



A Virtual Reality Investigation of the Impact of Wallpaper Pattern Scale on Qualitative Spaciousness Judgments and Action-Based Measures of Room Size Perception

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Abstract. Visual design elements influence the spaciousness of a room. Although wallpaper and stencil patterns are widely used in interior design, there is a lack of research on how these surface treatments affect people's perception of the space. We examined whether the dominant scale of a wallpaper pattern (i) impacts subjective spaciousness judgments, or (ii) alters action-based measures of a room's size. We found that both were true: participants reported lower subjective ratings of spaciousness in rooms covered with bolder (larger scale) texture patterns, and they also judged these rooms to be smaller than equivalently-sized rooms covered with finer-scaled patterns in action-based estimates of their egocentric distance from the opposing wall of the room. This research reinforces the utility of VR as a supporting technology for architecture and design, as the information we gathered from these experiments can help designers and consumers make better informed decisions about interior surface treatments.

Keywords: Virtual environments · Wallpaper patterns
Spaciousness perception · Egocentric distance judgments · Interior design

1 Introduction

As increasing research emerges on the interaction between architectural design and the perceptual human experience, interior designers and architects have begun to consider the visual attributes that affect user perception of architectural quality. Studies show that, among these attributes, spaciousness is an important quality on which people base their descriptions and assessments of the environment [5]. Ozdemir's research [12] also indicates a positive correlation between people's satisfaction and their sense of spaciousness of the environment. Therefore, a knowledge of architectural attributes that

cause a perception of increased spaciousness will contribute to the future efforts of architects and interior designers.

There has been extensive research on how the presence of various architectural attributes, such as windows and lighting, can affect the perception of spaciousness. However, there have been very few studies on the subject of wallpaper patterns, which is a crucial element of interior design. A lack of knowledge in this area may cause inaccurate judgement in interior environment quality due to professional bias or the absence of user input in design selection [4]. Such judgment can lead to negative interior experience and thus affect people's everyday life.

To assist architects to design pleasing interior environments and to establish a basis for further research in this area, we investigated the potential relationship between the scale of a wallpaper pattern and people's perception of the environment's spaciousness. By using immersive virtual reality technology, we were able to easily manipulate the main factors of metric room size and wallpaper pattern scale and at the same time fully control for other features that could potentially affect the sense of spaciousness of the room, such as lighting, ceiling height, windows, etc.

2 Previous Work

There are many previous studies that suggest that certain architectural and design features impact our visual perception of a space. In examining how the physical characteristics of a room affect its perceived spaciousness, researchers have found a positive correlation between the horizontal area and/or ceiling height of a room and its perceived spaciousness [15]. Changing the aspect ratio of a room can also lead to an altered perception of spaciousness even though the total floor area remains constant. Experiments have found that elongated rooms – spaces with a higher ratio of length to width – are judged as less spacious than square rooms of equivalent size [14]. The manipulation of furnishing within a room can also affect the visual perception of spaciousness; the more objects that take up a room, the more crowded and cramped a room can feel, which results in a decrease in perceived room spaciousness [1]. It has also been found that rooms with lighter-colored walls appear bigger, and that lighter-colored ceilings feel taller, which in turn increases people's spaciousness ratings of a space, while the luminance of the floor doesn't appear to affect spaciousness judgments [11, 12]. Designers have also opined that certain stripes and patterns can subjectively widen or narrow a space [6].

From the aforementioned previous work, we have learned that an abundance of architectural design elements can influence our perceived sense of the spaciousness of a room. However, quantitative studies regarding whether wallpaper patterns impact our judgment of room proportions – particularly in an immersive virtual environment – have yet to be thoroughly explored and performed. We were able to use immersive virtual reality to control for many other variables that would be almost impossible to do in real physical rooms and look at how the scale of the elements in wallpaper pattern affects the sense of a room's spaciousness and size.

It is important to also acknowledge that there is an abundance of research in the virtual reality and psychology fields showing that people tend to systematically

underestimate egocentric distances when viewing virtual environments using head-mounted displays [9] and the root cause of this problem is still not well-understood [13]. While researchers are actively investigating potential methods for facilitating more veridical spatial judgments in VR [7], and we cannot yet assume that spaciousness judgments made in VR will exactly match spaciousness judgments made in the real world, we nevertheless feel that virtual reality can provide a robust platform for studying potential differences in subjective and objective measures of room size and spaciousness caused by differences in surface treatments [3].

3 Experiment

Our experiment consisted of two parts. In the first part, we asked participants to provide subjective ratings of spaciousness in seven differently-sized rooms, each with five different interior surface treatments (four differently-scaled texture patterns and a solid color that represented the average intensity of the texture). In the second part, we asked participants to make action-based estimates [8] of their egocentric distance from the opposing wall in four differently-sized rooms, each with four differently-scaled texture patterns.

Our hypotheses were that (1) the scale of the wallpaper texture would affect people's perceived sense of spaciousness in a room, but that (2) their action-based judgments of the metric size of the room would not be affected.

3.1 Participants

A total of 14 participants from our local community completed the study (7 m., 7f., ages 19–30, $\mu = 21.3 \pm 2.7$). We had recruited 15 overall, but one participant experienced cybersickness halfway through the second block of trials and was unable to continue; their data was not included in the analysis. Two of the participants were members of our lab, though they were not involved in the design or implementation of the experiment. However, they did have some prior knowledge about the hypotheses being tested. We recruited by word of mouth among personal contacts and students from other Research Experience for Undergraduates (REU) programs. All participants who were not lab members were compensated with a \$10 Amazon gift card; participants who were members of our lab were not compensated, to avoid conflict of interest. The experiment was approved by the Institutional Review Board at the University of Minnesota, and all participants gave written informed consent.

3.2 Materials

We created a set of nine different sized square-shaped rooms, the largest and smallest of which were only shown once and used to anchor participants' spaciousness judgments. We chose to use seven room sizes for testing so that the participants couldn't easily store the size of each room in their short term memory. The room sizes were: 4.00 m $\times$ 4.00 m, 4.33 m $\times$ 4.33 m, 4.67 m $\times$ 4.67 m, 5.00 m $\times$ 5.00 m, 5.33 m $\times$ 5.33 m, 5.67 m $\times$ 5.67 m and 6.00 m $\times$ 6.00 m. All rooms had a ceiling height of

2.743 m. The range was chosen to be wide enough that participants could easily differentiate between the largest and smallest sizes, but with small enough increments that the difference between rooms adjacent in size could potentially be mistaken. Each room had a textureless white ceiling and neutral grey floor. We applied five different types of surface treatments to the four walls of each room: a wallpaper texture featuring small (11.60 cm), medium (15.55 cm), large (23.30 cm), or extra large (46.65 cm) diamond-shaped elements, or a solid grey color representing the average of all pixel colors in the wallpaper used. This resulted in a total of 35 different rooms. Figure 1 shows the nine different room sizes rendered with the solid color and Fig. 2 shows what each of the different wallpaper patterns looked like on the same-sized room.

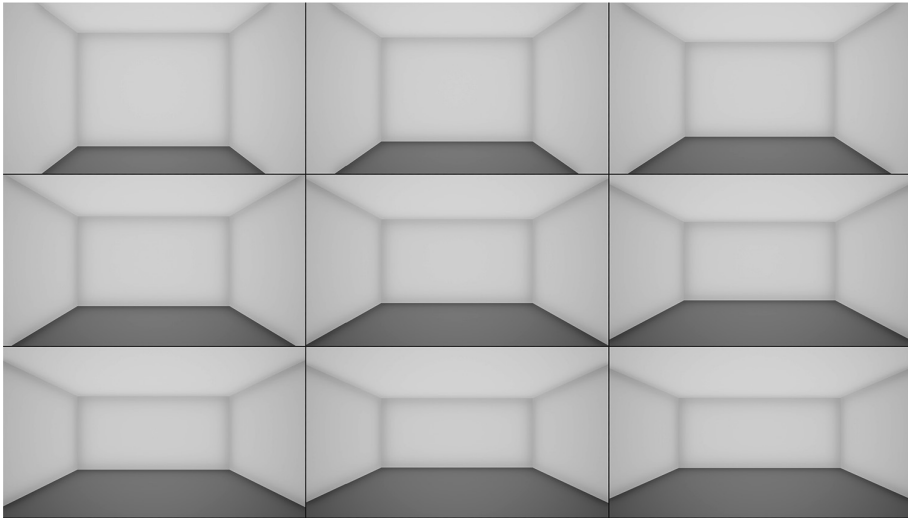


Fig. 1. Top row: 3.67 m, 4.00 m, 4.33 m; Middle row: 4.67 m, 5.00 m, 5.33 m; Bottom row: 5.67 m, 6.00 m, 6.33 m.

We built the rooms in Google SketchUp and then imported them into the Unreal Engine to apply the textures, wall colors, and lighting. The wallpaper texture was inspired by an example from Pinterest¹, recreated using Powerpoint and Photoshop, then proportionally scaled in the Unreal Engine to achieve the four different sizes used. We chose a design featuring oblique elements in order to avoid any inadvertent visual synchrony between the wallpaper pattern and the horizontal and vertical lines formed by the edges between the walls, ceiling, and floor. The individual elements were offset from each other to ensure that smaller elements did not visually group when viewed from far away to form larger elements, such as dominant lines going through the pattern. The diamond shape was chosen because there is no scale intrinsically

¹ <https://ar.pinterest.com/pin/366269382190103454/>.

associated with that element (e.g. unlike a rectangle, which might be intuitively associated with a standard sized brick) and because when grouped together they do not evoke any horizontal or vertical lines. The lighting was done as emissive lighting in the Unreal Engine, meaning that there was no direct light source, although there was some darkening in the corners achieved via ambient occlusion. This was done in order to ensure that the lighting was consistent in all of the differently-sized rooms. We chose a black-and-white color scheme to achieve maximum pattern contrast.

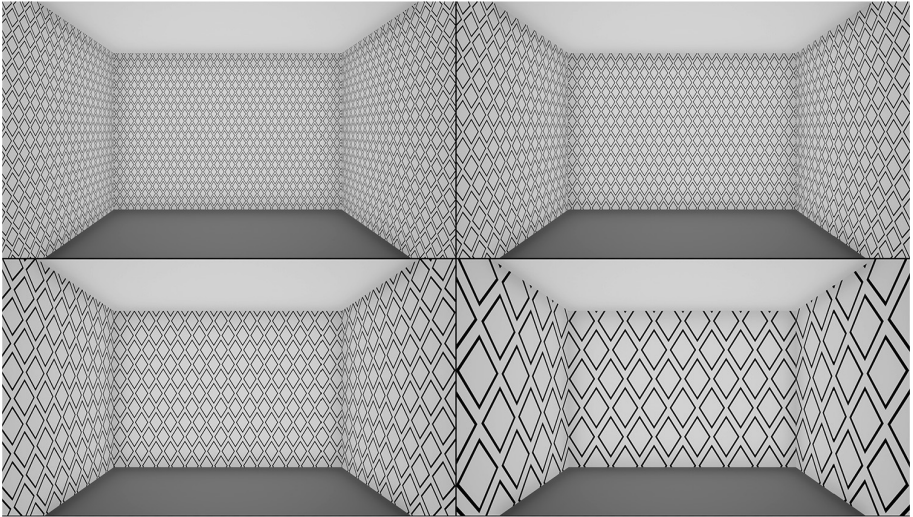


Fig. 2. The four differently-scaled wallpaper patterns applied to the 4 m room.

Participants were immersed in the virtual environment using an HTC Vive head-mounted display and their viewpoint was tracked using the Valve's Lighthouse Tracking system. The HTC Vive head-mounted display weighs about one pound and offers a 110° field of view. It has two OLED displays, each with a resolution of 1080×1200 pixels.

This study took place in our lab space of approximately $8.83 \text{ m} \times 9.14 \text{ m}$. The HTC Vive automatically shows a boundary square on the ground when one nears the edge of what the system has predetermined to be the edge of the tracked space. In reality, the Valve's Lighthouse Tracking system provides accurate tracking beyond this space, and in the second part of the experiment, participants often walked beyond these bounds.

3.3 Procedure

Participants were scheduled individually by appointment so that no participant was exposed to the any activity of any other participant. Each participant was welcomed into the lab by the same experimenter and screened for adequate visual acuity, defined by the ability to successfully read lines of letters corresponding to 20/70 or above on a

wall-mounted eye chart from a distance of 20'. Next, participants were screened for stereo vision by asking them to describe the contents of two different random dot stereograms presented on the HTC Vive. The ability to pass both of these screenings determined a participant's eligibility to participate in the experiment. All participants passed both the visual and stereo acuity tests. After they passed the screenings, participants were asked to sign an informed consent form and were given written instructions for the first half of the experiment. Written instructions for the second half of the experiment were provided after participants had completed the first part.

For the first half of the experiment, participants were asked to stand at a predefined location in the real-world environment that was marked by a piece of tape on the floor. For each trial, the Unreal engine set the virtual camera to be at a random coordinate in the horizontal direction between two-sevenths and five-sevenths of the room's width while maintaining a constant 0.95 m distance from the wall at their back. We chose 0.95 m so that participants could have a fairly wide view of the virtual room in front of them while not being able to touch the walls of the real lab space behind them. At the start of the experiment, participants were shown two rooms to anchor their spaciousness ratings. They were shown a 3.67 m $\times$ 3.67 m room (smaller than any other room in the experiment) and told that they should consider this room to be a 1 on the spaciousness scale, and a 6.33 m $\times$ 6.33 m room (bigger than any other room in the experiment) and told that they should consider this to be a 10 on the spaciousness scale. Both of these rooms had solid colored walls, the same grey that was the average of all the pixels in the wallpaper used in the experiment. Next, the 35 different rooms were shown to the participant in a randomized order that was unique for each participant. For each room, the participant was asked to verbally rate the room's spaciousness on the scale of 1–10. Each room was faded in from black, the participant gave a spaciousness rating, and then the room was faded out to black and after a very brief delay the next room was faded in. The purpose of this transition was to discourage participants from making comparative judgments. When each room faded in, the participant found themselves at a slightly different spot in the room but always the same distance from the wall. Figure 3 shows the leftmost and rightmost extents of the interval across which the viewpoint was randomly distributed. The rating process took about 10–15 min in total for the 35 rooms. After finishing the first block of trials, participants were given a five minute break during which they had to take off the headset. The same process was then repeated for a second time. The participants then removed the headset after this second block of trials and took a ten minute break before beginning the second half of the experiment.

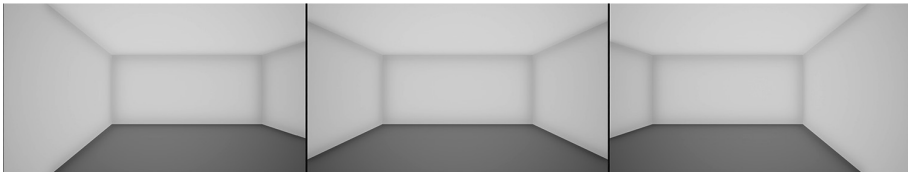


Fig. 3. These images illustrate the maximum extent of the random sideways shift that was applied to the participant's position in the room between each trial.

In the second half of the experiment, the participants were asked to make action-based judgments of egocentric distance in a subset of the original 35 rooms. This subset consisted of the rooms that were $4.00\text{ m} \times 4.00\text{ m}$, $4.67\text{ m} \times 4.67\text{ m}$, $5.33\text{ m} \times 5.33\text{ m}$ and $6.00\text{ m} \times 6.00\text{ m}$, each with all of the different sized wallpapers (not including the solid-colored condition) for a total of 16 rooms. We chose to limit the number of trials to 16 in this part of the experiment so as to not exhaust the participant. During this part of the experiment, the participants wore noise cancelling headphones to block out ambient sounds that might otherwise have provided audio cues to their location in the physical world. Each room faded in with the participant standing at a point where two-thirds of the room's width was in front of them and the walls on each side were equidistant. We chose this configuration so as to keep the participant within the tracked space during the course of each trial. For each trial, the participant was told that they should close their eyes, after which time the walls of the room would be removed, and that they should then walk through the room until they feel that their body is at the exact location where the opposite wall used to be. The experimenter pressed a key to record the starting position of the participant when the room as faded in, and when the participant had stopped walking the experimenter pressed another key to record their ending position. To ensure that the participant could not see where they were in relation to the room, the visuals were turned to black when the participant indicated that they were ready to walk. We recorded their starting and ending coordinates using the Valve's Lighthouse Tracking system to calculate the distance they walked. To avoid allowing the participants to familiarize themselves with the space, we verbally guided them on a random, circuitous path back to the starting position. The experiment ended after the participant had completed these 16 trials.

4 Results

The first result from our first experiment is the observation that people's spaciousness judgments increased linearly with the room size. A two-way ANOVA (7 room sizes $\times$ 5 texture scales) found a significant main effect of room size on spaciousness judgments $\{F(6, 455) = 205.15, p < 0.001\}$, and all pairwise differences were found to be significant at $\alpha = 0.05$ according to the Tukey HSD test, except between the two largest rooms. The number of degrees-of-freedom reflects the fact that each participant's repeated ratings (between the first and second blocks of trials) were averaged to a single value before performing the statistical analysis. Figure 4 shows these results. This finding, while expected, provides a robust sanity check on the overall validity of the experimental procedure.

Since each participant made spaciousness ratings for each room twice, we were able to assess the consistency of their ratings. We found that two participants had a median difference of 3 in their ratings between the blocks of trials, and a maximum difference of 9, meaning that on at least one occasion they had rated the same room as having a spaciousness of 1 in one block and a spaciousness of 10 in the other block. Two additional participants had a median inter-block difference of 2 in their subjective spaciousness ratings, and maximum differences of 7 and 8. Each of the remaining 10 participants had a median difference of 1 in their spaciousness ratings between blocks

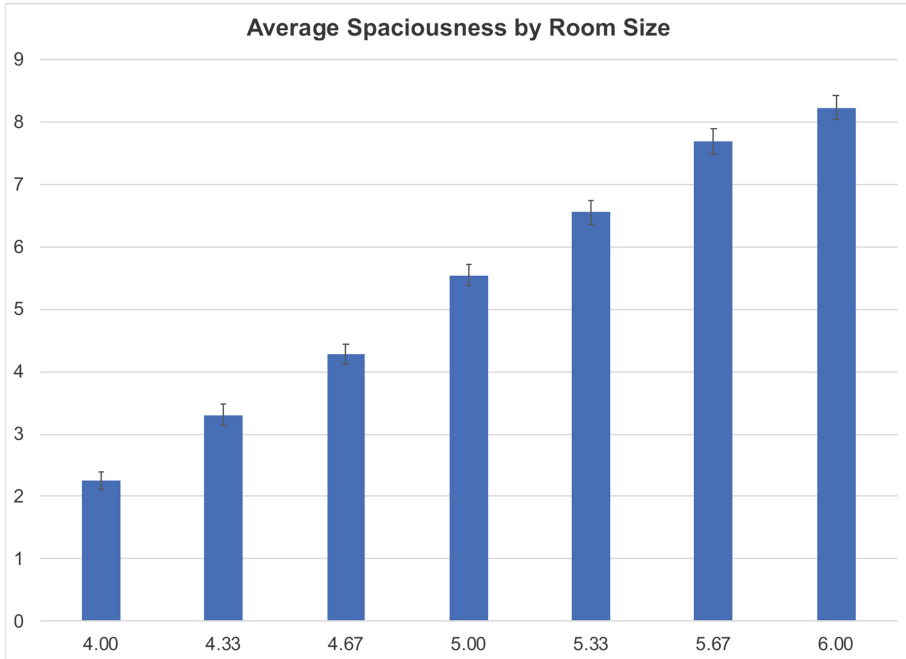


Fig. 4. Participants’ spaciousness ratings, averaged over all surface treatments for each room size presented. The error bars represent ± 1 standard error.

and a maximum difference of between 3–5. Overall, while some rating inconsistencies did occur, they do not appear to have significantly affected the outcome of the experiment.

The most interesting finding from our first experiment is that participants’ spaciousness ratings are inversely related to the scale of the wallpaper texture. The same two-way ANOVA also found a significant main effect of texture scale on room spaciousness judgments $\{F(4, 455) = 32.30, p < 0.001\}$. The Tukey HSD test found that the rooms with the largest-size texture elements (XL) were judged to be significantly less spacious than equivalently-sized rooms textured with the small (S) and medium sized (M) elements as well as the solid colored room ($p < 0.01$), and the rooms with the next-to-largest texture elements (L) were judged to be significantly less spacious than rooms with the finest-scale texture elements (S) ($p < 0.05$). These results support the first part of our hypothesis that as the wallpaper texture scale increases, people’s subjective perception of the spaciousness of the room decreases. Figure 5 shows a plot of these findings.

The two-way ANOVA did not find any significant interaction between room size and texture scale $\{F(24, 455) = 0.711, p = 0.842\}$.

The first result from the second part of our experiment is the finding that people walked longer distances when the wall was farther away from them. A two-way ANOVA (4 room sizes $\times$ 4 texture scales) found a statistically significant main effect of room size on distance walked $\{F(3, 208) = 49.14, p < 0.001\}$, and Tukey HSD

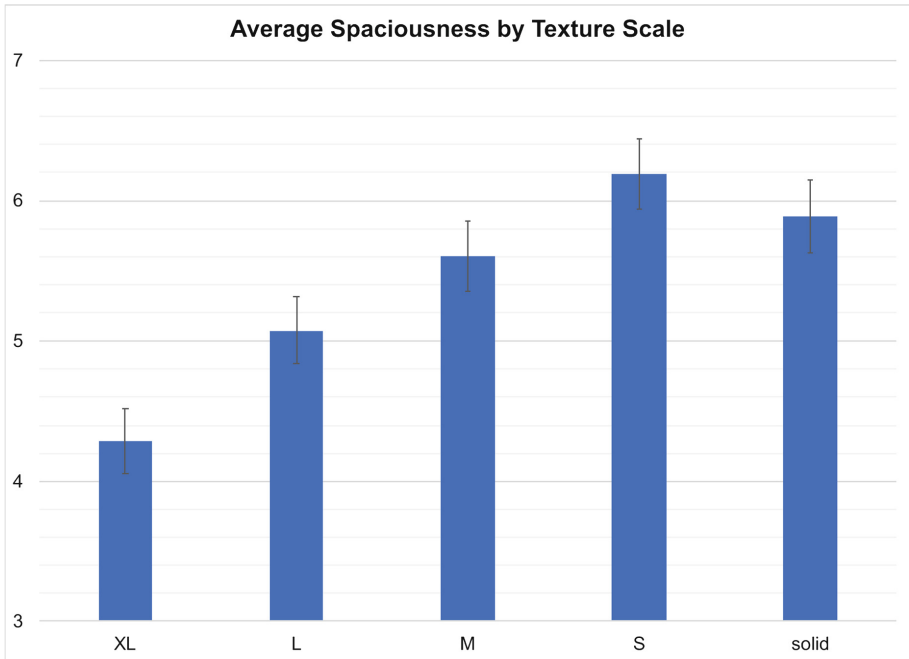


Fig. 5. Participants' spaciousness ratings, averaged over all room sizes for each texture scale. The error bars represent ± 1 standard error.

post-hoc tests found that all pairwise differences were also significant at $p < 0.05$. This result provides a reassuring sanity check on the validity of the experimental process.

Figure 6 shows a scatter plot of each individual distance judgment, with a bold line showing the linear trend. As can be seen from this figure, most people walked significantly shorter than the actual distance of the virtual wall. The overall average amount of distance underestimation, computed across all participants, all rooms, and all textures, was 29.7%. This finding is consistent with classical reports of systematic distance underestimation in virtual environments [13].

The most interesting finding from our second experiment is that, on average, people tended to physically underestimate distances more as the scale of the wallpaper pattern increased. The same two-way ANOVA found a significant main effect of texture scale on distance walked $\{F(3, 208) = 8.21, p < 0.01\}$, and Tukey HSD post-hoc tests found that people walked significantly shorter in the rooms with the two largest scale wallpaper textures (L, XL) than in the room with the finest scale pattern (S), with $p < 0.05$ and $p < 0.01$, respectively. Figure 7 shows these results.

The two-way ANOVA did not find a significant interaction between room size and texture scale $\{F(9, 208) = 1.694, p = 0.092\}$. However we observed a slight trend towards the texture scale having a stronger effect on distance walked as the rooms became larger.

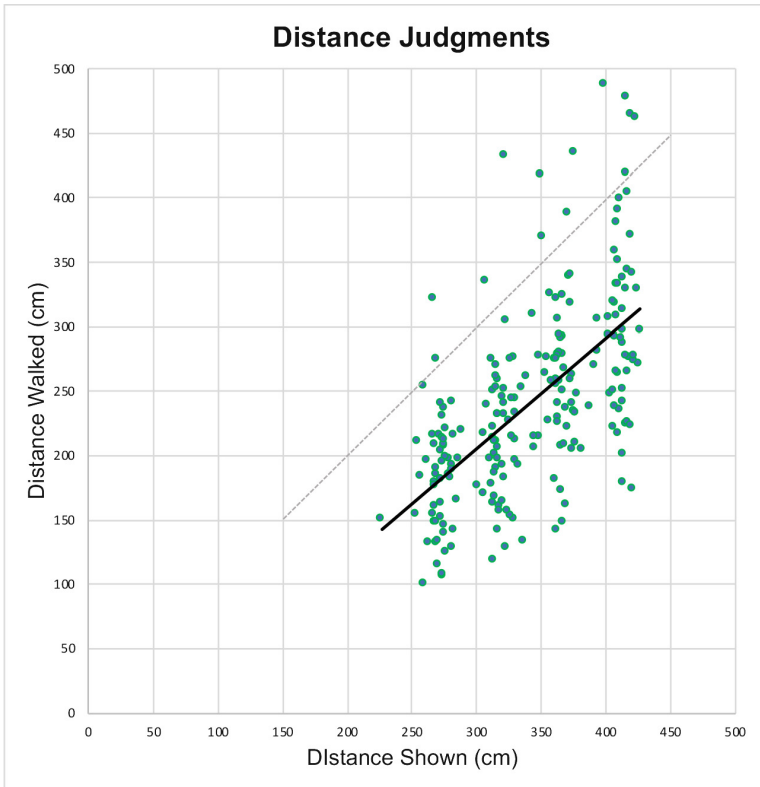


Fig. 6. A scatter plot showing each distance judgment made by each participant. The slight variation in the distances shown is due to participants not starting exactly at the prescribed starting location used to define the initial relationship between the viewer and the room in our software. The bold trendline plots the linear trend in the data; the light grey line shows where ideal performance would lie.

In a separate statistical test, we verified that there was no significant difference $\{F(3, 220) = 0.038, p = 0.99\}$ in the overall average distance shown (from the observer to the far wall of the room) between texture conditions, as might have potentially occurred because participants did not stand exactly on the starting line at the start of each trial.

The results from our second experiment refute the second part of our hypothesis that the size of the wallpaper texture would not affect people’s action-based egocentric judgement of the size of the room. Rather, they extend our first hypothesis – that people’s perception of the spaciousness of a room will decrease as the scale of the wallpaper pattern increases – to an effect on metric size judgments as well.

5 Discussion

Our findings – that the dominant scale of a wallpaper texture pattern can have a significant impact both on people’s subjective feeling of the spaciousness of a room and on their action-based judgments of the actual locations of the walls of the room – make sense in the context of our everyday experience of the statistics of built environments. In 2003, Torralba and Oliva [16] showed that in a collection of hundreds of images, the characteristics of the dominant spatial frequencies varied systematically with the distance of the camera from the imaged scene, on a scale ranging from less than one meter to a kilometer or more. In indoor or external views of man-made environments, they found that images taken from closer views tended to be dominated by lower spatial frequency content, and that as camera distances increased, the images’ spectral signatures reflected a greater presence of higher spatial frequencies, particularly in the horizontal and vertical directions. It may be that people have developed an intuitive sense of the typical range of spatial frequencies associated with their experience of being in close-in versus larger spaces, and that texture patterns with “unnaturally” bold features may feel somehow enlarged, evoking an impression that they are closer than they really are.

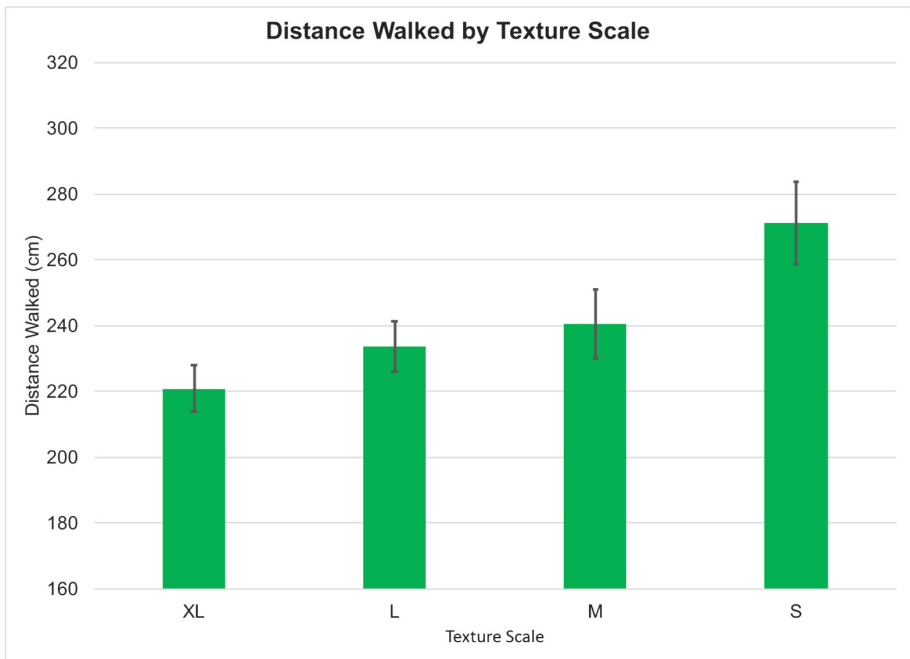


Fig. 7. A plot of the average distance walked by all participants, averaged over all room sizes, for each texture scale. The error bars represent ± 1 standard error.

It could also be that as the dominant features in the wallpaper pattern get larger, they become more individually noticeable and thereby create a greater sense of clutter that could also make a room feel less spacious. We deliberately chose to use a starkly contrasting pattern in our present study to allow the texture's scale to be readily apparent across a wide range of distances. It might be interesting to explore a wider range of pattern contrasts in future work, as lower-contrast patterns might have less impact on people's sense of the spaciousness of a room regardless of the dominant scale of the texture.

It is important to note that the pattern of the smallest scale texture appeared slightly blurry when viewed through the head-mounted display. Particularly, the lines making up each of the elements of the smallest patterned wallpaper were notably less distinct on the opposite side of the room than on the more nearby walls. This effect is due to the limited resolution of the OLED displays on the current HTC Vive, as only 1200 pixels are available to subtend 110° of visual angle in the vertical direction, while the naked eye can resolve two points of light separated by a visual angle of one arc minute ($1/60^\circ$), a difference of $5.5\times$. The phenomenon of decreasing clarity with increasing distance is a hallmark of atmospheric attenuation, a recognized cue to depth [2]. It is therefore possible that the greater apparent blurriness of smaller texture features could evoke a heightened impression that those surfaces are located farther away than comparable surfaces on which the texture features appear more distinct.

In Fig. 5, it may be noted that the solid-colored rooms appear to have been rated, on average, as slightly less spacious than the rooms featuring the finest wallpaper pattern. This suggests the possible potential of using very finely-textured wallpaper to enhance the sense of spaciousness in a room. However, we must emphasize that our experiment did not find these differences to be statistically significant, and further studies with more participants would be necessary to support any claim that a room's sense of spaciousness might have the potential to be enhanced, rather than diminished, by the application of an appropriately chosen wallpaper pattern.

Finally, we acknowledge the possibility that some participants may have disregarded the written instructions provided to them. We observed one participant in particular verbally counting steps during the second half of the experiment, even though the written instructions (which can be seen in the appendices to this paper) had explicitly requested that they avoid doing so and warned that using such artificial strategies would interfere with the research goals of the study. It is additionally possible that other participants could have been counting steps non-verbally, without our being aware of it. We did not debrief participants to find out what strategies they had used to reach the target because our written instructions had so clearly specified the process we wanted them to use that we did not anticipate non-compliance. Also, even though participants were explicitly told to keep their eyes closed at all times during the second part of the experiment except when viewing the room at the very beginning of each trial, the possibility remains that some participants might have opened their eyes as they walked. In such an event, they might have been able to see the bounding line of the Vive's tracking space, which would appear as a dark grey square on the ground whenever the participant traveled farther than 2.79 m beyond the designated starting position. However, our data do not show any evidence of a change in error rates at longer distances; the proportion of distance underestimation in the largest rooms is similar to that in the smaller ones where the grid would not have been active.

6 Conclusions and Future Work

This study provides potentially useful insights to architects and interior designers by showing that the scale of a wallpaper pattern can not only affect people's subjective impression of spaciousness in a room, which is primarily an emotional sensation [5], but that it can also affect their action-based judgments of how far away from them the walls of a room are located. This understanding of how the dominant scale of a wallpaper pattern impacts spatial judgments can be deployed when designing spaces to make them seem more spacious or, alternatively, more cozy. In addition to wall treatments, there are many other features of a room's design that can affect its perceived spaciousness, and we plan to continue our efforts to use virtual reality technology to explore other design-related hypotheses and to better support an informed design process overall.

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Appendix A: Written Instructions (Part 1)

You will be asked to perform two simple tasks multiple times for this experiment. Please try to perform each task at a natural and consistent pace. To make things easier to remember, we will give you the instructions for each task separately.

Preparation: If you look at the carpet in our lab, you will see a red colored tape mark. Please stand on top of the tape so that your heels align with the back edge of the tape mark. (Note, you will not see this tape in the virtual reality environment). Once you are in the correct position, we will ask you to put on a head mounted display (HTC Vive). Please take some time to adjust the straps on the device so that it fits your head comfortably. We will then ask you to go through a brief calibration procedure to optimize the visuals for your individual head shape.

Task: We will show you a series of virtual rooms and will ask you to rate how spacious they feel to you using a scale from 1 to 10. We will start out by showing you two rooms that you can use to help anchor this scale; you can consider the first room to be an example of a place that has a spaciousness of "1" and the second room to be an example of a place that has a spaciousness of "10". We will then show you, one at a time, a series of 35 different rooms. As each room becomes visible, please briefly look around (without taking any steps) and then verbally tell us the number that best corresponds to how spacious the room feels to you. After we record your rating, the

screen will briefly turn black and then a different virtual room will become visible. Please note that you will be seeing each room from a slightly different position. After you have provided a verbal rating for each of the 35 rooms we will ask you to take off the head-mounted display and have a short break. Following this break, we will show you a different set of 35 rooms and will ask you to provide another set of spaciousness ratings. If at any point, during any of the trials, you start to feel tired, distracted, impatient, or otherwise uncomfortable or unhappy, please let us know and we will pause the experiment to let you rest.

It is important for us to stress that there are no right or wrong answers in any part of this task. We are just very interested to know how each room makes you feel. What is important to the integrity of our experiment is that you treat each judgment independently and devote the same level of attention and care to all of the judgments you make. We expect that this portion of the experiment will take about 20–30 min in total, and after this part is completed we will give you a long break.

Please remember that you are always free to discontinue your participation in this experiment at any time, for any reason. In that event you would still be compensated with a gift card of value proportional to the time you spent.

Thank you in advance for your participation. Please ask us if you have any questions at any time.

Appendix B: Written Instructions (Part 2)

Task: In this part of the experiment, we will ask you to wear a set of headphones (playing an ambient sound track) in addition to wearing the head-mounted display. Please start out by standing at the same red tape mark as before. After you have put on the head-mounted display, we will show you a series of 16 different virtual rooms. In each room, we will ask you to take visual aim at the opposite wall of the room (located directly in front of you), then close your eyes. After you have closed your eyes, please say “ready” and we will remove the walls of the room. We then ask that you keep your eyes closed and physically walk through the room that you remember until you feel that you have reached the exact location of where the wall used to be. Please stop walking when you feel that your head and eyes would be exactly inside of the wall, if the wall were still there. When you believe you have reached the target location, please keep your eyes closed and wait a few moments for us to record your position. We will then verbally direct you to walk, with your eyes still closed, in a circuitous path back to a different starting point for the next trial. Please be sure to keep your eyes closed for the entire time until we explicitly tell you to open them again.

In each trial, as you walk from your starting point to the wall, please try to imagine what the virtual room would look like as you move through it. It is very important to the integrity of our experiment that you do not use any artificial strategies to reach the wall, such as numerically estimating the distance from the starting point and then counting steps, or referring back to your memory of a previous room and abstractly pre-deciding to just take more or fewer steps than you did before, as that would invalidate

our research. We need to stress that our goal in this experiment is not to “judge” the task performance of any individual against any sort of benchmark. Our goal is to better understand how the human brain interprets 3D space as people physically walk around with their eyes closed in virtual reality, and we cannot do that properly unless the described protocol is carefully followed. What is most important to us is that you let your intuition guide you, on each trial independently, in knowing when you have reached the wall of each virtual room. We expect that this portion of the experiment will take about 30–40 min.

End: All data will be de-identified before it is analyzed, so we will not be able to share your individual results with you, as we will have no way to know them ourselves. But we will be happy to share our overall findings with you after the experiment has been completed. If you would like to receive a copy of any eventual publication on this experiment, please let us know.

Within two weeks from the completion date of the experiment, we will ask the Department of Computer Science to order a \$10 Amazon gift card for you, in compensation for your participation. The email containing the gift certificate will come directly from amazon.com and will be sent to the email address you provided on the consent form. The gift card will not expire. If for any reason you fail to receive the email with the gift card, or you inadvertently lose the email before having a chance to use the gift card, you can always contact us to have the gift card re-issued, even after a delay of many months or years.

Please remember that you are always free to discontinue your participation in the experiment at any time, for any reason. In that event you would still be compensated with a gift card of value proportional to the time you spent.

Thank you in advance for your participation. Please ask us if you have any questions at any time.

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