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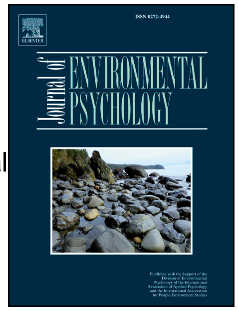

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The Influence of Spatial Dimensions of Virtual Environments on Attitudes and Nonverbal Behaviors During Social Interactions

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Abstract

Research on physical-world environments has shown that the spatial properties of built worlds are consequential for shaping psychological states and social behavior. However, it has been difficult to empirically test this in natural settings in the physical world. This study uses immersive virtual reality (VR) environments, which have shown to have comparable effects to physical-world environments, to investigate the influence of two spatial dimensions (ceiling height and floor area) on individuals' attitudes and nonverbal behaviors during social interactions. In the present study, groups of three to four physically remote participants wore VR headsets (n = 110) and took part in discussions every week for four weeks in one of four virtual environments that varied in their spatial dimensions (low or high ceilings, small or large floor areas). Results showed that, when in a virtual environment with a high ceiling, participants reported feeling greater perceived restorativeness, awe, and momentary affective well-being, compared to when they were in virtual environments with low ceilings. Participants also paid more social attention (i.e., looked at other group members), when they were in virtual environments with high ceilings. When in a virtual environment with a large floor area, participants reported having a greater sense of awe, compared to environments with small floor areas. Furthermore, when in a large environment with a high ceiling, participants physically moved their heads more slowly and virtually stood further apart from their group members, compared to the other three conditions. We discuss implications for theoretical work on context and behaviors as well as design of social VR environments.

Key words: *virtual reality, social virtual reality, environmental context, social interaction, nonverbal behavior*

Introduction

Virtual reality (VR) is a unique tool that can be used to study psychological and behavioral experiences. Several studies have shown that environments accessed through VR have similar effects on people as environments in the physical world (e.g., Cha et al., 2019; Heydarian et al., 2015; Valtchanov et al., 2010). Furthermore, VR allows researchers to timely, cost-effectively, and flexibly create environments that are otherwise challenging to access or build in the physical world (e.g., OMITTED; Presti et al., 2022). Taken together, VR has been considered a viable tool to easily create environments that can be used for psychological well-being (promoting well-being, Yeo et al., 2020; affecting mood, Jung et al., 2023; reducing stress, Anderson et al., 2017), or train individuals in situations that might be dangerous, impossible, counterproductive, or expensive to create in the physical world (see DICE model, Bailenson, 2018; e.g., Carattin et al., 2012).

There are several gaps within the literature, namely on how the virtual environment influences individuals when they are with others, and consequently, how it shapes the social interactions that take place. Most previous literature focuses on how the virtual environment influences individuals when they are alone. However, social interaction is not only an important part of the human experience, but also one of the most popular and powerful use cases of VR (Lanier & Biocca, 1992). Given its unique affordances, such as spatiality, presence, and embodiment, VR has the unique ability to connect people with themselves, others, and their environments (Lombard & Ditton, 1997). Furthermore, a fundamental premise of the field of social psychology is that the presence of another – actual, implied, or imagined – can influence the feelings and behaviors of individuals (Allport, 1954). As a result, it is critical to understand how virtual environments influence people's experiences when they are alone, but also when they are socially interacting with others.

The goals of the present paper are twofold. First, we contribute to the research on the psychological and behavioral effects of virtual environments, in particular their spatial dimensions of ceiling height and floor area. Second, we contribute to the growing research of social interactions in virtual environments. In what follows, we review past literature on how the spatial properties of environments, both physical and virtual, can influence individual and social outcomes. We then introduce a study that, over four weeks, cycled through 16 different virtual environments that varied in ceiling height (low versus high) and floor area (small versus large), to investigate how these properties influence individuals' attitudes and nonverbal behaviors.

1.1 The Influence of the Spatial Properties of Environments

The spatial properties of environments have been shown to influence people and their emotional (for a review, see Bower et al., 2019), physical, psychological, and social well-being (for a review, see Colenberg et al., 2020), and social and cognitive development (for a review, see van Liempd et al., 2020). One spatial property that has been identified as a salient one is ceiling height. Meyers-Levy and Zhu (2007), for instance, found that ceiling height can affect how people process information. In their study, participants were placed in rooms with either high ceilings (3.048 m or 10 ft) or low ceilings (2.44 m or 8 ft). Ceiling height was hypothesized to influence participants' perceived body state and prime different kinds of processing. Within these rooms, participants engaged in computer-based tasks, such as solving anagrams, categorization tasks, and memory recall. Exposure to high ceilings was found to prompt thoughts related to freedom and elicit more abstract processing, whereas exposure to low ceilings prompted feelings of confinement and elicited item-specific processing. These types of processing emerged when ceiling height was salient, such that participants were made aware that the ceiling height was low or high, through placements of lanterns. The authors note that these results were most likely due to ceiling height increasing or decreasing vertical room volume, but also highlight that these outcomes could be specific to variation in ceiling height and may not have occurred if horizontal room volume was controlled for. In other words, it is unclear how these findings replicate if room width is varied.

An argument can be made here that the effects of ceiling height are due to an increased perceived spaciousness of an environment. In other words, floor area may play a role, as well. For example, Worchel (1986) conducted a study manipulating the size and shape of a room. Participants were placed in either a small square (85.6 ft^2 or 7.95 m^2), small rectangular (84 ft^2 or 7.804 m^2), large square (196 ft^2 or 18.2 m^2), or large rectangular room (192 ft^2 or 17.8 m^2) and had a 5-minute discussion with a confederate. Results showed that participants kept greater distances from a stranger when in a smaller room than in a larger one, though this effect only showed in rectangular, not square, rooms. A main takeaway from this study was that the floor size (i.e., room size) is not the only – or even the most – important room variable that determines people's responses, and that other factors can play a role. In other words, it is critical to understand how multiple spatial properties can exert influence and interact with one another.

Spatial properties have been shown to be salient in virtual environments, as well. For instance, Presti and colleagues (2022) investigated how virtual architectural designs impact affective states by building 54 virtual environments that varied in terms of sidewall distance, ceiling height, window height, and color. Results showed that decreasing ceiling height produced unpleasant judgments of the virtual environment. In their study, ceiling height varied from 3.2-

4.8 m. Similarly, another study by Cha and colleagues (2019) found that high ceilings (3.2 m) yielded more positive affective responses, compared to low ceilings (2.6 m).

While these studies highlight that results found in the physical world can be replicated in virtual ones, there are still differences between how people perceive and move around in physical and virtual environments. Although they both provide similar perceived affordances – visible characteristics of the environment that inform behavioral actions (Gibson, 1977) – there are factors that lead to slight differences in how people perceive virtual environments differently from physical ones (Loomis & Knapp, 2003). Studies have shown that people tend to underestimate size and distance in virtual environments (for a review, see Renner et al., 2013). Scholars speculate that there are factors related to the hardware (e.g., Willemsen et al., 2009), software (e.g., Vienne et al., 2020), and human perception (e.g., Rzepka et al., 2022) that contribute to this difference (Kenyon et al., 2007; Creem-Regehr et al., 2022), and that newer commercial head-mounted displays (HMDs), which come with improvements in resolution, wider field of view, and graphical fidelity, may eventually resolve these differences (Bhargava et al., 2020). Still, even studies relying on such newer HMDs show that people respond differently to spatial features in the physical versus virtual environment, underscoring that spatial distortions in VR cannot be entirely attributed to the aforementioned factors (e.g., OMITTED, in press). For example, Bhargava and colleagues (2020) showed that although people achieved a comparable level of judgment accuracy during a task in which they evaluated whether a door's width was passable, people need more dynamic sources of information when judging in VR (i.e., needed to physically move and walk towards the door to make their judgment). Although how people perceive spatial information may be in many ways similar in the physical and virtual world, there are still differences in how people perceive and act upon these affordances.

1.2 How the Physical and Virtual Environment Shapes Social Interactions

The environment has also been found to shape social interactions (Altman, 1975). Architectural designs can encourage or discourage social interaction, as theorized by Gibson (1977). Past research shows that light and room decor can influence the intimacy of interpersonal communication (dyads; Gifford, 1988); that ceiling height and wall color can influence cooperative behavior of children (small groups; Read et al., 1999); and that type of lighting can influence self-disclosure and form impressions during client-counselor interactions (dyads; Miwa & Hanyu, 2006).

Prior research on VR has shown that social interactions taking place in virtual environments are similar, though not identical to those found in the physical world. People respond socially to avatars (i.e., a virtual being controlled by a person), and agents (i.e., a virtual being controlled by a computer), such that they maintain interpersonal distance and eye contact (Bailenson et al., 2001; Bailenson et al., 2003). As a result, VR has been considered a viable tool for research in social psychology and understanding social interactions (Blascovich et al., 2002). However, there are factors unique to VR that influence people's social responses, such as how visually and behaviorally real a virtual being is, how responsive they are, and their agency (Garau et al., 2003; Garau et al., 2005; von der Pütten et al., 2010; Fox et al., 2014). Furthermore, according to the Transformed Social Interaction framework, VR systems can produce subtle and large changes, either intentional or unintentional, that filter and modify the appearance of avatars, sensory capabilities, and the environment, which ultimately shapes the nature of the social interactions (Bailenson et al., 2004).

As aforementioned, the environment is one of the main factors that can influence social interactions in VR. We see evidence of this in studies such as Miller and colleagues' (2021), who explored how the virtual environment can affect team dynamics during the design process. Triads met inside a social VR platform and engaged in various tasks in either a conference room or a garage. Results showed that participants were more in synchrony with one another during sessions that took place in conference rooms. The authors conclude that virtual environments in which collaboration occurs should be selected mindfully, as they can inform or constrain activities.

The importance of the virtual environment has been shown on a larger and longer scale, as well. More recently, OMITTED investigated how visible space and setting influenced social interactions in VR. Every week for eight weeks, groups of 2-11 participants had a discussion in one of 192 different virtual environments that varied in visible space and setting. These environments were either constrained or panoramic (i.e., people could see wide and far), and indoors or outdoors (i.e., surrounded by nature). Results showed the beneficial effects of being in large virtual environments and nature: spacious, panoramic environments led to an increase in motion synchrony, reports of greater perceived restorativeness, entitativity, pleasure, arousal, self and spatial presence, enjoyment, and realism. Furthermore, being in outdoor virtual environments surrounded by nature led to greater perceived restorativeness and enjoyment. However, one factor that was not controlled for was ceiling height. All stimuli environments had high ceilings, and thus what role ceiling height space played, rather than floor area, remains unclear.

On a macro level, McVeigh-Schultz and colleagues' study (2019) sheds light on the implications of the design of environments in shaping longer-term cultures. This study found that the aesthetics and architecture of the virtual environment are intentionally designed to stimulate social activities and shape social expectations, such as with furniture. The authors note the critical role of place in social interactions and how environmental factors can shape expectations, behaviors, and cultures. In other words, place matters, and it has the power to shape how people interact with one another.

Current Study

As aforementioned, there are two goals of this present paper. First, we use VR to further investigate how different spatial dimensions, particularly ceiling height and floor area, influence people's responses. Namely, we investigate their effects on perceived restorativeness, awe, momentary affective well-being, and how people move both their physical and virtual bodies, pay attention to others, and maintain interpersonal distance. We modify the salience of ceiling height and floor area by leveraging VR's ability to easily create extremely low and high ceilings, as well as environments with extremely small and large floor areas.

Second, we further examine how the virtual environment can affect responses when people are together and interacting with others. Although the effects of the environment have received considerable attention on people's experiences when they are alone, how they affect individuals when they are socially interacting with others remains underexplored, particularly related to nonverbal behaviors. This is especially critical given social interaction is one of the most prevalent use cases for VR.

In general, the driving principle of this work is that given their beneficial properties, virtual environments with high ceilings and large floor areas would elicit positive outcomes. Drawing on previous research findings, we formulated and pre-registered hypotheses concerning the interaction between ceiling height and floor area (pre-registration at OMITTED)[1].

[1] We pre-registered and tested additional confirmatory hypotheses which were less relevant to the current manuscript, for example presence and realism. Of these hypotheses, four were not significant, and three were not

H1: When participants are in a virtual environment with a high ceiling and large floor area, they will report experiencing greater awe.

H2: When participants are in a virtual environment with a high ceiling and large floor area, they will report experiencing greater momentary affective well-being.

We also report on exploratory research questions and analyses that have no prior assumptions regarding expected hypotheses.

RQ1: Will participants who are in a virtual environment with a high ceiling and large floor area report experiencing greater perceived restorativeness?

RQ2: Will participants' nonverbal behaviors differ depending on the ceiling height and floor area of the virtual environment?

In general, the driving principle of this work is that given their beneficial properties, virtual environments with high ceilings and large floor areas would elicit positive outcomes.

Methods

1.1 Participants

The present data is a previously unreported subset of the OMITTED Dataset, which includes data from approximately 500 students across two years, each of whom took one of four separate courses about VR that were taught using the ENGAGE social VR platform accessed via Meta Quest 2 VR headsets (OMITTED, in press). At the beginning of the course, students were invited to participate in an Institutional Review Board-approved (IRB) study of how various

examined for the scope of this paper. We do not report them here, nor do we introduce those outcome variables in the measures section, due to space constraints and relevance to the current narrative. However, the OSF pre-registration outlines these hypotheses in detail.

exposures to VR influenced their behavior. While all students who were part of the course took part in all the VR activities, only those who consented to participate in the study contributed data for analysis. Safeguards implemented to ensure privacy and consent included review both by the IRB and a second university ethics organization, and third-party oversight of the consent process and data collection, and recurring reminders that they were being recorded at the beginning of every session.

Of the 152 students who took part in the course, 117 consented to participate in the study. The 110 participants (M = 47, F = 61, something else = 2) who provided usable data[2] were between ages 18 and 59 years (M = 21.6, SD = 5.85, $n_{18\sim20} = 56$, $n_{18\sim20} = 47$, $n_{24\sim59} = 6$, declined to or did not respond = 1) and identified as Asian or Asian-American (n = 48), White (n = 20), bi- or multiracial (n = 13), Hispanic or Latin X (n = 13), African, African-American, or Black (n = 10), Middle Eastern (n = 3), Indigenous/Native American, Alaska Native, First Nations (n = 1), Native Hawaiian or other Pacific Island (n = 1), and declined to or did not respond (n = 1). Participants had varying levels of experience with VR, with 43 (39%) having never used VR before, 22 (20%) having tried VR once, 39 (35.5%) having used it several times (2-10 times before), and 6 (5.46%) being regular users (20-100 times before). This sample represents a demographic of people who may use VR (i.e., young adults).

1.2 VR Hardware and Software

At the beginning of the course, all participants were provided with a Meta Quest 2 headset: standalone head-mounted displays (HMDs) with 1832 × 1920 resolution per eye,

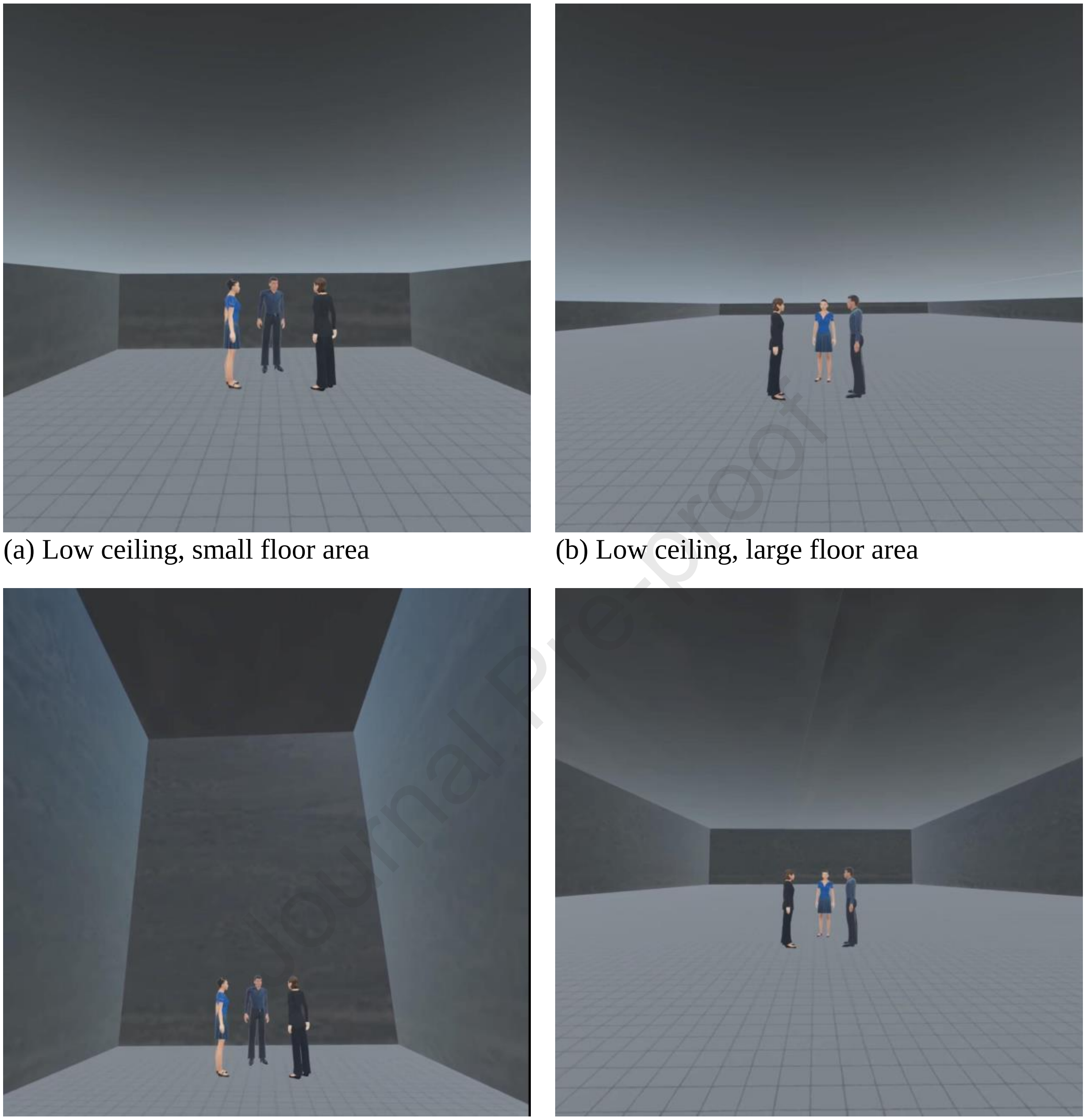
[2] Cases where participants experienced technical errors such as an incorrectly loaded world, tampered with the boundaries of the world, were the only group member that showed up that session, or submitted a file format not compatible with data analysis (i.e., not a .myrec format) were excluded from data analysis.

104.00° horizontal FOV, 98.00° FOV, 90 Hz refresh rate, and six-degree-of-freedom inside-out head and hand tracking (503 g) and two hand controllers (126 g), which they could use in their personal environment.

Weekly sessions were hosted in ENGAGE, a collaborative social VR platform designed for education. Every week, the virtual environment consisted of a private (password restricted) room in which students could create 3D drawings, write on personal whiteboards/stickies, add immersive effects/3D objects, and display media content. In ENGAGE, users are represented by avatars. These avatars allow users to embody a virtual body and interact with other avatars from a first-person point of view. Students could move using the joystick on their hand controllers to teleport (i.e., transferring to a selected spot) or translate (i.e., continuous directional movement) in the virtual world.

1.3 Virtual Environment

There were four types of virtual environments (2 ceiling heights × 2 floor areas) with: (a) a low ceiling, small floor area, (b) a low ceiling, large floor area, (c) a high ceiling, small floor area, or (d) a high ceiling, large floor area (Figure 1). There were four environments for each of the conditions, resulting in 16 uniquely built virtual environments that differed in ceiling heights and the size of floor areas.



(a) Low ceiling, small floor area (b) Low ceiling, large floor area

(c) High ceiling, small floor area (d) High ceiling, large floor area

Figure 1. Virtual environment types used. There were 4 possible types of virtual environments (2 ceiling heights × 2 floor areas): low ceiling, small floor area (top left); low ceiling, large floor area (top right); high ceiling, small floor area (bottom left); high ceiling, large floor area (bottom right). A group of avatars is included for scale.

By design, the low ceilings were made to be about an arm's length away from the top of an average avatar's head, and high ceilings were made to be taller than the ceiling of most large rooms encountered in the physical world, such as gymnasiums or auditoriums. By design, small virtual environments were made to resemble the size of conference rooms, and large virtual environments were made to resemble the size of stadiums. All the virtual environments were visibly square in shape, but rectangular polygons in dimensions. Furthermore, the virtual environments did not contain any furniture and differed only across the color/pattern of the floor and walls (Figure 2).

Figure 2. Bird's eye point of view of the floor area of the large (bottom row) and small (top row) virtual environments showcasing shape and differences in color/pattern. A group of avatars is included for scale. The figure's contrast and sharpness were raised to show the group of avatars.

The ceiling heights and floor areas were calculated by adding positional markers to the corners and ceilings of the virtual environments inside ENGAGE. The average high ceiling (M = 19.5 m, SD = 18.8, max = 65.6, min = 9.04) was 712.5% higher than the average low ceiling (M = 2.40 m, SD = 0.14, max = 2.65, min = 2.25), and the average large virtual environment (M = 3817.5 m^2, SD = 2311.2, max = 8610.5, min = 1400.3; length of longer side: M = 70.51 m, SD = 22.6; length of shorter side: M = 50.402 m, SD = 14.7) was 4356.5% larger than the average small virtual environment (M = 85.6 m^2, SD = 1.53, max = 87.4, min = 83.5; length of longer side: M = 10.109 m, SD = 0.129; length of shorter side: M = 8.47 m, SD = 0.0766).

Furthermore, a manipulation check was performed, in which participants were asked to evaluate their perceived spaciousness of the virtual environments after each session. Results based on analyses using the same multilevel models outlined in the Data Analysis section showed that participants perceived virtual environments with high ceilings (p < .05), large floor areas (p < .001), and high ceilings with large floor areas as being more spacious (p < .05), and that these evaluations did not change across weeks (p = .984).

Each virtual environment was built by research personnel and the first author using 3D objects. Invisible boundaries were set along each wall that limited students from leaving the virtual environment.

1.4 Procedure

Participants were randomly assigned to a group of 3-4 students (n_1 = 3.24, *SD* = 0.831; n_2 = 3.35, *SD* = 0.769; n_3 = 3.29, *SD* = 0.772; n_4 = 3.13, SD = 0.8502). Each group was assigned at random via a Latin square randomization scheme where each condition (ceiling height and floor area) appeared only once per row and per column in a 4 x 4 matrix (conditions x week). Group members stayed consistent every week (low ceiling: n_1 = 45, n_2 = 47, n_3 = 19, n_4 = 26; high ceiling: n_1 = 36, n_2 = 50, n_3 = 37, n_4 = 49; small floor area: n_1 = 35, n_2 = 42, n_3 = 36, n_4 = 39; large floor area: n_1 = 46, n_2 = 55, n_3 = 20, n_4 = 36).

During the first and second weeks of the course, students underwent training to familiarize themselves with the ENGAGE platform. Students were instructed to create an avatar that looked and felt like themselves to use for their weekly ENGAGE sessions.

At the beginning of each session, all participants first met on Zoom, a video-conferencing platform, at the designated course time. Participants were physically located in their own personal spaces (e.g., dorm room, house). For the first 5-10 minutes over Zoom, an instructor described that week's session discussion topics and directions. Then, altogether, participants moved over to ENGAGE and joined their respective group's session, which were set up prior by the instructor. In the virtual environment, participants had a discussion with their group members for approximately 20 minutes (*M* = 21.4 min, *SD* = 6.096 min). The discussion topics included 2-4 questions and a physical activity related to the course topic for that week (Table 1).

A screen showing the discussion prompts was kept on the Zoom screen during the VR portion as reference. The Zoom session also served as a technical support call that was monitored by an instructor. Students were encouraged to copy and paste the prompts into a virtual sticky note inside ENGAGE to refer to while inside the virtual environment. Following each respective session, participants completed a questionnaire with outcome variables measuring various aspects of how they perceived their experience. Additionally, each participant was instructed to record their session and upload the resulting behavioral data file after each respective session.

Table 1. Discussion session prompts and activities

Session	Prompt	Activity
1	Introductions (name, year, major, what you are most excited about learning in the course, favorite VR experience) Discussion on preliminary ideas for course final project Discussion on accessibility of ENGAGE (e.g., constraints)	Using sticky notes, make a list of pros and cons of the accessibility of ENGAGE (1 pro and 1 con per group member).
2	Consider the templates of the storyboards provided for the course storyboard assignment: What are some elements you are considering including in your storyboard? How do you plan on using the affordances unique to VR, such as presence, the ability to move around in 3D space, spatialized sound, etc.? Are you planning on showcasing this in your storyboard?	Reimagine what your avatar would look like. Either draw an avatar that you wish represents you or an avatar you would like to embody. This avatar can, but doesn't have to, be a human avatar. Once done, share your avatar with group members.
3	Consider the medical applications we learned in the readings, class, and meditation AltspaceVR journey: What was the most surprising, promising, or concerning? How does this class change your perception of using VR for medical purposes?	Collaboratively work with your group members to create a meditation room or a safe space using any of the ENGAGE tools (e.g., 3D pen, IFX, sticky notes, etc.).

4	Consider a target audience/population (e.g., students of a certain age group, students with a certain learning disability, older students) Consider a goal (e.g., retaining factual information, having students experience something) Consider a topic of interest (e.g., language, STEM, social skills)	Empathize, Define, Ideate, and Prototype an application tailored to your audience, goal, and topic. Have a member of your group test out/role-play a student using the application.

1.5 Measures

1.5.1 Self-report Measures

Multiple aspects of individuals' attitudes were measured via online survey at the start of the study (pre-test) and after each of the four weekly sessions ($n_1 \approx 81$, $n_2 \approx 97$, $n_3 \approx 56$, $n_4 \approx 75$). All items were rated on a 5-point Likert scale (1 = Not at all to 5 = Extremely).

Perceived Restorativeness. Perceived restorativeness, the restorative quality and potential of environments, was measured using three items adapted from the Perceived Restorativeness Scale (Hartig et al., 1996). Sample items include "Spending time here gave me a good break from my day-to-day routine" and "I could find ways to enjoy myself in an environment like this." Weekly perceived restorativeness scores were calculated as the mean of three item responses (Cronbach's $\alpha = 0.78$), with higher scores indicating greater perceived restorativeness of the environment ($M = 2.53$, $SD = 0.91$).

Awe. Awe is generally defined as the feeling of overwhelming admiration mixed with wonder or fear. Situational awe, in specific, concerns experiences that influence perceived vastness of the situation and self-diminishment. Four items were adapted from the Situational Awe Scale (Krenzer, 2018). Sample items include "I felt goosebumps" and "I felt like I was trivial, in the grand scheme of things." Weekly awe scores were calculated as the mean of four item responses (Cronbach's $\alpha = 0.75$), with higher scores indicating greater awe ($M = 1.47$, $SD = 0.61$).

Momentary Affective well-being. Momentary affective well-being, or the emotional component of an individual's subjective well-being at the present moment, was measured using 5 items adapted from the Socio-Economic Panel scales (see Richter et al., 2017). Sample items include "I am feeling angry" and "I am feeling stressed." Weekly momentary affective well-being scores were reverse-coded, then calculated as the mean of 5 item responses (Cronbach's $\alpha = 0.79$), with higher scores indicating greater momentary affective well-being ($M = 4.53$, $SD = 0.56$).

1.5.2 Nonverbal Behavioral Measures

Multiple aspects of individuals' nonverbal behaviors were measured during each of the four weekly sessions ($n_1 \approx 81$, $n_2 \approx 97$, $n_3 \approx 56$, $n_4 \approx 75$). Nonverbal behavioral measures were calculated using motion data of 18 degrees of freedom of movement (yaw, pitch, and roll of head, left, and right hands) every one-thirtieth of a second (30 Hz). Calculations of all measures follow the procedure used in OMITTED and OMITTED. Given the exploratory nature of the nonverbal behavioral measures, multiple others were collected, but were excluded from this study[3]. Part of the exploratory process was figuring out what measures to investigate further.

Instances where tracking data was lost (i.e., the distance between the head and hands positional vector was greater than 3 m) were filtered out (<5%). Motion data was analyzed using the most complete recordings (i.e., had all the members present and were longest in length). There were two sessions in which one group member arrived late, but the late member was

[3] Other nonverbal behavioral measures were calculated, including avatar speed, physical left and right hands' speeds, and mutual gaze. All tests were conducted, but there were no main effects of ceiling height or floor area, or any interaction effect. Therefore, they were not included in the manuscript for simplicity.

present in at least half of the session. In these specific sessions, recordings with all members present were used.

Physical Head Speed. Motion within the physical environment, or motion an individual produces with their physical self, was operationalized by the physical head speed. Speed can also be understood as distance traveled in a given portion of time. The average physical head speed for each individual was calculated by taking the speed of the head in a given moment in frame, which was multiplied by 30 to get the speed per second, and then averaged (M = 0.05, SD = 0.02). Final units are in meters per second.

Social Attention. Social attention, or the amount of spatial attention allocated to another person in a session, was calculated as the percentage of time a given individual had at least one group member within 15° of the center of their HMD's view (M = 0.28, SD = 0.12).

Interpersonal Distance. Interpersonal distance, or the virtual distance between the participants' avatars, for each individual was calculated as the distance, in meters, that they stood from each group member's avatars, averaged across members of the group. The distance between each pair of participants was taken after filtering out the smallest 150 distance points (i.e., ~5 seconds), to account for haphazard entrance behaviors that spawn individuals in the same spot when they join the environment, rather than intentional movement. Interpersonal distance was calculated based on the Euclidean distance between head positions of avatars (M = 1.20, SD = 0.73).

1.6 Data Analysis

Individual differences in how individuals' attitudes and nonverbal behaviors changed over time (4 weeks) and in relation to 2 ceiling heights (low, high) and 2 floor areas (small, large) were examined using multilevel models that accommodated the nested nature of the data[4]. With group-level variance accounting for between 0% and 35.5%, person-level variance accounting for between 0% and 54.6%, and session-specific variance for between 45.4% and 74.1% of total variance, we formalized the analysis of all outcomes using a 3-level multilevel structure with both participant and group random effects. Specifically, each of the repeated measures outcomes were modeled using standard RMANOVA as

$$\begin{aligned} outcome_{tig} = \gamma_{000} + \gamma_{100}(week_{tig}) + \gamma_{200}(ceiling\ height_{tig}) \\ + \gamma_{300}(floor\ area_{tig}) + \\ + \gamma_{400}(ceiling\ height_{tig} \bullet floor\ area_{tig}) + v_{00g} + u_{0ig} + e_{tig} \end{aligned}$$

where the outcome of interest at occasion *t* for person *i* in group *g*, $outcome_{tig}$ is modeled as a function of a grand intercept, γ_{000} that indicates the expected level of the outcome on the first week for a virtual environment with a low ceiling height and a small floor area; a time-related trend, γ_{100}, indicating prototypical rate of change across weeks; the ceiling effect, γ_{200}; the floor area effect, γ_{300}; the ceiling by floor area interaction, γ_{400}; and residual group-specific, v_{00g}, person-specific, u_{0ig}, and occasion-specific deviations, e_{tig}, that were assumed normally distributed with standard deviations σ_{v00}, σ_{u0}, and σ_e. 95% confidence intervals for each effect and estimated effect sizes (η_p^2) are reported.

Sessions where there were technical errors such as an incorrectly loaded world or participants tampering with the boundaries of the world, cases where the nonverbal behavioral outcomes were less or greater than 3 standard deviations (i.e., outliers), and straight-liners in the self-report surveys were removed from the analyses. Incomplete data were treated as missing at random. Statistical significance was evaluated at alpha = .05. All models were fit to the data in R

[4] An interaction term between ceiling height and floor area was included in our current model, which was missing in our pre-registered data analysis plan. This term was included to test the hypotheses.

using the nlme library (Pinheiro, 2023) and visualized using the ggplot2 library (Wickham, 2016).

Results

Results from the multilevel models with time-varying predictors week, ceiling height, floor area, and interactions between ceiling height and floor area are presented for self-reported (perceived restorativeness, awe, momentary affective well-being) and nonverbal behavioral (physical head speed, social attention, interpersonal distance) outcomes. Plots of the raw data overlaid with relevant prototypical trajectories are given in Figures 3 and 4.

1.1 How do spatial properties of virtual environments influence individual attitudes?

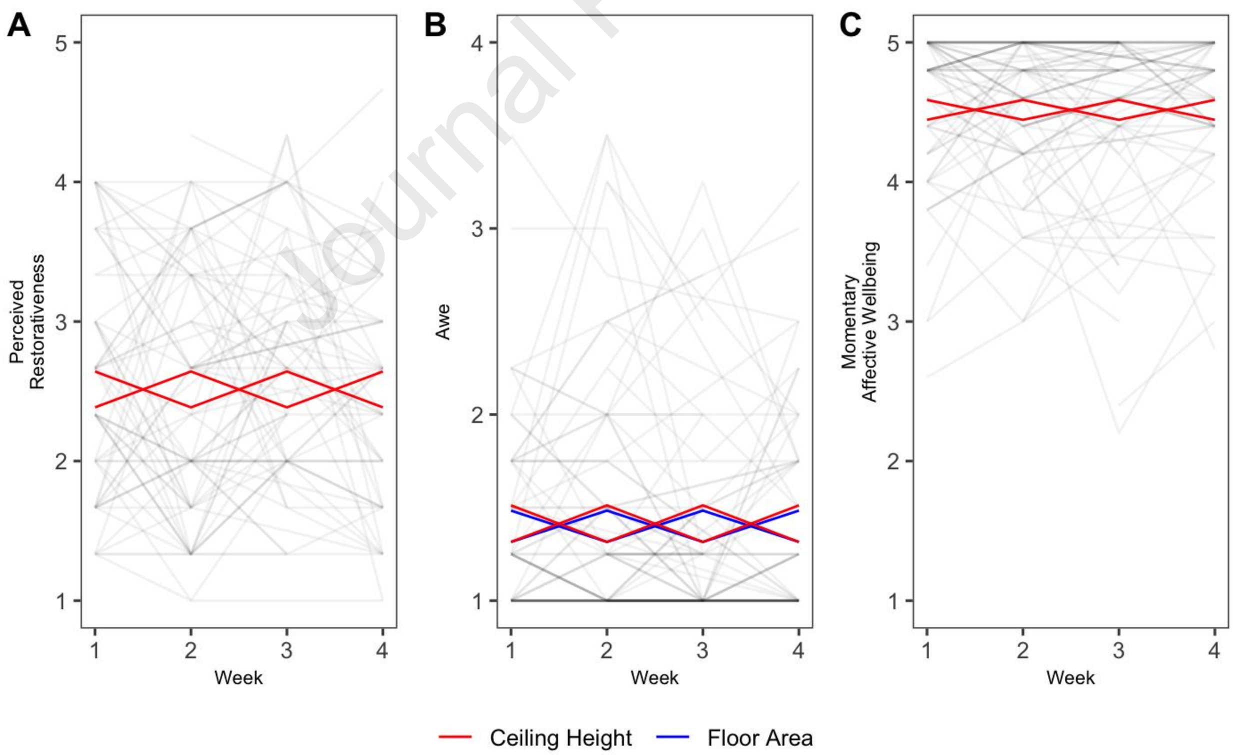


Figure 3. Graphs represent the prototypical student's trajectory showing how their outcome variable changed over time. The two different lines show the weekly alternation between the two

conditions. The lower points in the trajectories represent the low ceiling (red) and small floor area (blue) conditions. The colors represent the main effects of ceiling height (red) and floor area (blue).

Perceived Restorativeness

The prototypical participant's perceived restorativeness decreased from an initial value of $\gamma_{000} = 2.49$ points, $p < .001$ (on a 5-point scale), though not significantly, at a rate of $\gamma_{100} = -0.0464$ points per week, $p = .251$. There was a significant effect of ceiling height, such that individuals reported feeling greater perceived restorativeness when in a virtual environment with a high ceiling than a low ceiling, $\gamma_{200} = 0.286$ points [$p = .0325$, CI (0.0242, 0.548), $\eta_p^2 = 0.01$]. Prototypical trajectories showing how perceived restorativeness changed over time for hypothetical individuals who alternated weekly between the two ceiling height conditions are shown as red lines in Panel A of Figure 3. There was no evidence that the floor area manipulation influenced perceived restorativeness or of any interaction effects (all p-values $> .1304$) (RQ1).

Awe

The prototypical participant's awe decreased from an initial value of $\gamma_{000} = 1.33$ points, $p < .001$ (on a 5-point scale), though not significantly, at a rate of $\gamma_{100} = -0.00833$ points per week, $p = .7301$. There was a significant effect of ceiling height, such that individuals reported feeling greater awe when in a virtual environment with a high ceiling than a low ceiling, $\gamma_{200} = 0.20205$ points [$p = .0121$, CI (0.0449, 0.349), $\eta_p^2 = 0.03$]. Additionally, there was a significant effect of floor area, such that individuals reported feeling greater awe when in a virtual environment with a large floor area than a small floor area, $\gamma_{300} = 0.168$ points [$p = .0376$, CI (0.00972, 0.326), η_p^2

= 0.02]. Prototypical trajectories showing how awe changed over time for hypothetical individuals who alternated weekly between the two ceiling height and floor area conditions are shown as red and blue lines, respectively, in Panel B of Figure 3. There was no evidence of any interaction effects. Our hypothesis (H1) was partially supported, such that there were significant main effects for each independent variable, separately, but no significant interaction effect.

Momentary Affective Well-being

The prototypical participant's momentary affective well-being decreased from an initial value of $\gamma_{000} = 4.49$ points, $p < .001$ (on a 5-point scale), though not significantly, at a rate of $\gamma_{100} = -0.0178$ points per week, $p = .433$. There was a significant effect of ceiling height, such that individuals reported feeling greater momentary affective well-being when in a virtual environment with a high ceiling than a low ceiling, $\gamma_{200} = 0.152$ points [$p = .0388$, CI (0.00789, 0.296), $\eta_p^2 = 0.04$]. Prototypical trajectories showing how momentary affective well-being changed over time for hypothetical individuals who alternated weekly between the two ceiling height conditions are shown as red lines in Panel C of Figure 3. There was no evidence that the floor area manipulation influenced perceived restorativeness or of any interaction effects (all p-values > .639). Our hypothesis (H2) was partially supported, such that there was only one significant main effect of ceiling height found, and no significant interaction effect.

1.2 How do spatial properties of virtual environments influence nonverbal behaviors?

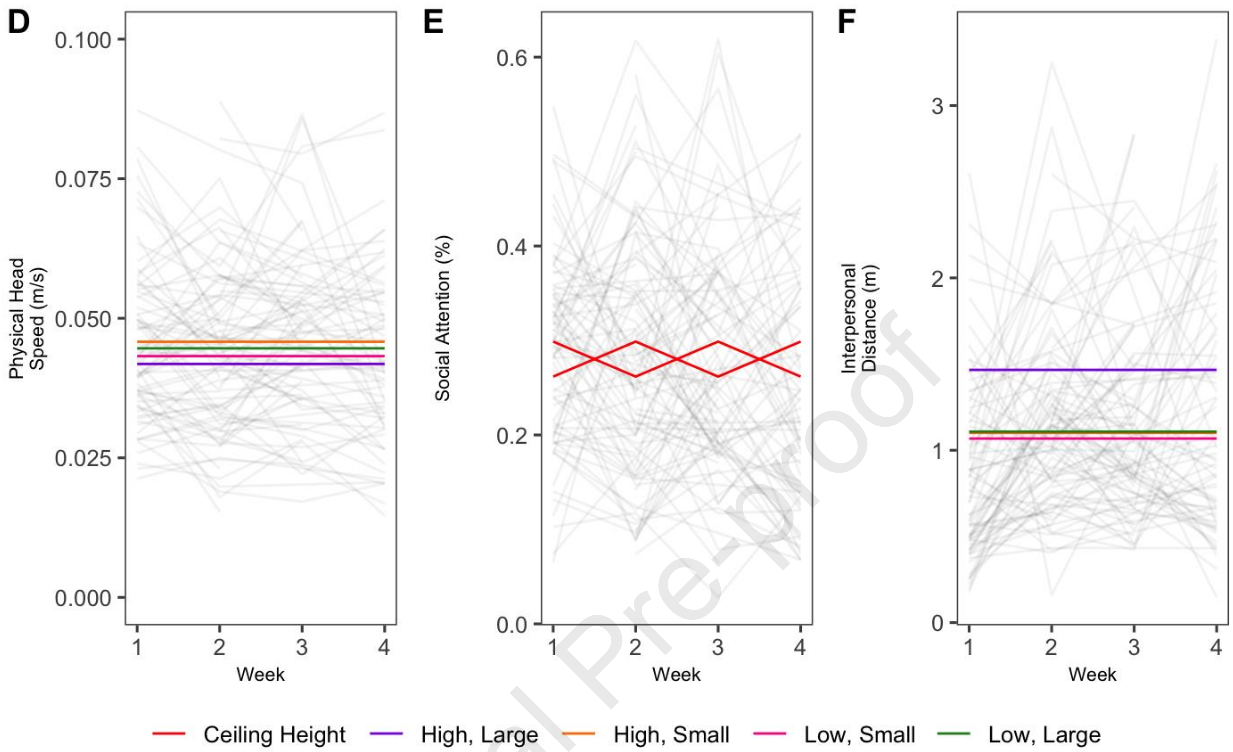


Figure 4. Graphs represent the prototypical student's trajectory showing how their outcome variable changed over time. The two different lines show the weekly alternation between the two conditions. The lower points in the trajectories represent the low ceiling (red) condition. The colors represent the main effect of ceiling height (red) and the interaction term between ceiling height and floor area (purple, orange, pink, and green lines).

Physical Head Speed

The prototypical participant's physical head speed decreased from an initial value of γ_{000} = 0.0458 m/s, $p < .001$ at a rate of γ_{100} = -0.00115 m/s per week [p = .0410, CI (-0.00224, 0.0000475), η_p^2 = 0.02]. There was a significant interaction between ceiling height and floor area, such that individuals moved their heads more slowly when in a virtual environment with a high ceiling and large floor area, $\gamma_{400} = -0.00552$ m/s [$p = .0257$, CI (-0.01036, -0.000675), $\eta_p^2 = 0.03$]. Prototypical trajectories showing how physical head speed changed over time for hypothetical individuals in a virtual environment with a high-ceiling and large floor area are shown as purple lines in Panel D of Figure 4. There was no evidence that ceiling height or floor area manipulation influenced physical head speed, separately (all *p*-values > .0767) (RQ2).

Social Attention

The prototypical participant's social attention decreased from an initial value of $\gamma_{000} = 0.294\%$, $p < .001$ at a rate of $\gamma_{100} = -0.0144\%$ per week [$p = .0114$, CI (-0.0255, -0.00328), $\eta_p^2 = 0.02$]. There was a significant effect of ceiling height, such that individuals paid more social attention when in a virtual environment with a high ceiling than a low ceiling, $\gamma_{200} = 0.0445\%$ [$p = .0156$, CI (-0.00852, 0.08056), $\eta_p^2 = 0.03$]. Prototypical trajectories showing how social attention changed over time for hypothetical individuals who alternated weekly between the two ceiling height conditions are shown as red lines in Panel E of Figure 4. There was no evidence that the floor area manipulation influenced social attention or of any interaction effects (all *p*-values > .372) (RQ2).

Interpersonal Distance

The prototypical participant's interpersonal distance increased from an initial value of $\gamma_{000} = 0.761$ meters, $p < .001$ at a rate of $\gamma_{100} = 0.137$ meters per week [$p = .000$, CI (0.0877, 0.187), $\eta_p^2 = 0.13$]. There was a significant interaction between ceiling height and floor area, such that individuals had greater interpersonal distances when in a virtual environment with a high ceiling and large floor area, $\gamma_{400} = 0.350$ meters [$p = .0022$, CI (0.128, 0.572), $\eta_p^2 = 0.05$]. Prototypical trajectories showing how physical head speed changed over time for hypothetical individuals in a virtual environment with a high ceiling and large floor area are shown as purple lines in Panel F of Figure 4. There was no evidence that ceiling height or floor area manipulation influenced interpersonal distance, separately (all *p*-values > .429) (RQ2).

Discussion

The present study examined how the ceiling height and floor area of a virtual environment influenced individual responses and nonverbal behaviors in social interactions. Every week for four weeks, groups of 3-4 participants had a 20-minute discussion in virtual environments that varied in ceiling height (low versus high) and floor area (small versus large). Participants' self-report attitudes were collected after each weekly session, as well as their nonverbal behaviors during the weekly sessions. Results showed that, when in a virtual environment with a high ceiling, participants reported feeling greater perceived restorativeness (RQ1), awe (H1), momentary affective well-being (H2), and paid more social attention to other group members (RQ2). When in a virtual environment with a large floor area, participants reported having a greater sense of awe (H1). Furthermore, when in a virtual environment with a high ceiling and large floor area, participants physically moved their heads more slowly and stood further apart from their group members (RQ2).

1.1 Individual Effects

Our findings of the positive effects of high ceilings on greater perceived restorativeness and momentary affective well-being are in line with past research. As for our finding that high ceilings yield greater awe, this is also theoretically in line with the argument that buildings with high ceilings such as cathedrals are awe-inspiring and "reminiscent of the freedom and openness of the cosmos" (Hall, 1966; Meyers-Levy & Zhu, 2007). Virtual environments with high ceilings may have awe-inspiring and restorative properties, compared to more confining, low-ceiling environments.

We also found effects of floor area: participants reported having a greater sense of awe when they were in a virtual environment with a large floor area, compared to when they were in a virtual environment with a small floor area. This may be because the virtual environments with a large floor area were drastically bigger than what is available in the physical world. In this study, we leveraged VR's unique ability to build any type of world, which allowed us to create stimuli in which the average large-floor area virtual environment was 3817.5 m^2. Exposure to such enormous spaces, which are not easily accessible or typically accessed on a regular basis such as large conference halls, auditoriums, or cathedrals, likely inspired awe.

Beyond awe, we did not find that floor area affected our other measured variables. This is somewhat in contrast to past research on panoramic environments, which have been shown to lead to greater positive outcomes, including perceived restorativeness and affective states (i.e., pleasure and arousal) (OMITTED). This may be due to the differences in the types of environments we investigated in the current study. First, in OMITTED, there was great variance in the type of environments, in order to do stimulus sampling (Reeves et al., 2015). While stimulus sampling has its strengths, such as allowing stimuli to reflect the variance that naturally exists in media and prevent having a single or limited idealized representative stimuli, it can also make pinpointing certain features of the stimuli challenging. Although the virtual environments in the current study were stark compared to those used in OMITTED, they allowed us to isolate our two manipulated variables. Panoramic environments have both great vertical and horizontal visible space. Our lack of significant findings on floor area (i.e., what is equivalent to horizontal visible space), but significant findings on ceiling height (i.e., what is equivalent to vertical visible space), underscores the importance of ceiling height.

Interestingly, when looking at what would be considered a panoramic environment – large environments with high ceilings – we did not find any effects aligned with that of past research (OMITTED). Instead, we found that, when in a large environment with a high ceiling, participants physically moved their head more slowly. While it is unclear why participants moved their head more slowly, we speculate that it may be because of two reasons. First, we found that participants moved their avatars faster when in a virtual environment with a large floor area, suggesting that they used their avatar to navigate and explore their surroundings. Instead of using their physical head to look around the vast horizontal space, participants may have been using their virtual selves to move on their behalf. Second, in order to look above at a high ceiling, a participant would have to crane their head and look up. The physical effort needed to look up with an HMD may have caused participants to move their head more slowly.

1.2 Group Effects

As aforementioned, one of our central goals of this study was to explore how the virtual environment can affect individuals' attitudes and nonverbal behaviors during social interactions. We found that the positive effects of high ceilings also translate into the social aspect: we found that participants paid more social attention to other group members when they were in virtual environments with high ceilings, compared to when they were in virtual environments with low ceilings. Low ceilings may have caused participants to focus on other aspects of the virtual environment, such as the ceiling itself, whereas higher ceilings, which were not as visible in the participants' immediate field of view (i.e., the ceilings were placed much higher and would require the participant to look up) may have allowed participants to focus on the social others.

Given that ceiling height can easily be raised or lowered within VR, having higher ceilings may be beneficial for fostering more social attention.

As for our findings on interpersonal distance, these results are somewhat counterintuitive. We found that participants stood further apart from their group members when in a virtual environment with a high ceiling and large floor area. Past literature suggests that, in a small room, the social others would have been made more salient, and as a result, the interpersonal distance greater (Worchel, 1986; Okken et al., 2011). This is in line with Argyle and Dean’s (1965) classic equilibrium theory, which makes sense of how contextual variables affect intimacy. One possibility here is that being in a large virtual environment with high ceilings may have made the social others also salient, much like it would have in a small virtual environment. Considering that the task at hand was to hold a discussion while being in an empty enclosed space, the vastness of a large virtual environment with a high ceiling, combined with the social nature of the tasks, may have made the presence of others more salient. Whereas any other type of virtual environment may have had other more salient components, such as the ceiling height or floor area, separately, the large high-ceiling virtual environment may have emphasized the presence of other group members. Another possibility is a simpler one: the vastness of the virtual environment may have encouraged participants to take up more space.

Conclusion

1.1 Limitations and Future Directions

This study was conducted across four weeks with many groups and participants handling HMDs. Inevitably, technical challenges were encountered in some weeks. One such challenge was collecting the recording data. All participants were asked to submit a recording of the session, as logistics-wise, research personnel or teaching staff could not be synchronously present in all group sessions to record. As a result, there were some discrepancies in terms of how long the recordings were (i.e., differences in when the recording started and ended). While we addressed this issue with a conservative strategy that only included the longest and most complete recordings, we note that this was a limitation that could be better controlled for in future studies.

Another factor that could have been better controlled for was our tasks. Each session involved discussions with questions and an activity. This activity portion encouraged participants to use the platform interface to bring in 3D models, drawings, and other media into the virtual environment. Furniture can give off cues such as interpersonal distance (e.g., Okken et al., 2011), and thus could have played a significant role in how participants' perceptions and behaviors. Although we designed these tasks considering how they could foster more naturalistic social interactions, future studies should control for the type of tasks.

Lastly, we note that this study was a field experiment, which has its strengths and limitations. At once, field experiments allow for researchers to implement interventions and measure outcomes in naturalistic settings, but also constrain how much control they have on external conditions and potential intervening variables. The nature of the course and its students (i.e., individuals interested in learning about VR) may have played critical roles. Other factors were out of our control or were difficult to control for, such as the physical location of the participants during the sessions (i.e., participants may have been located in their dorm room, house, empty classroom, etc.).

Currently, there are only a handful of studies on social interactions in virtual environments. OMITTED summarizes past synchronous multi-user studies in shared virtual environments, and discusses some social outcomes, such as trust, persuasion, quality of interactions, compliance, and performance in collaboration. Given many available commercial platforms in VR serve a social purpose, it is important to understand how their affordances shape interactions. In the same vein, it is equally important to explore what other social outcomes can be measured and what they theoretically represent, such as how interactants talk to one another, approach one another, and feel during and after interactions.

1.2 Implications

This study reports that the virtual environment's ceiling height and floor area affect people's attitudes and nonverbal behaviors during social interactions. Our findings translate to implications for designers of social VR platforms, instructors and educators interested in networked VR for teaching, teams interested in VR-based collaborations, and practitioners interested in VR experiences for promoting well-being.

For designers of social VR platforms, we found that, in addition to the other restorative and affective properties, high ceilings encourage people to focus on social others. If the goal is to promote opportunities for people to focus on others and their interactions, one way to foster this is through higher ceilings. This may be particularly important in classroom or collaborative settings where it may not be ideal to have people distracted by other features, such as the ceiling, that are not relevant to the social atmosphere. While we also found that people stood further apart from one another in virtual environments with a high ceiling and large floor area, the cause of this is unknown, and demands further research. However, given that large floor areas resulted in a greater sense of awe, how this is understood and considered in conjunction with ceiling height depends on the goal of the interaction. If awe is the goal, it may be beneficial to have a large floor area.

From a well-being standpoint, when in a virtual environment with a high ceiling, participants reported feeling greater perceived restorativeness, awe, and momentary affective well-being. VR eases the process of building awe-inspiring and restorative environments, as space is free, infinite, and easily accessible. Designers can tap into the positive properties of environments and create environments that are otherwise difficult to access for certain individuals, such as those living in small spaces in urban cities, or those with limited mobility or time.

Data Statement

The data underlying this article cannot be shared publicly due to the privacy of individuals that participated in the study. The data will be shared on reasonable request to the corresponding author.

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Highlights

- Virtual environments with higher ceilings led to reports of greater perceived restorativeness, awe, and momentary affective well-being.
- Virtual environments with higher ceilings led to more social attention between group members.
- Virtual environments with large floor areas led to reports of greater sense of awe.
- Participants moved their physical head more slowly and virtually stood further apart from other group members when in large virtual environments with high ceilings.