
1. Accessibility			
2. Safety	0.648 [0.607, 0.685]		
3. Comfort	0.689 [0.653, 0.722]	0.704 [0.669, 0.736]	
4. Pleasurability	0.570 [0.523, 0.613]	0.618 [0.575, 0.657]	0.655 [0.615, 0.691]

Table C.4

Model fit indices for separate walking needs excluding 2 participants visiting area < 1x/week

Note. Bold indicates the best fitting model for each outcome.

Outcome	Fixed effects	Random effects	saBIC
Accessibility	Intercepts Condition slopes Control slopes	NA	7238.432
	Condition slopes Control slopes	Intercepts	6936.920
	Intercepts Control slopes	Condition slopes	7150.304
	Control slopes	Intercepts Condition slopes	6944.678
Safety	Intercepts Condition slopes Control slopes	NA	7596.257
	Condition slopes Control slopes	Intercepts	7193.373
	Intercepts Control slopes	Condition slopes	7478.128
	Control slopes	Intercepts Condition slopes	7200.680
Comfort	Intercepts Condition slopes Control slopes	NA	7357.898
	Condition slopes Control slopes	Intercepts	6769.364
	Intercepts Control slopes	Condition slopes	7189.501

Outcome	Fixed effects	Random effects	saBIC
	Control slopes	Intercepts Condition slopes	6776.313
Pleasurability	Intercepts Condition slopes Control slopes	NA	7348.666
	Condition slopes Control slopes	Intercepts	6831.700
	Intercepts Control slopes	Condition slopes	7191.388
	Control slopes	Intercepts Condition slopes	6838.948

Table C.5

Level-2 variability in separate walking needs excluding 2 participants visiting area < 1x/week

	SD (intercept)
Accessibility	16.408
Safety	17.773
Comfort	19.340
Pleasurability	19.314

Table C.6

Level-1 results of best fitting model for separate walking needs excluding 2 participants visiting area < 1x/week

Note. * indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$.

Outcome	Predictor	β [95%CI]	b [95%CI]	SE	p
Accessibility	Flexible delineators	0.111 [0.050, 0.172]	4.799 [2.141, 7.456]	0.031	< 0.001***
	Concrete barriers	0.066 [-0.013, 0.145]	2.869 [-0.527, 6.266]	0.040	0.099
	Location Pair A	0.277 [0.169, 0.385]	13.062 [8.233, 17.890]	0.055	< 0.001***
	Location Pair B	0.286 [0.210, 0.363]	13.500 [9.875, 17.126]	0.039	< 0.001***
	Location Pair C	-0.092 [-0.191, 0.007]	-4.326 [-9.159, 0.506]	0.051	0.069
	Trial number	-0.013 [-0.081, 0.055]	-0.075 [-0.478, 0.328]	0.035	0.714
Safety	Flexible delineators	0.155 [0.093, 0.217]	5.927 [3.559, 8.295]	0.032	< 0.001***
	Concrete barriers	0.190 [0.123, 0.257]	7.280 [4.560, 9.999]	0.034	< 0.001***
	Location Pair A	0.057 [-0.031, 0.145]	2.381 [-1.258, 6.019]	0.045	0.202
	Location Pair B	0.116 [0.021, 0.212]	4.856 [0.758, 8.953]	0.049	0.017*
	Location Pair C	-0.107 [-0.196, -0.018]	-4.461 [-8.215, -0.707]	0.045	0.018*
	Trial number	0.007 [-0.075, 0.089]	0.037 [-0.394, 0.469]	0.042	0.866

Outcome	Predictor	β [95%CI]	b [95%CI]	SE	p
Comfort	Flexible delineators	0.131 [0.070, 0.191]	4.295 [2.344, 6.247]	0.031	< 0.001***
	Concrete barriers	0.107 [0.027, 0.188]	3.534 [0.796, 6.272]	0.041	0.009**
	Location Pair A	0.128 [0.028, 0.228]	4.599 [1.241, 7.957]	0.051	0.012*
	Location Pair B	0.156 [0.072, 0.241]	5.606 [2.541, 8.671]	0.043	< 0.001***
	Location Pair C	-0.111 [-0.197, -0.024]	-3.967 [-7.271, -0.664]	0.044	0.012*
	Trial number	-0.053 [-0.142, 0.035]	-0.241 [-0.641, 0.160]	0.045	0.236
Pleasurability	Flexible delineators	0.113 [0.040, 0.185]	4.077 [1.490, 6.665]	0.037	0.002**
	Concrete barriers	0.073 [-0.001, 0.147]	2.650 [-0.008, 5.308]	0.038	0.053
	Location Pair A	0.135 [0.058, 0.213]	5.328 [2.249, 8.407]	0.040	0.001**
	Location Pair B	0.387 [0.283, 0.490]	15.208 [10.917, 19.499]	0.053	< 0.001***
	Location Pair C	0.029 [-0.041, 0.099]	1.141 [-1.583, 3.866]	0.036	0.414
	Trial number	-0.082 [-0.157, -0.008]	-0.408 [-0.792, -0.024]	0.038	0.031*

Latent variables

Table C.7

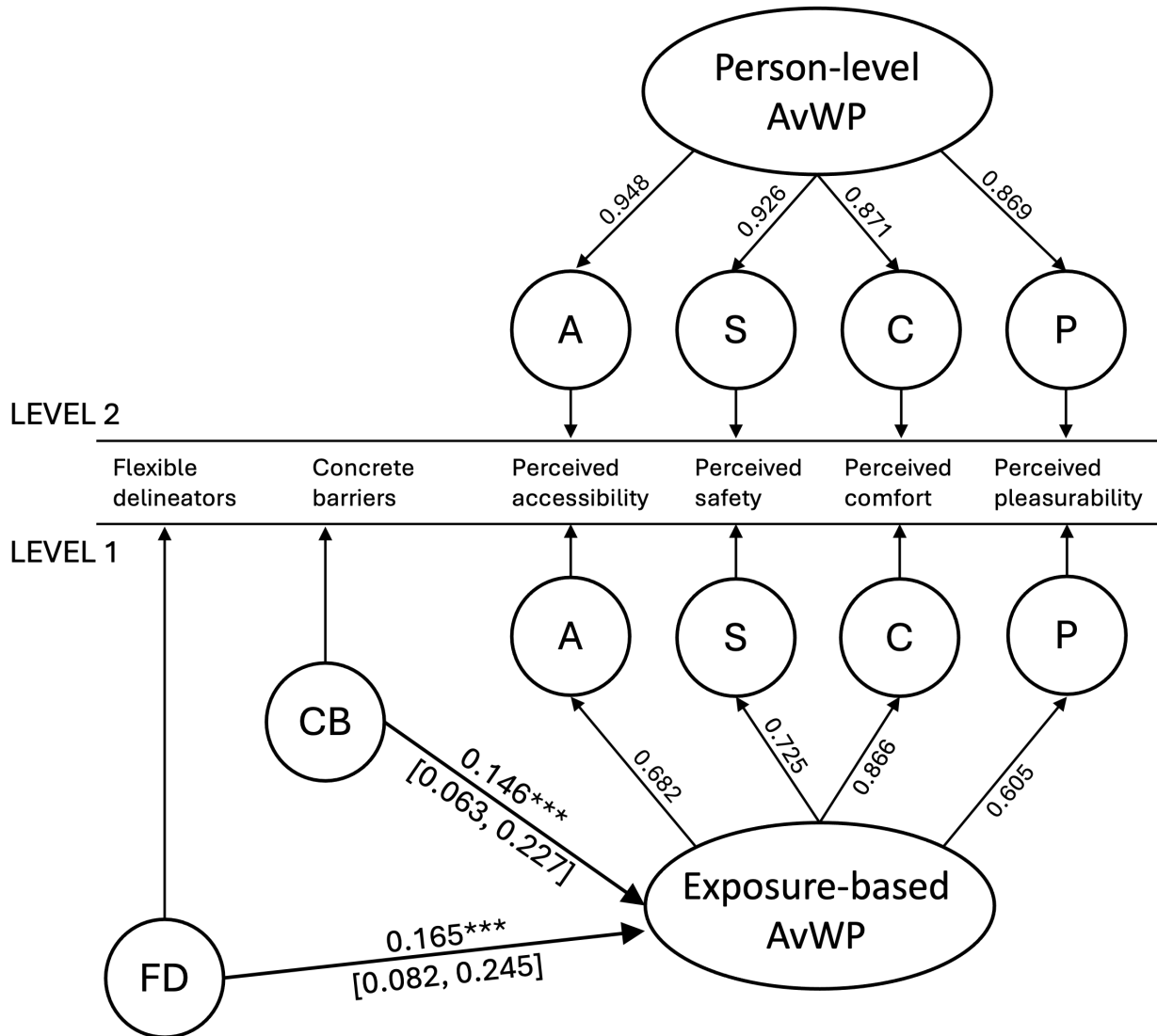
Latent variable structural model fit indices excluding 2 participants visiting area < 1x/week

Note. Bold indicates the best fitting model. ^aIndicates this model did not meet convergence criteria with 80,000 iterations.

Random effects	Fixed effects	PPP	DIC	PSR
Intercept	Condition	0.273	28410.443	1.000
Intercept Condition	NA	NA	28418.331	1.003
Intercept	Condition Location Pair	0.000	28332.363	4.591 ^a
Intercept	Condition Trial number	0.138	28408.982	1.001
Intercept	Condition Location Pair Trial number	0.000	28315.938	1.000

Figure C.1

Standardized path diagram for latent variable results excluding 2 participants visiting area < 1x/week



Note. [LL, UL] indicates a 95% CrI. Condition reference: as-built. AvWP refers to audiovisual walkability perceptions. * indicates $p < 0.05$, ** indicates $p < 0.01$, *** indicates $p < 0.001$.

Midblock crossings

Table C.8

Frequency table of incidence of marked crossings by condition with exclusions

Exclusion	Condition	Marked	Unmarked	Total
<i>Participants visiting area < 1x/week</i>	Flexible delineators	213	77	290
	Concrete barriers	241	54	295
	As-built	179	116	295
	Total	633	247	880
<i>Crossings manually categorized</i>	Flexible delineators	217	80	297
	Concrete barriers	247	55	302
	As-built	183	120	303
	Total	647	255	902
<i>Participants visiting area < 1x/week & crossings manually categorized</i>	Flexible delineators	212	77	289
	Concrete barriers	241	53	294
	As-built	179	116	295
	Total	632	246	880

Table C.9

Inference results for condition predictor of multilevel logistic regression model estimating use of marked crosswalk with exclusions

Note. * indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$.

Exclusion	χ^2	p
<i>Participants visiting area < 1x/week</i>	42.336	< 0.0001***
<i>Crossings manually categorized</i>	44.874	< 0.0001***
<i>Participants visiting area < 1x/week & crossings manually categorized</i>	43.337	< 0.0001***

Table C.10

Odds ratios for use of marked crosswalk excluding 2 participants visiting area < 1x/week

Note. * indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$.

Condition	1	2
1. Flexible delineators		
2. Contiguous concrete barriers	OR = 0.547; 95%CI[0.354, 0.845]; $\chi^2 = -2.722$; $p = 0.006^{**}$	
3. As-built	OR = 2.159; 95%CI[1.452, 3.212]; $\chi^2 = 3.799$; $p = 0.0001^{***}$	OR = 3.949; 95%CI[2.575, 6.057]; $\chi^2 = 6.292$; $p < 0.0001^{***}$

Table C.11

Odds ratios for use of marked crossing excluding 2 crossings manually categorized

Note. * indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$.

Condition	1	2
1. Flexible delineators		
2. Contiguous concrete barriers	OR = 0.531; 95%CI[0.345, 0.816]; $\chi^2 = -2.887$; $p = 0.004^{**}$	
3. As-built	OR = 2.156; 95%CI[1.457, 3.191]; $\chi^2 = 3.840$; $p = 0.0001^{***}$	OR = 4.064; 95%CI[2.659, 6.211]; $\chi^2 = 6.477$; $p < 0.0001^{***}$

Table C.12

Odds ratios for use of marked crossing excluding participants visiting area < 1x/week and crossings manually categorized

Note. * indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$.

Condition	1	2
1. Flexible delineators		
2. Contiguous concrete barriers	OR = 0.534; 95%CI[0.345, 0.826]; $\chi^2 = -2.818$; $p = 0.005^{***}$	
3. As-built	OR = 2.155; 95%CI[1.449, 3.207]; $\chi^2 = 3.788$; $p = 0.0002^{***}$	OR = 4.039; 95%CI[2.627, 6.208]; $\chi^2 = 6.363$; $p < 0.0001^{***}$

Preferences

Table C.13

Frequency table for street design preferences excluding 2 participants visiting area < 1x/week

Preference	Flexible delineators	Concrete barriers	As-built
Top	38	18	16
Lowest	4	43	25

Table C.14

Chi-square goodness of fit results for street design preferences excluding 2 participants visiting area < 1x/week

Note. * indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$.

Preference	χ^2	p
Top	12.333	0.002**
Lowest	31.750	< 0.0001***

Table C.15

Odds ratios for top street design preferences excluding 2 participants visiting area < 1x/week

Note. * indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$.

Condition	1	2
1. Flexible delineators		
2. Contiguous concrete barriers	OR = 3.245; 95%CI[1.634, 6.600]; $p = 0.0008^{***}$	-
3. As-built	OR = 3.773; 95%CI[1.872, 7.814]; $p = 0.0002^{***}$	OR = 1.163; 95%CI[0.544, 2.494]; $p = 0.702$

Table C.16

Odds ratios for lowest street design preferences excluding 2 participants visiting area < 1x/week

Note. * indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$.

Condition	1	2
1. Flexible delineators		
2. Contiguous concrete barriers	OR = 0.044; 95%CI[0.014, 0.121]; $p < 0.0001^{***}$	
3. As-built	OR = 0.117; 95%CI[0.038, 0.331]; $p < 0.0001^{***}$	OR = 2.693; 95%CI[1.395, 5.297]; $p = 0.003^{**}$

Route distance

Table C.17

Route distance model fit indices excluding 2 participants visiting area < 1x/week

Note. Bold indicates the best fitting model.

Random effects	Fixed effects	PPP	DIC	PSR
NA	Intercept Condition Location pair Trial number	0.495	9560.481	1.000
Intercept	Condition Location pair Trial number	0.493	9495.183	1.002
Intercept Condition	Location pair Trial number	NA	9501.685	1.004
Intercept Location pair	Condition Trial number	NA	9407.728	1.001
Intercept Location pair Condition	Trial number	NA	9413.877	1.016
Intercept	Condition Location pair Cond* Loc pair Trial number	0.491	9448.085	1.000
Intercept Condition Location pair Condition * Location pair	Trial number	NA	9358.916	1.002

Table C.18

Results of best fitting model for route distance excluding 2 participants visiting area < 1x/week

Note. * indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$.

Fixed effects	b [95%CI]	posterior SD	<i>p</i>
Trial number	-0.035 [-1.053, 0.980]	0.522	0.474
Random effects	Mean (b) [95%CI]	posterior SD	<i>p</i>
Flexible delineators	-38.655 [-55.045, -22.706]	8.240	< 0.001***
Concrete barriers	-25.333 [-41.077, -8.349]	8.700	0.002**
Location Pair A	-167.746 [-184.61, -151.087]	8.516	< 0.001***
Location Pair B	-128.320 [-143.835, -111.845]	8.093	< 0.001***
Location Pair C	-14.185 [-35.101, 6.371]	10.611	0.090
Flexible delineators*A	40.956 [18.527, 64.890]	11.729	0.003**
Flexible delineators*B	37.282 [14.712, 60.316]	11.429	< 0.001***
Flexible delineators*C	-8.276 [-31.489, 15.789]	12.038	0.250
Concrete barriers*A	62.631 [38.579, 87.192]	12.296	< 0.001***
Concrete barriers*B	24.763 [-1.116, 48.719]	12.571	0.032*
Concrete barriers*C	-24.774 [-49.120, -0.784]	12.420	0.021*

Table C.19

Unstandardized pairwise comparisons between conditions by location pair excluding 2 participants visiting area < 1x/week

Note. Units for estimates are in meters.

Location pair	Condition	1 Mean(b) [95%CrI]	2 Mean(b) [95%CrI]
A	1. Flexible delineators		
	2. Concrete barriers	-35.332; 95%CrI[-45.901, -24.668]; $p < 0.001^{***}$	
	3. As-built	2.413; 95%CrI[-14.245, 18.301]; $p = 0.385$	37.444; 95%CrI[20.809, 53.454]; $p < 0.001^{***}$
B	1. Flexible delineators		
	2. Concrete barriers	-0.453; 95%CrI[-9.630, 8.784] $p = 0.462$	
	3. As-built	-1.023; 95%CrI[-17.451, 14.819]; $p = 0.450$	-0.811; 95%CrI[-17.715, 16.243]; $p = 0.463$
C	1. Flexible delineators		
	2. Concrete barriers	3.339; 95%CrI[-10.277, 16.891]; $p = 0.314$	

	3. As-built	-46.748; 95%CrI[-63.749, -29.537]; $p < 0.001^{***}$	-50.182; 95%CrI-67.355, -32.711]; $p < 0.001^{***}$
D	1. Flexible delineators		
	2. Concrete barriers	-12.851; 95%CrI[-22.602, -3.953]; $p = 0.002^{**}$	
	3. As-built	-38.655; 95%CrI[-55.045; -22.706]; $p < 0.001^{***}$	-25.333; 95%CrI-41.077, -8.349]; $p = 0.002^{**}$

APPENDIX D. STUDY SURVEYS

Screening questionnaire

Thank you very much for your interest in our study titled "Using Virtual Reality to Promote Outdoor Walking on a College Campus." To make sure you are eligible to participate, we have a couple questions for you.

Are you 18 or older?

- ☐ Yes
- ☐ No

Are you susceptible to motion sickness?

- ☐ Yes
- ☐ No

Do you experience dizziness, epilepsy, vertigo, or any other problems that would preclude you from using virtual reality technology?

- ☐ Yes
 - ☐ No
-

Great! We just have one more question to determine eligibility. Please look at the map below.



During the academic year, how frequently do you visit the Lake Street area between the CSU Health Center (College Ave) and Canvas Stadium (Meridian Ave) [outlined above in yellow]?

This can be traveling through the area (e.g., walking, cycling, driving) or stopping in the area (e.g., entering an academic building or parking garage).

- ☐ Never
- ☐ Less than 1x per week
- ☐ 1-2x per week
- ☐ 3-4x per week
- ☐ 5x-6x per week
- ☐ more than 6x per week

You meet our eligibility criteria!

What is your email? This will be used to communicate study information (e.g., meeting location).

The next page may provide you an opportunity to schedule your study session.

Study 1

Pre-VR items asked verbally by the researcher

“Throughout your time in VR, prompts will ask to you report how you feel on a scale from 0 to 20, where 0 is no sickness at all and 20 is frank sickness. For these questions, please focus on nausea, general discomfort, and stomach problems. Please do not include any effects due to nervousness, boredom, or fatigue in this rating. We are going to start with how you feel right now, so on a scale from 0 to 20, where 0 is no sickness at all and 20 is frank sickness, please rate your current level.”

“Are you left- or right-handed?”

In-VR survey

Tutorial - Completed once

For this study, convenience is how hard it is to get to your destination (the red arch).

Safety relates to perceived risk of harm from other road users or the environment itself.

Comfort is about how the environment feels to your senses – like how being in this space feels, looks, and sounds.

Pleasure is about how enjoyable the environment is.

On a scale from 0 to 20, where 0 is no sickness at all and 20 is frank sickness, please rate your current level out loud for the researcher. The researcher will record it.

Please focus on nausea, general discomfort, and stomach problems. Please do not include any effects due to nervousness, boredom, or fatigue in this rating.

Trial survey - Completed 1x/trial

You have arrived at the destination. Please complete the following survey. For each question, pay careful attention to the response scale.

1/7

Trial #/12

How would you evaluate the environment you just experienced?



Extremely
inconvenient to
access my
destination

Extremely
convenient to
access my
destination

Convenience = Ease of getting to destination

2/7

Trial #/12

How would you evaluate the environment you just experienced?



Extremely
unsafe

Extremely
safe

Safety = Perception of low risk of harm

3/7

Trial #/12

How would you evaluate the environment you just experienced?



Extremely
uncomfortable

Extremely
comfortable

Comfort = How the surrounding environment feels to your senses

4/7

Trial #/12

How would you evaluate the environment you just experienced?



Extremely
unpleasant

Extremely
pleasant

Pleasure = Enjoyment of environment

5/7

Trial #/12

On a scale from 0 to 20, where 0 is no sickness at all and 20 is frank sickness, please rate your current level out loud for the researcher.

Please focus on nausea, general discomfort, and stomach problems. Please do not include any effects due to nervousness, boredom, or fatigue in this rating.

6/7

Thank you for your responses. Press "finish" to start the next trial.

7/7

Post-VR survey

Participant ID - Please ask the researcher to provide you with your participant ID number.

Now you'll see some statements about experiences. Please indicate whether or not each statement applies to your experience. You can use the whole range of answers. There are no right or wrong answers, only your opinion counts. You will notice that some questions are very similar to each other. This is necessary for statistical reasons. And please remember: Answer all these questions only referring to this one experience.

How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?

Extremely aware -3	-2	-1	Moderately aware 0	+1	+2	Not aware at all +3
-----------------------	----	----	-----------------------	----	----	------------------------

How real did the virtual world seem to you?

Completely real -3	-2	-1	0	+1	+2	Not real at all +3
-----------------------	----	----	---	----	----	-----------------------

I had a sense of acting in the virtual space, rather than operating something from outside.

Fully disagree -3	-2	-1	0	+1	+2	Fully agree +3
----------------------	----	----	---	----	----	-------------------

How much did your experience in the virtual environment seem consistent with your real world experience?

Not consistent -3	-2	-1	Moderately consistent 0	+1	+2	Very consistent +3
----------------------	----	----	----------------------------	----	----	-----------------------

How real did the virtual world seem to you?

About as real as an imagined world -3	-2	-1	0	+1	+2	Indistinguishable from the real world +3
--	----	----	---	----	----	---

I did not feel present in the virtual space.

Did not feel -3	-2	-1	0	+1	+2	Felt present +3
--------------------	----	----	---	----	----	--------------------

I was not aware of my real environment.

Extremely aware -3	-2	-1	0	+1	+2	Not aware at all +3
-----------------------	----	----	---	----	----	------------------------

In the computer generated world, I had a sense of "being there."

Not at all -3	-2	-1	0	+1	+2	Very much +3
------------------	----	----	---	----	----	-----------------

Somehow I felt that the virtual world surrounded me.

Fully disagree -3	-2	-1	0	+1	+2	Fully agree +3
----------------------	----	----	---	----	----	-------------------

I felt present in the virtual space.

Fully disagree -3	-2	-1	0	+1	+2	Fully agree +3
----------------------	----	----	---	----	----	-------------------

I still paid attention to the real environment.

Fully disagree -3	-2	-1	0	+1	+2	Fully agree +3
-------------------	----	----	---	----	----	----------------

The virtual world seemed more realistic than the real world.

Fully disagree -3	-2	-1	0	+1	+2	Fully agree +3
-------------------	----	----	---	----	----	----------------

I felt like I was just perceiving pictures.

Fully disagree -3	-2	-1	0	+1	+2	Fully agree +3
-------------------	----	----	---	----	----	----------------

I was completely captivated by the virtual world.

Fully disagree -3	-2	-1	0	+1	+2	Fully agree +3
-------------------	----	----	---	----	----	----------------

Please, from 1 to 7, choose the response that closely represents your opinion.

What is the level of immersion you experienced?

1 Extremely Low	2 Very Low	3 Low	4 Neutral	5 High	6 Very High	7 Extremely High
--------------------	------------	-------	-----------	--------	-------------	---------------------

Please write below any additional comments and/or suggestions relevant to the question

above:

What was your level of enjoyment of the VR experience?

1 Extremely Low	2 Very Low	3 Low	4 Neutral	5 High	6 Very High	7 Extremely High
-----------------------	------------	-------	-----------	--------	----------------	------------------------

Please write below any additional comments and/or suggestions relevant to the question above:

How was the quality of the graphics?

1 Extremely Low	2 Very Low	3 Low	4 Neutral	5 High	6 Very High	7 Extremely High
-----------------------	------------	-------	-----------	--------	----------------	------------------------

Please write below any additional comments and/or suggestions relevant to the question above:

How was the quality of the sound?

1 Extremely Low	2 Very Low	3 Low	4 Neutral	5 High	6 Very High	7 Extremely High
-----------------------	------------	-------	-----------	--------	----------------	------------------------

Please write below any additional comments and/or suggestions relevant to the question above:

How was the quality of the VR technology overall (i.e. hardware & peripherals)?

1 Extremely Low	2 Very Low	3 Low	4 Neutral	5 High	6 Very High	7 Extremely High
-----------------------	------------	-------	-----------	--------	----------------	------------------------

Please write below any additional comments and/or suggestions relevant to the question above:

Please, from 1 to 7, choose the response that closely represents your opinion.

How easy was it to use the navigation system (e.g. step-in-place) in the virtual environment?

1 Extremely Difficult	2 Very Difficult	3 Difficult	4 Neutral	5 Easy	6 Very Easy	7 Extremely Easy
-----------------------------	---------------------	-------------	-----------	--------	-------------	------------------------

Please write below any additional comments and/or suggestions relevant to the question above:

How easy was it to use the handheld GPS in the virtual environment?

1 Extremely Difficult	2 Very Difficult	3 Difficult	4 Neutral	5 Easy	6 Very Easy	7 Extremely Easy
-----------------------------	---------------------	-------------	-----------	--------	-------------	------------------------

Please write below any additional comments and/or suggestions relevant to the question

above:

How easy was it to interact with objects and screens in the virtual environment?

1 Extremely Difficult	2 Very Difficult	3 Difficult	4 Neutral	5 Easy	6 Very Easy	7 Extremely Easy
-----------------------------	---------------------	-------------	-----------	--------	-------------	------------------------

Please write below any additional comments and/or suggestions relevant to the question

above:

Please, from 1 to 7, choose the response that closely represents your opinion.

How easy was it to complete the tutorial(s)?

1 Extremely Difficult	2 Very Difficult	3 Difficult	4 Neutral	5 Easy	6 Very Easy	7 Extremely Easy
-----------------------------	---------------------	-------------	-----------	--------	-------------	------------------------

Please write below any additional comments and/or suggestions relevant to the question

above:

How helpful was/were the tutorial(s)?

1 Extremely Unhelpful	2 Very Unhelpful	3 Unhelpful	4 Neutral	5 Helpful	6 Very Helpful	7 Extremely Helpful
-----------------------------	---------------------	----------------	-----------	-----------	-------------------	---------------------------

Please write below any additional comments and/or suggestions relevant to the question above:

How did you feel about the duration of the tutorial(s)?

1 Extremely More Time Needed	2 Much More Time Needed	3 More Time Needed	4 Neutral	5 Enough Time Available	6 Much Time Available	7 Plenty of Time Available
---------------------------------------	-------------------------------	--------------------------	-----------	-------------------------------	-----------------------------	----------------------------------

Please write below any additional comments and/or suggestions relevant to the question above:

Please, from 1 to 7, choose the response that closely represents your opinion.

Did you experience nausea?

1 Extremely Intense Feeling	2 Very Intense Feeling	3 Intense Feeling	4 Moderate Feeling	5 Mild Feeling	6 Very Mild Feeling	7 Absent
--------------------------------------	------------------------------	----------------------	--------------------------	-------------------	---------------------------	----------

Please write below any additional comments and/or suggestions relevant to the question above:

Did you experience disorientation?

1 Extremely Intense Feeling	2 Very Intense Feeling	3 Intense Feeling	4 Moderate Feeling	5 Mild Feeling	6 Very Mild Feeling	7 Absent
--------------------------------------	------------------------------	----------------------	--------------------------	-------------------	---------------------------	----------

Please write below any additional comments and/or suggestions relevant to the question above:

Did you experience dizziness?

1 Extremely Intense Feeling	2 Very Intense Feeling	3 Intense Feeling	4 Moderate Feeling	5 Mild Feeling	6 Very Mild Feeling	7 Absent
--------------------------------------	------------------------------	----------------------	--------------------------	-------------------	---------------------------	----------

Please write below any additional comments and/or suggestions relevant to the question above:

Did you experience fatigue?

1 Extremely Intense Feeling	2 Very Intense Feeling	3 Intense Feeling	4 Moderate Feeling	5 Mild Feeling	6 Very Mild Feeling	7 Absent
--------------------------------------	------------------------------	----------------------	--------------------------	-------------------	---------------------------	----------

Please write below any additional comments and/or suggestions relevant to the question above:

Did you experience instability?

1 Extremely Intense Feeling	2 Very Intense Feeling	3 Intense Feeling	4 Moderate Feeling	5 Mild Feeling	6 Very Mild Feeling	7 Absent
--------------------------------------	------------------------------	----------------------	--------------------------	-------------------	---------------------------	----------

Please write below any additional comments and/or suggestions relevant to the question above:

Please share any preferences you have regarding the street designs you experienced today in VR.

Today, you experienced three different street designs shown below:

A: Plastic barrier
between cars and pedestrians



B: Concrete barrier
between cars and pedestrians



C: No barrier
between cars and pedestrians



Please rank your overall preference for the street designs you experienced in VR. Rank your highest preference as 1 and your lowest preference as 3.

_____ A: Plastic barrier between cars and pedestrians

_____ B: Concrete barrier between cars and pedestrians

_____ C: No barrier

Please share why you ranked **\${TopPreference}** as your top preference.

Please share why you ranked **\${LowestPreference}** as your least preferred option.

The handheld control was easy to understand and use

1-Strongly disagree	2	3	4	5-Strongly agree
---------------------	---	---	---	------------------

The equipment was comfortable and easy to wear

1-Strongly disagree	2	3	4	5-Strongly agree
---------------------	---	---	---	------------------

The tasks were easy to complete

1-Strongly disagree	2	3	4	5-Strongly agree
---------------------	---	---	---	------------------

About how long did it take for you to adjust to the VR environment, meaning you felt comfortable moving around without any disorientation?

- ☐ 1-2 minutes
- ☐ 3-4 minutes
- ☐ 5 or more minutes
- ☐ I never adjusted to the VR environment

I am a:

- ☐ CSU student
- ☐ CSU employee
- ☐ Northern Colorado resident not affiliated with CSU
- ☐ Other _____

What is your gender?

- ☐ Woman
 - ☐ Man
 - ☐ I identify my gender as: (Please specify)
-

- ☐ Prefer not to answer

What is your sex assigned at birth?

- ☐ Male
- ☐ Female
- ☐ Other / Decline to state

What is your age in years?

How tall are you?

- ☐ shorter than 4 feet, 0 inches (<122cm)
- ☐ 4 feet, 0 inches (122cm)
- ☐ 4 feet, 1 inch (125cm)
- ☐ 4 feet, 2 inches (127cm)
- ☐ 4 feet, 3 inches (130cm)
- ☐ 4 feet, 4 inches (132cm)
- ☐ 4 feet, 5 inches (135cm)
- ☐ 4 feet, 6 inches (137cm)
- ☐ 4 feet, 7 inches (140cm)
- ☐ 4 feet, 8 inches (142cm)
- ☐ 4 feet, 9 inches (145cm)
- ☐ 4 feet, 10 inches (147cm)
- ☐ 4 feet, 11 inches (150cm)

- 5 feet, 0 inches (152cm)
 - 5 feet, 1 inch (155cm)
 - 5 feet, 2 inches (157cm)
 - 5 feet, 3 inches (160cm)
 - 5 feet, 4 inches (162cm)
 - 5 feet, 5 inches (165cm)
 - 5 feet, 6 inches (167cm)
 - 5 feet, 7 inches (170cm)
 - 5 feet, 8 inches (172cm)
 - 5 feet, 9 inches (175cm)
 - 5 feet, 10 inches (177cm)
 - 5 feet, 11 inches (180cm)
 - 6 feet, 0 inches (182cm)
 - 6 feet, 1 inch (185cm)
 - 6 feet, 2 inches (188cm)
 - 6 feet, 3 inches (191cm)
 - 6 feet, 4 inches (193cm)
 - 6 feet, 5 inches (196cm)
 - 6 feet, 6 inches (198cm)
 - 6 feet, 7 inches (201cm)
 - 6 feet, 8 inches (203cm)
 - 6 feet, 9 inches (206cm)
 - 6 feet, 10 inches (208cm)
 - Taller than 6 feet, 10 inches (>208cm)
-

Please look at the below map.



During the academic year, how frequently do you visit the Lake Street area between the CSU Health Center (College Ave) and Canvas Stadium (Meridian Ave) [outlined above in yellow]?

This can be traveling through the area (e.g., walking, cycling, driving) or stopping in the area (e.g., entering an academic building or parking garage).

- ☐ Never
 - ☐ Less than 1x per week
 - ☐ 1-2x per week
 - ☐ 3-4x per week
 - ☐ 5x-6x per week
 - ☐ more than 6x per week
-

During the academic year, how often do you patron the Lake Street Parking Garage?

- ☐ Never
- ☐ Less than 1x per week
- ☐ 1-2x per week
- ☐ 3-4x per week
- ☐ 5x-6x per week
- ☐ More than 6x per week

Do you live at or frequently visit Aggie Village Apartments on Lake St?

- ☐ Yes
- ☐ No

During the academic year, how often do you ride a bicycle for the following reasons?

	5+ times a week	1-4 times a week	1-3 times a month	Never
To work/school	☐	☐	☐	☐
To get other places	☐	☐	☐	☐
Just for exercise/fun	☐	☐	☐	☐

During the academic year, how often do you walk for the following reasons?

	5+ times a week	1-4 times a week	1-3 times a month	Never
To work/school	☐	☐	☐	☐
To get other places	☐	☐	☐	☐
Just for exercise/fun	☐	☐	☐	☐

During the academic year, how often do you ride MAX or other buses for the following reasons?

	5+ times a week	1-4 times a week	1-3 times a month	Never
To work/school	☐	☐	☐	☐
To get other places	☐	☐	☐	☐
Just for exercise/fun	☐	☐	☐	☐

During the academic year, how often do you carpool/vanpool for the following reasons?

	5+ times a week	1-4 times a week	1-3 times a month	Never
To work/school	☐	☐	☐	☐
To get other places	☐	☐	☐	☐
Just for exercise/fun	☐	☐	☐	☐

If you used a commute mode besides driving alone in the past year (e.g., bike, bus, walk, vanpool, carpool), what were your primary reasons for doing so? (Check up to 3 for each)

	Save money	Save time	Avoid parking hassles	Improve air quality/ Environmental reasons	Increase physical activity/ Health reasons	Save wear and tear on personal vehicle	Don't have a personal vehicle	Other
Walk/ Bike/ Bus	☐	☐	☐	☐	☐	☐	☐	☐
Carpool/ Vanpool	☐	☐	☐	☐	☐	☐	☐	☐

Which of the following do you have? (Check all that apply)

- ☐ Bike cage membership (CSU or City)
- ☐ E-bike, E-scooter membership (SPIN)
- ☐ Car Share membership (ZipCar)
- ☐ Ride Share membership (Uber/Lyft)
- ☐ CSU parking permit
- ☐ Downtown (City) parking permit
- ☐ None of the above

Please check your most frequently used travel mode to work or school.

- ☐ Telecommute/Work from home
 - ☐ Walk
 - ☐ Bicycle
 - ☐ Take bus
 - ☐ Drive alone
 - ☐ Drive with adult from household (e.g., roommate)
 - ☐ Drive with adult NOT from household
 - ☐ Drive with children from household
 - ☐ Drive with children NOT from household
-

Have you ever experienced a virtual reality environment before today?

- ☐ No
 - ☐ Yes
-

Approximately how many times have you previously experienced VR?

- ☐ 1-5
- ☐ 6-20
- ☐ 21-50
- ☐ more than 50

In which of the following settings have you experienced VR?

- ☐ Video Games
 - ☐ Research
 - ☐ Educational/ Entertainment (i.e. museum, arcade)
-

How did you hear about this study? Please select all that apply.

- ☐ Flyer in Parking Garage
 - ☐ Flyer in Aggie Village
 - ☐ Flyer in academic building
 - ☐ Flyer in other building. Please specify, if possible.
-

- ☐ Email
- ☐ Online post/forum
- ☐ Personal communication (i.e., a friend, professor, colleague told me)

Study 2

Pre-VR items asked verbally by the researcher

The pre-VR survey for Study 2 was identical to that of Study 1.

In-VR survey

Tutorial - Completed once

For this study, convenience is the level of ease of reaching your destination (the red arch).

Safety is the perceived level of absence of risk for conflict between pedestrians and cyclists/motorized traffic.

Comfort is the level of physical ease and absence of distress experienced during walking.

Pleasure is the level of aesthetic enjoyment and positive emotional responses elicited during walking.

On a scale from 0 to 20, where 0 is no sickness at all and 20 is frank sickness, please rate your current level out loud for the researcher. The researcher will record it.

Please focus on nausea, general discomfort, and stomach problems. Please do not include any effects due to nervousness, boredom, or fatigue in this rating.

Trial survey - Completed 1x/trial

You have arrived at the destination. Please complete the following survey. For each question, pay careful attention to the response scale.

1/7

Trial #/12

How would you evaluate the environment you just experienced?



Extremely hard
to reach my
destination

Extremely easy
to reach my
destination

Convenience is the level of ease of reaching your destination.

2/7

Trial #/12

How would you evaluate the environment you just experienced?



Extremely
unsafe

Extremely
safe

Safety is the perceived level of absence of risk for conflict
between pedestrians and cyclists/motorized traffic.

3/7

Trial #/12

How would you evaluate the environment you just experienced?



Extremely
uncomfortable

Extremely
comfortable

Comfort is the level of physical ease and
absence of distress experienced while walking.

4/7

Trial #/12

How would you evaluate the environment you just experienced?



Extremely
unpleasant

Extremely
pleasant

Pleasure is the level of aesthetic enjoyment and
positive emotional responses elicited during walking.

5/7

Trial #/12

On a scale from 0 to 20, where 0 is no sickness at all and 20 is frank sickness, please rate your
current level out loud for the researcher.

Please focus on nausea, general discomfort, and stomach problems. Please do not include any
effects due to nervousness, boredom, or fatigue in this rating.

6/7

Thank you for your responses. Press "finish" to start the next trial.

7/7

Post-VR survey

The post-VR survey for Study 2 was identical to that of Study 1 with the following exceptions.

The preference item was altered from a single ranking question because Study 1 participants regularly commented that they misunderstood how preference mapped onto rank:

Today, you experienced three different street designs shown below:

A: Plastic barrier
between cars and pedestrians



B: Concrete barrier
between cars and pedestrians



C: No barrier
between cars and pedestrians



Which street design is your top preference?

- ☐ A: Plastic barrier between cars and pedestrians
- ☐ B: Concrete barrier between cars and pedestrians
- ☐ C: No barrier

Which street design is your least preferred option?

- ☐ A: Plastic barrier between cars and pedestrians
- ☐ B: Concrete barrier between cars and pedestrians
- ☐ C: No barrier

Ethnicity and race demographics items were added after the height item:

What is your ethnicity?

- ☐ Not Hispanic or Latino/a/x
- ☐ Hispanic or Latino/a/x
- ☐ Prefer not to answer

What is your race? (One or more categories may be selected.)

- ☐ African American/Black
 - ☐ Asian/Asian American/Pacific Islander
 - ☐ Native American
 - ☐ White
 - ☐ Other _____
 - ☐ Prefer not to answer
-

APPENDIX E. FREE RESPONSE CODING TABLE

Table E.1

Free response code frequency and examples by environment condition

Code	Flexible delineators	Concrete barriers	As-built condition
Safety			
Generally [un]safe	"It made me feel safer when crossing the street" (15) [(0)]	"I feel safer with the concrete barrier between cars and pedestrians" (20) ["adds potential hazard" (8)]	(0) ["Most unsafe" (10)]
[No] separation between motor traffic and pedestrians	"I like the separation between cars and pedestrians because it felt more safe than not having anything." (20) ["The lanes aren't as designated as the concrete barrier makes them" (1)]	"Made it easier to see what the bike lane versus the car lane was." (7) [(0)]	(0) ["I like there to be an easier way to identify the lanes. Having a physical barrier is a lot easier than just paint." (8)]

Code	Flexible delineators	Concrete barriers	As-built condition
[No] protection from impact	"The bikes and pedestrians are still protected from vehicles." (3) [(0)]	"With how fast cars go through campus, namely on that street it made me feel safe and that I would not get hit." (5) [(0)]	(0) ["If a car or bike were to swerve or crash into the sidewalk, there would be nothing preventing it from hitting a person" (8)]
[Does not] contain(s) pedestrians to designated zone	"Helps keep people in the area they need to be. IE: ... pedestrians on sidewalks." (1) ["pedestrians don't have to cross at the crosswalk." (2)]	"It forces the pedestrian to go to the crosswalk, which is great, I see a lot of people often just walking across the street." (6) [(0)]	(0) ["It gives one the option to just walk across the street without thinking twice." (5)]

Code	Flexible delineators	Concrete barriers	As-built condition
[Does not] contains other road users to designated zones	"I think it helps with keeping cars out of the bike lanes." (5) ["Sometimes even with plastic, some individuals still won't follow the rules so with concrete barriers, they will need to stay in that lane." (1)]	"Sometimes even with plastic, some individuals still won't follow the rules so with concrete barriers, they will need to stay in that lane." (2) [(0)]	(0) ["Issues with cars and cyclists getting too close to each other and cyclists sometimes riding on the sidewalk." (5)]
[Un]clear vision	"Still visually clear" (5) [(0)]	(0) ["obscured the view of the other side" (3)]	(0) [(0)]
Amenities			
[Lack of] free movement for pedestrians	"doesn't stop me from crossing even when I am not supposed to" (14) ["I like to wander into the street in front of cars and the plastic barrier impedes this activity" (1)]	(0) ["Sometimes I would prefer jay-walking but couldn't with the barriers there." (24)]	"Overall, made it fast and easy to cross and get directly to the destination." (12) [(0)]

Code	Flexible delineators	Concrete barriers	As-built condition
[Lack of] free movement for other road users	“The plastic barrier allows cars to pull into the bike [lane] if needed or a biker to pass into the road if needed” (7)	(0)	(0)
	[(0)]	["Concrete barriers restrict your movement options as a pedestrian, walking or biking." (1)]	[(0)]
[Lack of] open space	“I like that they leave the space feeling open.” (6)	“Paths felt clearer” (1)	“It's an empty and free space, feels clean also.” (5)
	["they are just in the way" (1)]	["Felt blocked out and trapped." (13)]	[(0)]
[Un]comfortable & [un]pleasant	“Better aesthetic” (5)	(0)	“It just looks amazing and more pretty.” (5)
	["I just didn't like the way that the plastic barriers looked" (2)]	["Looks ugly." (18)]	[(0)]

Code	Flexible delineators	Concrete barriers	As-built condition
Independent forces			
Mention of [im]balance	“Because it feels like a good middle ground between a concrete barrier and no barrier. The plastic barrier allows cars to pull into the bike lad if needed or a biker to pass into the road if needed while still allowing people to see that you shouldn’t.” (26) [“I just didn't like the way that the plastic barriers looked and there was space in between them so they were kind of pointless to have.”] (4)	(0) [“because it made my walk much longer to get to the cross walk further down, however it is the safer option. but it also just is not visually appealing, and I think detracts from the space” (14)]	(0) [(0)]

APPENDIX F. REPORT PROVIDED TO THE CITY OF FORT COLLINS AND CSU TRANSPORTATION

SS4A LAKE ST VIRTUAL REALITY STUDY

Prepared for:

Active Modes, City of Fort Collins

200 W. Mountain Ave. Fort Collins, CO 80521

CSU Transportation, Colorado State University

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Prepared by:

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December 2025

Funding provided by:

CSU Transportation, Colorado State University

Department of Psychology, Colorado State University

EXECUTIVE SUMMARY

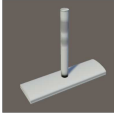
Problem. Promoting safe active transportation through street design is a powerful strategy to address two crises facing Coloradans: climate change and rising pedestrian deaths. Yet, current practice requires that transportation planners choose between potential safety countermeasures with limited available research, leading to ambiguity around which option will lead to the safest roads and most walking in their specific site. Being able to pretest potential countermeasures *in place* would be transformative within the transportation planning community. At the local level, the City of Fort Collins and CSU Transportation plan to implement a countermeasure in a high-priority section of campus. They have tasked us with collecting behavioral science data to clarify the most effective way to do so to promote safe walking.

Purpose. The current report's purpose is to use virtual reality (VR) to prospectively identify *pedestrian-related* strengths and vulnerabilities of 2 considered separated bike lanes (1. Flexible delineators and 2. Contiguous concrete barriers.) From collecting behavioral and self-reported data from 75 community members, the described study achieves 3 objectives: Compare the effect of the considered countermeasures against current conditions on promoting 1) use of marked crossings, 2) pedestrians' perceptions of safety, and 3) walking.

Findings. Contiguous concrete barriers resulted in the most frequent use of marked crossings though flexible delineators showed improvement on midblock crossings compared to as-built conditions. Both countermeasures boosted perceived safety, comfort, and overall walkability; however, flexible delineators also enhanced the convenience of accessing destinations and pedestrian pleasure. Community members showed an overwhelming preference for the flexible delineators, noting that they promoted safety while preserving a pleasant environment and allowing free movement of road users.

Recommendation. Focusing exclusively on pedestrians, we recommend a separated bike lane with flexible delineators along Lake St due to more robust evidence that they will promote walking, clear support for their effectiveness in directing pedestrians to marked crossings, and strong community support.

Summary of Findings

	 Flexible delineator	 Contiguous concrete barrier
Objective 1 Promoted:	✓	✓ ✓
Use of marked Xing		
Objective 2 Boosted:	✓	✓
Perceived safety		
Objective 3 Enhanced pedestrian:	✓	✗
Convenience		
Comfort	✓	✓
Pleasure	✓	✗
Overall walkability	✓	✓
Community preference	✓ ✓ "Gives a good distinction between the bike lane and car lane while still allowing a more open space..." "There is some separation and protection but it also still allows for easy movement."	✗ ✗ "Concrete barrier feels a bit too much. Made the atmosphere less pleasant and again I wouldn't be able to cut through the street." "Unappealing, and inconvenient"

ACKNOWLEDGEMENTS

We thank the following for their contributions to study design and analyses:

- Rachel Ruhlen, City of Fort Collins
- Aaron Fodge, CSU Transportation
- Jamie Gaskill, CSU Transportation
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BACKGROUND

Aug. 26, 2019: On his first day of classes, Colorado State University (CSU) freshman, Anthony "TJ" Avery, was out for a run on the CSU campus when he was hit by a motor vehicle: The injuries would take his life 4 days later (Colorado State University Safety & Risk Services, n.d.). In response to this preventable death, CSU signed the Vision Zero commitment. Five years later, there is still much work to do to ensure that students, employees, and visitors are safe on CSU's campus: Indeed, Colorado pedestrian deaths have jumped 77% in a similar amount of time (Colorado Department of Transportation, 2024). Through design of the physical transportation infrastructure, we can reduce the likelihood of serious crashes. Furthermore, increasing use of nonmotorized transportation, such as walking, is a key aspect of strategies promoting safe roads (Ecola et al., 2018). Higher numbers of pedestrians and bicyclists diminish the likelihood of a crash involving a pedestrian or bicyclist (Jacobsen, 2003). Indeed, CSU highlights increasing active transportation as critical in its Transportation Master Plan (Colorado State University, 2023). Furthermore, active transportation is important in curtailing the climate crisis as noted by CSU's Climate Action Plan (Colorado State University, 2022).

Promoting walking on CSU's campus is a powerful strategy to address these dual crises as 41% of CSU students primarily drive (Tapleshay, 2023), and walking requires no special equipment (Hajna et al., 2015). As noted by social-ecological models of behavior change (Sallis et al., 2008), intervening on the built environment [e.g., physical transportation infrastructure (Saelens & Handy, 2008)] is more efficient than attempting to persuade individuals to alter their actions. Essentially, interventions to CSU's physical campus can influence all 34,000 students (Colorado State University, n.d.-b) and nearly 11,000 employees (Colorado State University Institutional Research, Planning and Effectiveness, n.d.) while the impact of individual-level interventions is restricted to those who have the resources and time to participate.

DESCRIPTION OF PROBLEMS

Sector Level

Although there is research identifying which interventions are associated with walking (De Vos et al., 2023; Pontin et al., 2022) and safe roads (National Safety Council, n.d.), it can be difficult to determine which of the available countermeasure options will be the most effective at promoting walking safely in a particular location. Site-specificity is of particular importance as the effectiveness of an individual intervention depends on the local policy, culture, and previous built conditions (U.S. Department of Transportation Federal Highway Administration, 2007). As outlined by a Federal Highway Administration report (Tang et al., 2018), safety projects should consider how they fit into other initiatives, policies, and physical infrastructure. Thus, being able to pretest countermeasures *in place* would be transformative, leading to large increases in traffic safety.

Additionally, resources for built environmental countermeasures are finite, and potential designs are costly [e.g., adding a raised crosswalk costs ~\$10,000, adding a median costs ~\$404,000/mile (Bushell et al., 2013; CPI Inflation Calculator, n.d.)]. This reality requires design practitioners to choose between options with limited site-specific evidence. Moreover, it is

common for the effectiveness of pedestrian infrastructure projects to be evaluated *after* completion (Pontin et al., 2022; Y. Zhang et al., 2022). While this step is important and can inform future interventions (i.e., lessons learned), it is too late to affect the infrastructural project in question as dedicated resources have already been spent. Thus, it is vital to develop new approaches to *proactively* identify which countermeasures are most effective at promoting safe walking relative to cost within a particular geocultural setting. Furthermore, transportation planners are asked to defend the expense of a chosen countermeasure by governmental officials and publics. A strategy to pretest countermeasures would enable transportation planners to provide location-specific data to stakeholders.

Campus Level

The City of Fort Collins and CSU Transportation plans to redesign a section of CSU's campus on Lake St. This area is a known safety-concern (Rowe, 2023). A traffic safety study reports a single unsignalized intersection in the area can see up to 950 crossing pedestrians and 600 motor vehicles per hour. Crashes are not uncommon in this area. Unmarked midblock crossings are of particular concern as many individuals walk from common locations south of Lake St (e.g., apartment complexes) to busy destinations north of the area (e.g., classrooms). The City of Fort Collins and CSU Transportation plan to implement a countermeasure in this area within the next two years. They have tasked us with collecting behavioral and psychological data to clarify the most effective way to do so to promote safe walking. They are considering 2 countermeasures: creating a separated bike lane via 1. Adding flexible delineators and 2. Adding contiguous concrete barriers between pedestrian and motor vehicle traffic.

APPROACH

As described, current practice requires that transportation planners choose between potential countermeasures with limited available site-specific research indicating which option will lead to the safest roads and most walking. Unfortunately, pretesting countermeasures in place has historically been infeasible or impossible with this type of research—until virtual reality (VR) technology. VR technology enables standardization of other factors influencing walking (e.g., weather, traffic volumes), thereby enabling conclusions regarding which specific countermeasures will be the most effective. Furthermore, VR saves considerable time and money as it circumnavigates the permitting and construction stages necessary for modifications to the real environment. Our VR approach allows planners to affordably and quickly modify VR environments and collect site-specific data to assess vulnerabilities of roads.

As the current report is exclusive to pedestrians, the following is a brief overview of existing research concerning the utility of VR to study walking behavior and safety. Individuals estimate risk and safety equally in VR urban environments as real-world ones (Bhagavathula et al., 2018). Similarly, VR environments can stimulate realistic emotions (Newman et al., 2022). Notably, street crossing decisions (e.g., choosing the length of gap between cars necessary to cross) in VR are no different than those made in the real world (Angulo et al., 2023; Bhagavathula et al., 2018; Schwebel et al., 2008). Concerning judgements, individuals rate the same real-world and VR environments comparably on a number of perceptual domains, including beauty,

pleasantness, and motivation to walk (Nishio & Ito, 2020; Shi et al., 2020; Spitzer et al., 2025). Lastly, a study investigating pedestrian navigation in VR (Dong et al., 2022) reports that participants made the same number of errors in VR and the real world. Thus, VR is a viable solution to determining which countermeasures targeting pedestrian behavior are optimal for implementation in a particular context.

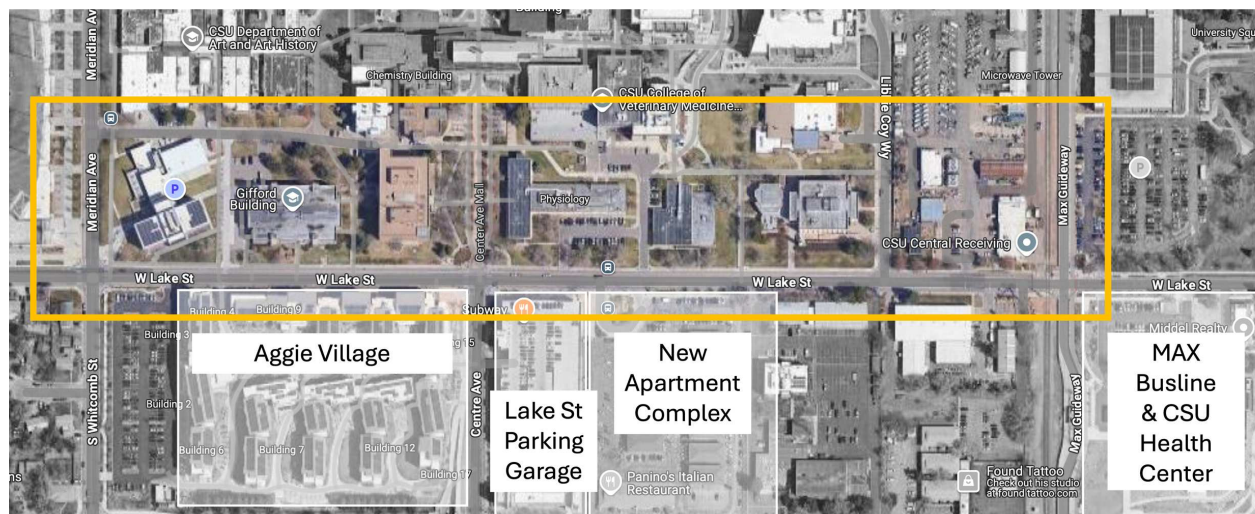
The current report

In the current report, we used VR to prospectively identify pedestrian-related strengths and vulnerabilities of 2 countermeasures (1. Flexible delineators, 2. Contiguous concrete barrier) currently under consideration for intervention on CSU's campus. This project was driven by 3 objectives. 1) Compare the effect of Countermeasures 1 and 2 against current conditions on use of marked crossings. 2) Compare the effect of Countermeasures 1 and 2 against current conditions in promoting pedestrians' perceptions of safety. It is valuable to study how the proposed countermeasures influence perceptions of safety in addition to objective metrics of safety because perceived safety is linked to increased walking (Kärmeniemi et al., 2018). 3) Compare the effect of Countermeasures 1 and 2 against current conditions in promoting walking.

We created a VR simulation of Lake St with simulation variants depicting the two potential countermeasures and the current conditions. This simulation depicts a 25.7-acre (104,000 m²) area, complete with buildings, cross streets, sidewalks, automobiles, and greenery to match the real environment. A map of the area is provided in Figure 1. Figure 2 shows still photographs of the computer-generated environment with each countermeasure. Information regarding the development of this simulation and additional photographs are presented in Appendices A and B, respectively.

Figure F.1

Map of area of investigation



Note. Gold rectangle represents VR simulation boundary.

Figure F.2

VR Simulation depicting tested countermeasures and as-built conditions

Separated – Flexible
delineator



Separated – Contiguous
concrete barrier



As-built conditions



We designed a research study that immersed community members as pedestrians in this VR simulation with and without the countermeasures in order to address our outlined objectives. In this study, community members who were familiar with the Lake St area participated in a 1-hr laboratory session. During this session, they were asked to self-navigate from common points of interest south of Lake St (e.g., existing apartment complexes) to common destinations north of Lake St (e.g., an academic building) and answer surveys querying their perceptions of the environment. Additional information regarding the study session's design is presented in Appendix A. This study was approved by Colorado State University's Institutional Review Board (Protocol #7136). A small pilot study with 21 community members indicated that this approach was feasible and acceptable to users.

FINDINGS

Seventy-five members of the CSU community participated in the described study. These community members were familiar with the intervention area (79% visited the area ≥ 3 x/week). All were students (89%) and/or employees of the university (15%). The most frequent mode of transport among these individuals was to drive (38%) though this group is underrepresented compared to university data (72%) (Colorado State University, n.d.-a). In contrast, pedestrians (31% v. 7%) and cyclists (22% v. 11%) were overrepresented. The proportion of our sample that most frequently bus to school/work (9%) was consistent with university data (8%). Compared to university-wide employee (Colorado State University Institutional Research, Planning and Effectiveness, n.d.) and student data (Colorado State University, n.d.-b), this sample of community members was more ethnically and racially diverse than the community population.

Objective 1: Compare the effect of flexible delineator and contiguous concrete barrier separated bike lanes against current conditions on use of marked crossings

Figure 3 illustrates the routes community members took while navigating the computer-generated Lake St as a pedestrian; moreover, it indicates where they crossed Lake St in relationship to marked crossings, stratified by countermeasure.

Figure F.3

Routes taken by community members by virtual environment



There were fewer unmarked midblock crossings in both environments with a separated bike lane than as-built conditions. Between the two separated bike lanes, the one composed of continuous concrete barriers was more effective at guiding pedestrians to marked crossings. Furthermore, Figure 3 shows that when community members crossed the street without using a marked crossing in the environments with a separated bike lane, they tended to do so at the end of a line of delineators/barriers. This pattern indicates more predictable unmarked midblock crossings. It also suggests that separated bike lane solutions to unmarked crossings may benefit from bookending with zebra crossings.

Objectives 2 and 3: Compare the effect of the countermeasures against current conditions in promoting perceived safety and walking

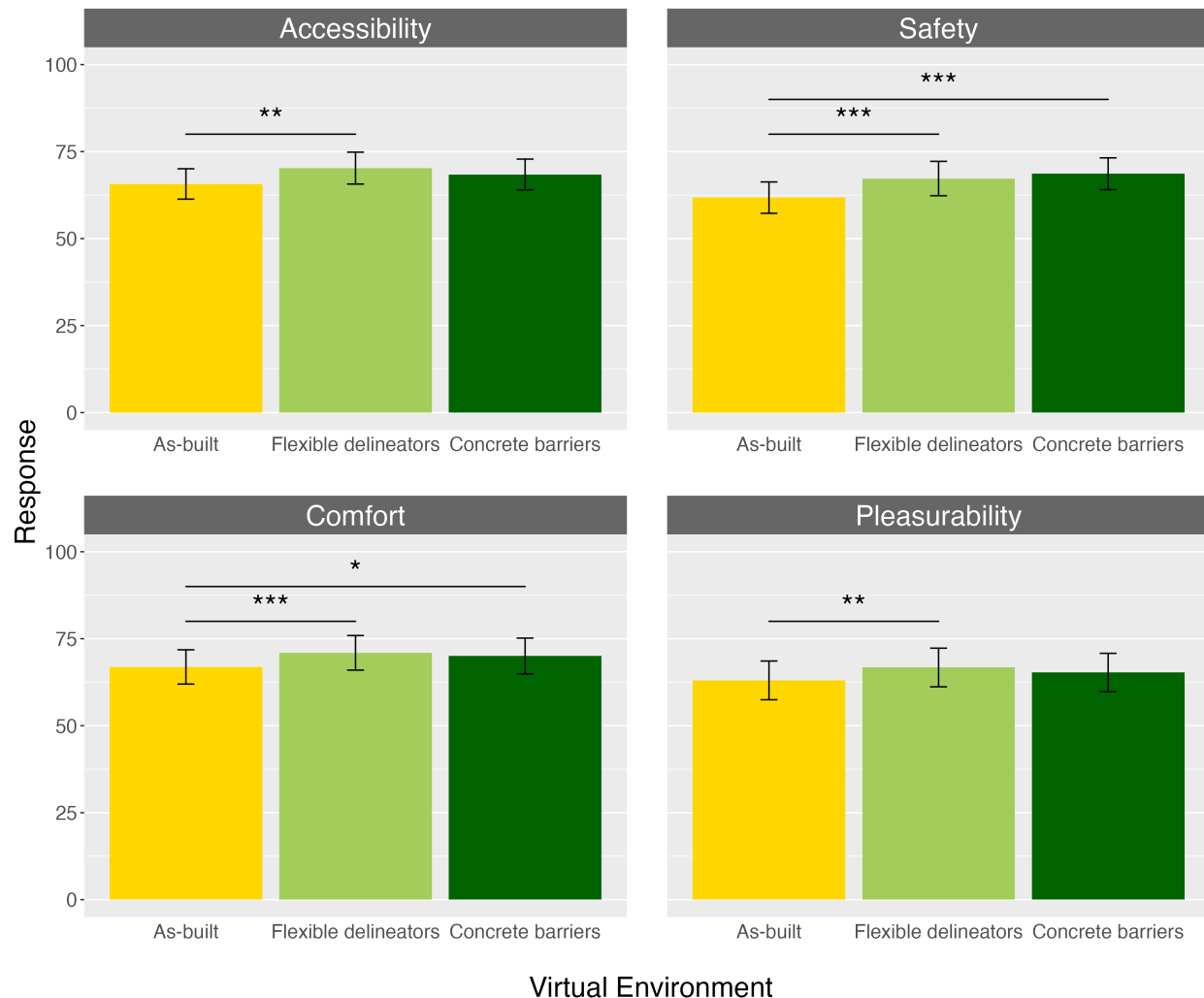
To assess pedestrians' perceived safety and likelihood of walking, community members reported how accessible, safe, comfortable, and pleasurable they found each version of the environment. Definitions of these concepts provided to those participating in our study are available in Appendix A. Notably, accessibility is defined as conceptualized by Alfonzo (Alfonzo, 2005): the level of ease of reaching a destination. Similar perceptions of walkability (e.g., safety, accessibility) are associated with walking behavior (De Vos et al., 2023). By measuring how participants perceived the simulated environments in relation to these domains, we can gather information regarding how the investigated countermeasures promote walking and create a composite metric of overall walkability.

The environment with the separated bike lane created with flexible delineators was perceived to be more accessible, safe, comfortable, and pleasurable from a pedestrian perspective than the environment depicting the as-built conditions. In contrast, there was only evidence that the separated bike lane with contiguous concrete barriers improved perceptions of safety and comfort when compared to the as-built condition. Interestingly, the differences in perceptions

of the contiguous concrete barriers compared to those of the flexible delineators were minimal. These findings are illustrated in Figure 4.

Figure F.4

Perceptions of countermeasures against as-built conditions



Note. *, **, and *** indicate statistical significance at the 0.05, 0.01, and 0.001 levels, respectively. Lower significance levels are indicative of stronger evidence that the two conditions are not the same.

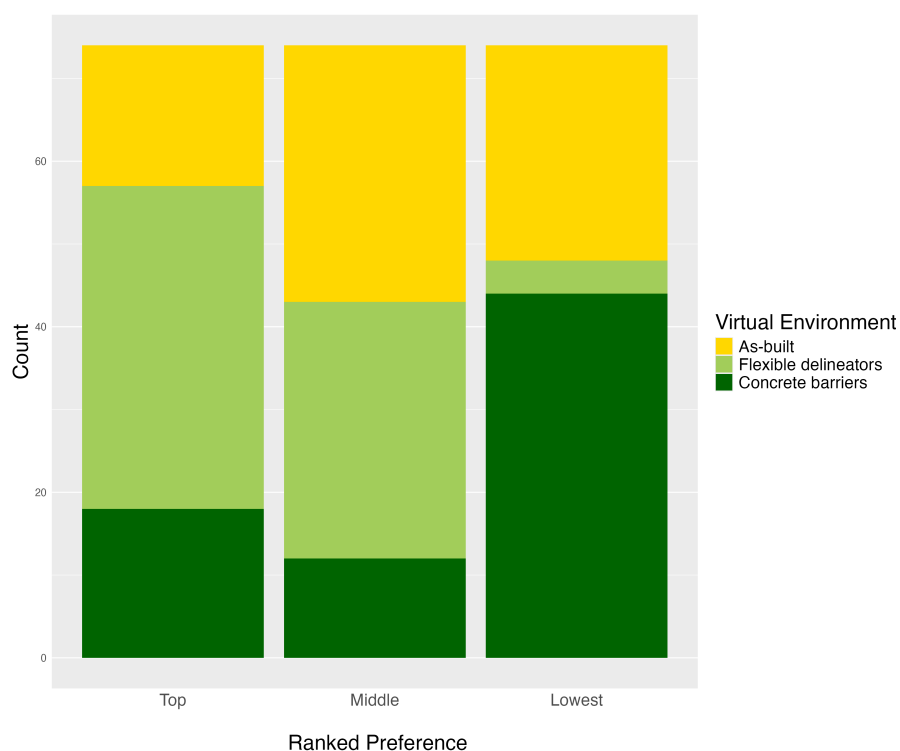
Both countermeasures resulted in small boosts to a composite metric representing overall walkability. Our models indicated that the overall walkability of the environment with the flexible delineators was 0.15 standard deviations higher than that of the as-built conditions. Similarly, the overall walkability of the environment with the contiguous concrete barriers was estimated to be 0.13 standard deviations above that of the as-built conditions. Again, there was a negligible difference between the two investigated countermeasures (0.02 standard deviations).

Community members' preferences

Community members ranked their preference for the countermeasures against as-built conditions, which is presented in Figure 5. Community members strongly preferred the separated bike lane with flexible delineators. When asked about their rationale of their top preference, those who selected the flexible delineators (39 individuals) regularly referenced “separation between the cars and pedestrians on the sidewalk” (20), general safety (15) and the ability for pedestrians (15) and other modes of transport (4) to move freely throughout the road. To a lesser degree, community members explained that the flexible delineators “still allowed a more open” (6) and pleasant space (5), “allow[ed] good vision” of the road and other road users (5), and protection from motor vehicles (4). A majority of those who favored the flexible delineators discussed them as “a good middle ground” (24). These individuals talked about a balance between safety (14), and/or separation of travel modes (12) with enabling free movement (15) and/or “not causing harm to the pleasantness” (4) or openness (6) of the space.

Figure F.5

Community members' preferences for tested street designs



All those who preferred the separated bike lane created with contiguous concrete barriers cited safety issues (18), namely “a physical object separating the pedestrians and the cars” (7), a barrier that can “deflect or slow down a car” (5), and a street design that “forces the pedestrian to go to the crosswalk” (5).

Lastly, those who favored the current street organization (17) reasoned that the free movement made it “easier to cross the street,” (9) particularly how it “d[id]n't prevent [them] from taking the most optimal route” (8). They mentioned that “it's more aesthetic” (5) and “more open” (5).

Conversely, most community members ranked the contiguous concrete barriers as their least preferred option. Those who least preferred this separated bike lane design (44) usually provided one of two primary reasons: issues of accessibility (16) and those of pleasantness (17), though some discussed both (8). Accessibility concerns centered on “restrict[ion] to your movement options” (20). Community members noted that they felt they had to use crosswalks that “sometimes can be pretty far away from the destination and inconvenient for walking” (14) or that the barriers “got in the way” (4). If contiguous concrete barriers are implemented, regular breaks in the barriers with zebra crossings may assuage this concern while preserving the strong effect of these barriers in reducing unmarked crossings. Issues around pleasantness included that the environment with the contiguous concrete barriers were “unappealing” (5) and “just looks terrible” (12). They explained that the barriers created a “congested” space (12), leading to feelings of “being cornered.” Several communicated that the concrete barriers were “overkill” (6). Additionally, a handful of community members voiced concerns that these barriers posed a “potential hazard” (7) or “obscured the view of the other side” (3).

Every community member who ranked the as-built conditions as their lowest preference mentioned a safety concern (26). A common reason for the low rank was the lack of separation between traffic modes (15) as one individual wrote “No barrier does not make me feel safe.” Several community members specifically wrote about “protection from a car” and “how there would be nothing preventing it from hitting a person” (8). Interestingly, a handful of community members perceived the ability for “people to go wherever they want” as a limitation of the as-built conditions (5) which is in opposition to the nine who preferred this environment for the very same reason.

Only four community members least preferred the flexible delineators. The most common rationale was that they resulted in some negative externality [e.g., unpleasantness (2)] and “they don't really do anything to help with safety” (3).

RECOMMENDATION

The described study was conducted to aid the City of Fort Collins and CSU Transportation in identifying which countermeasure will have the maximum positive impact on pedestrians. Our findings indicate more evidence that the separated bike lane with flexible delineators will increase walking in this area. Both investigated countermeasures improved pedestrian perceptions of walkability, comfort, and safety. Still, this study found stronger support for the flexible delineators in enhancing pedestrian accessibility and pleasurability. Additionally, this countermeasure was overwhelmingly preferred by community members for its safety impacts, relative pleasantness, and movement flexibility. Route analysis illustrated that flexible delineators greatly reduced unmarked midblock crossings though not to the extent of contiguous concrete barriers. It is our conclusion that the flexible delineators’ strong evidence for promoting walking and clear community preference offsets the marginal benefit of the

contiguous concrete barriers on use of marked crossings. When additional funding is available, CSU may consider the addition of zebra crossings at the culmination of a stretch of delineators/barriers.

Based on these findings, it is our recommendation to the City of Fort Collins and CSU Transportation that they implement a separated bike lane via flexible delineators on Lake St to promote safe walking behavior. This recommendation is made with exclusive reference to pedestrians as other travel modes were not included in the present investigation.