Egocentric biases in comparative volume judgments of rooms

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The elongation of a figure or object can induce a perceptual bias regarding its area or volume estimation. This bias is notable in Piagetian experiments in which participants tend to consider elongated cylinders to contain more liquid than shorter cylinders of equal volume. We investigated whether similar perceptual biases could be found in volume judgments of surrounding indoor spaces and whether those judgments were viewpoint dependent. Participants compared a variety of computer-generated rectangular rooms with a square room in a psychophysical task. We found that the elongation bias in figures or objects was also present in volume comparison judgments of indoor spaces. Further, the direction of the bias (larger or smaller) depended on the observer's viewpoint. Similar results were obtained from a monoscopic computer display (Experiment 1) and stereoscopic head-mounted display with head tracking (Experiment 2). We used generalized linear mixed-effect models to model participants' volume judgments using a function of room depth and width. A good fit to the data was found when applying weight on the depth relative to the width, suggesting that participants' judgments were biased by egocentric properties of the space. We discuss how biases in comparative volume judgments of rooms might reflect the use of simplified strategies, such as anchoring on one salient dimension of the space.

Introduction

Spatial judgments related to indoor spaces are an integral part of our everyday life. People need to make volume judgments about the amount of space that is offered to them. This is the case when moving into a new house and comparing room size or estimating how much furniture can fit into a space. While parts of visual space perception—specifically depth perception, exocentric extents, size of objects, and navigation—are well documented (Glennerster, Gilson, Tcheang, & Parker, 2003; J. Loomis & Knapp, 2003; J. M. Loomis, Silva, Philbeck, & Fukusima, 1996; Renner, Velichkovsky, & Helmert, 2013; Ruddle, Payne, & Jones, 1997; Wiener et al., 2007), there are just a few studies investigating how humans treat visual information related to volume perception of indoor space (Franz, von der Heyde, & Bülthoff, 2005; Gärling, 1970; Glennerster et al., 2003; Sadalla & Oxley, 1984). Some experiments tackling this open question explored the contribution of vision by asking the participants to estimate the single dimensions that contribute to the volume of an indoor space—namely to estimate the space's length, width, and height (Henry & Furness, 1993; Leyrer, Linkenauger, Bülthoff, Kloos, & Mohler, 2011). While the mathematical description of volume (length $\times$ width $\times$ height) is easily understandable, this description might not be the way we perceive visual volume. Instead, we suggest that humans refer to heuristics when emitting judgments about visual volume perception of indoor spaces.

Cognitive heuristics are simplified strategies used to make decisions in difficult cognitive environments (Tversky & Kahneman, 1974). Although heuristics are efficient under most circumstances, they can also lead

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to systematic cognitive biases. The most famous example of this type of bias is probably Piaget's experiments with young children on the conservation of liquid (Piaget & Inhelder, 1969). In Piaget's experiments, the same quantity of liquid was poured from a tall, thin cylinder to another cylinder that was broader and shorter. Most children indicated that there was more liquid in the taller cylinder. According to Piaget, the results illustrated the fact that young children tend to make their judgment by focusing on the longest linear dimension of objects.

Similar biases were found with drawn geometrical figures such as rectangles: The more elongated a figure, the larger its size estimation (rectangle > square of equal area; Holmberg & Holmberg, 1969; Verge & Bogartz, 1978). This phenomenon has been termed *elongation bias* and has been confirmed with adult participants in several other studies (Anastasi, 1936; Krider, Raghubir, & Krishna, 2001; Raghubir & Krishna, 1999). In marketing research, for example, consumers were found to be biased by container shape and appeared to use the height of packaging to make their volume judgment (Raghubir & Krishna, 1999). This example illustrates that even adults refer to simplified strategies to make volume judgments concerning different objects.

In order to explain elongation biases in two- and three-dimensional figures and objects, Krider et al. (2001) proposed a model of area comparisons in which the primary comparison between figures is made on the basis of a single comparable dimension due to its perceptual salience—a salient dimension hypothesis expressed as a power law—with an adjustment of the result of this initial comparison based on the remaining dimensions. A stimulus is described as salient when it stands out from other stimuli due to particular physical characteristics (e.g., longest dimension; Holmberg, 1975) or cognitive features (e.g., biological significance or acquired relevance of a stimulus; Mackintosh, 1975; Tsakanikos, 2004).

The salient dimension that biases observers' perception of a figure, object, or space could be allocentric (independent of viewing perspective) or egocentric (dependent on viewing perspective). An example of an allocentric dimension is the longest dimension of the space (Holmberg, 1975). This would mean that observers judge a rectangle to be larger than a square regardless of orientation or viewpoint. On the other hand, an egocentric dimension is viewpoint relative (e.g., the vertical or horizontal dimension of a rectangle relative to the observer). If the vertical dimension of a rectangle was salient, participants would judge an upright rectangle depicted as resting on its short side to be larger than a rectangle of equal area depicted as resting on its long side (similar to a Piaget experiment; Piaget & Inhelder, 1969).

Applied to visual volume perception of indoor spaces, this would mean that perceivers' judgments could be biased by one salient dimension of the enclosure. This hypothesis is consistent with architectural findings showing elongation biases in area judgments of rectangular indoor spaces (e.g., rooms: Inui & Miyata, 1973; Sadalla & Oxley, 1984) and outdoor spaces (e.g., streets: Gärling, 1970; Ishikawa, Okabe, Sadahiro, & Kakumoto, 1998). Typically, rectangular architectural spaces are judged to be larger than square spaces of equal area (Inui & Miyata, 1973; Sadalla & Oxley, 1984). In the case of urban streets presented on a computer screen, the greater the depth of the street scene, the more spacious it appeared (Ishikawa et al., 1998). Similar findings were reported for real outdoor environments and photographs or drawings of streets (Gärling, 1970). Overall, results from different studies suggest a close correspondence between judged depth and size of space (Gärling, 1970; Gilinsky, 1951). One could therefore assume that the perceived size of a space is dependent on perceived depth from the viewpoint of the observer. Hence, space size perception might be egocentric.

However, other evidence suggests that space size perception might be independent of the observer's viewpoint. Sadalla and Oxley (1984) designed a study in which participants were placed inside temporarily constructed rooms, with wood-panel walls creating an equal floor area (without ceiling) that varied in aspect ratio, ranging from a 1:1 width:length ratio (i.e., a square room) up to a 1:9 ratio. Independently of the rooms' viewing perspective (middle of the short wall, long wall, or room center), the results indicated that rooms with the greatest width:length ratio were always estimated to be larger than less rectangular rooms of equal floor area. The authors suggested that room size perception could be biased by the longest linear dimension of the space (i.e., the length of the room; Sadalla & Oxley, 1984). This would indicate that space size perception is allocentric (Holmberg, 1975; Holmberg & Holmberg, 1969). In the case of Sadalla and Oxley's (1984) study, some procedural variables could have limited the generality of their results. For instance, no ceilings were constructed over the rooms. This means that participants' judgments could have been influenced by the open nature of the space; for example, subjects may have tended toward area judgments of floor space.

Overall, the processes and biases involved in visual room size perception remain unclear. To clarify those aspects, the current study examined (a) whether volume perception of computer-generated rooms is biased by the elongation (aspect ratio) of the space (e.g., whether rectangular rooms are perceived as larger than square rooms of equal volume), and (b) whether this bias is allocentric (independent of viewing perspective) or

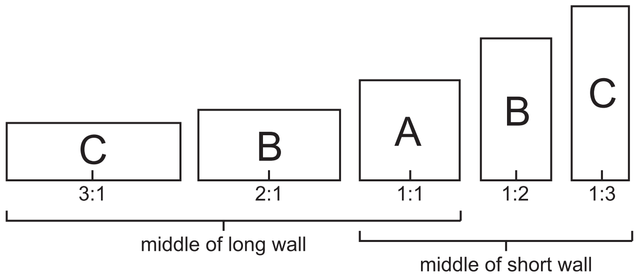

Figure 1. Stimuli and viewing perspective. Rectangles represent indoor spaces depicted from above; within the rectangles, vertical lines represent the viewer's position. Numbers represent width:depth ratio (room elongation). The experiment was run with two viewing conditions (viewing from the middle of the long wall or the short wall; see Method), with the square rooms included in both conditions to provide a baseline comparison. The stimuli can be thought of as rooms of three different aspect ratios (labeled A, B, and C) viewed from two perspectives or, equivalently, five different ratios. Stimuli were selected from these ratios and presented at sizes ranging from 21 to 165 m^3.

egocentric (dependent on viewing perspective of the space). The two accounts make different predictions with regards to the viewpoint dependency of volumetric judgements in rooms. If observers' comparative volume judgments of rooms are biased by the use of allocentric strategies (e.g., anchoring on absolute properties of the space, such as the longest dimension of the room), results should be independent of the viewing perspectives; rectangular rooms should always be perceived as larger than square rooms of equal volume. In contrast, if observers' comparative volume judgments of rooms are biased by the use of egocentric strategies (e.g., anchoring on the depth relative to the observer's viewpoint), rectangular rooms should be perceived differently (larger vs. smaller) depending on the observer's viewing perspective. We investigated those questions by displaying rooms using a monoscopic computer display in Experiment 1 and a stereoscopic head-mounted display (HMD) with head tracking in Experiment 2.

Experiment 1

In Experiment 1, participants had to make comparative volume judgments between a rectangular room varying in width:depth aspect ratio (hereafter referred to as *room elongation*) and a constant square room of reference displayed on a computer screen. To determine whether visual volume comparisons of rooms are egocentric (dependent on the observer's viewpoint) or allocentric (independent of the observer's viewpoint), we manipulated the viewing perspective of the rooms (viewing the room from the middle of the short wall vs. from the middle of the long wall; see Figure 1). Compared with constructing rooms in physical spaces, using computer-generated rooms provided the opportunity to test volume perception on a greater variety of rooms, including small and large rooms (rooms from 21 to 165 m^3) of different aspect ratios (see Figure 1). This diversity of rooms enabled us to fit a psychometric function onto our data and to measure participants' sensitivity to changes in room size (i.e., measure the slope of the psychometric function) and see whether the slope varied with the rooms' elongation (i.e., deviation from square shape).

Participants

A total of 36 participants participated in Experiment 1 (22 males, 14 females; mean age = 28.75 years, SD = 7.38). Participants were divided into two groups to reduce the duration of the experiment. Group 1 (18 participants) saw the rooms from the perspective of the middle of the short wall, and group 2 (18 participants) saw the rooms from the perspective of the middle of the long wall. All participants gave written informed consent prior to the study and were paid for their participation. Participants and the obtained data were treated strictly in accordance with the Declaration of Helsinki.

Technical setup

Experiment 1 was conducted on a monoscopic laptop computer (MacBook Pro 2.1: Core 2 Duo T7600 at 2.33 GHz, 2-GB random-access memory, and an ATI Mobility Radeon X1600 graphics processor with 256-MB GDDR3 video memory) running at native 1680 × 1050 resolution on a 17-in. display. The visualization and experiment workflow were implemented using the Unity Pro game engine (Version 3.5.4fl, Unity Technologies, San Francisco, CA) running at a constant frame rate of 60 frames/s. The geometric field of view (used by the computer to render three-dimensional graphics) was 53.5° horizontal and 35.0° vertical. Participants used a Logitech Rumblepad analog stick to look around the rooms (i.e., change orientation in yaw and pitch). Evidence suggests that it is important to stop auditory cues from interfering with visual area or volume judgments of the spaces (Larsson, Västfjäll, & Kleiner, 2002). Thus, participants wore noise-cancelling headphones with white noise to help mask auditory influences.

Stimuli

The virtual room was made with a carpet texture for the floor and a plain office wall texture for the walls. The room was rendered using perspective projection. Static lightmaps were calculated in Unity with ambient occlusion. The rendering backend was Direct3D 9. The room appearance can be seen in the video in the supplementary materials. All rooms were empty and presented with a ceiling (and no windows) so participants could get the feeling of being completely surrounded and enclosed by the space. The height of all rooms was kept at 3 m (within the range of average room height). Rooms varied in volume from 21 to 165 m^3 and in their degree of elongation (width:depth ratio) as per Figure 1.

Method

We used a two-alternative forced-choice psychophysics task in which participants had to compare rectangular virtual rooms varying in their width:depth ratio with a square virtual room presented at constant volume (93 m^3). The trials (i.e., rooms of different sizes and ratios) were presented in a random order. The constant stimulus was always presented in the first interval. Within each aspect ratio category (e.g., 1:1, 1:2, and 1:3—rooms A, B, and C, respectively, in Figure 1), 90 rooms were displayed, varying in volume difference compared with the constant stimulus, for a total of 270 trials (3 aspect ratio categories $\times$ 90 rooms). The volume differences between the first and second rooms were 0, $\pm$9, $\pm$18, $\pm$45, and $\pm$72 m^3. We presented 10 rooms in each of the volume differences (90 rooms total). Rooms were viewed by participants starting with a randomized orientation in yaw and pitch ($\pm$4°, $\pm$8°, and $\pm$12°) to avoid simple matching between the two rooms and to encourage participants to look around the space with the joypad. Participants' stimuli data (room size, aspect ratio, and pitch and yaw of orientation for each trial) were generated with Matlab R2011a (64 bit; The MathWorks, Natick, MA) before the experiment.

Procedure

Participants were seated on a chair laterally aligned with the screen. They viewed the screen from a distance of approximately 37 cm, and the geometrical field of view of the rendered image matched the visible field of view of the monitor. The distance was approximate because participants' heads were not constrained by a head rest. There were no stereo cues and no head tracking updating the displayed image based on head movements; these cues were added in Experiment 2. Instead, participants explored the room via a joypad and were instructed to keep their head still and maintain their direction of gaze toward the screen for the duration of the experiment. Subjects had to compare the volume of two virtual rooms displayed on the laptop screen. Volume judgments were defined as the subjective impression of overall size provided by the room. Participants had to indicate whether the second room was larger or smaller than the first room. Individuals were clearly told to base their judgments on their feeling of how big or small the overall space appeared to them as if they were seated against the back wall of the virtual room. The back wall position corresponded to the middle of either the short dimension (group 1) or the long dimension (group 2) of the rectangular room. In each group, participants were presented with the first room. Participants had to look around the room for 5 s by controlling the virtual camera with the joypad. Pilot participants felt that 5 s was long enough to rotate the camera view from one side of the room to the opposite side. Following this, a fixation cross appeared on the screen (2 s) and the second room was displayed. After observing the second room for 5 s, participants had to respond to the question "The second room is . . ." with either *larger* (upper-right button on the joypad) or *smaller* (upper-left button). An image of the controller was displayed to remind participants of the buttons. Participants were given breaks of approximately 3 min three times during the task (70, 140, and 210 trials). The duration of the sessions between the breaks was approximately 18 min for both groups. Individuals went through a training session of 10 trials (not included in analysis). The experiment lasted around 1 hr 30 min, including instruction time.

Analysis

The experiment was a 3 $\times$ 2 design. One factor was room elongation (three room ratio types; see rooms A, B, and C in Figure 1), and the second factor was viewing perspective (middle of the short wall, middle of the long wall). The dependent variable was the probability that the experiment stimulus was perceived as being larger than the constant stimulus.

We analyzed the results using generalized linear mixed-effect models with a probit link function (Agresti, 2007; Venables & Ripley, 2002). Mixed-effect models enable modeling and analysis of the data when there are repeated trials for each subject (Field, Miles, & Field, 2012), and generalized mixed-effect models are particularly well suited for analyzing psychophysical data at the population level (Moscatelli, Mezzetti, & Lacquaniti, 2012). The analysis models the whole

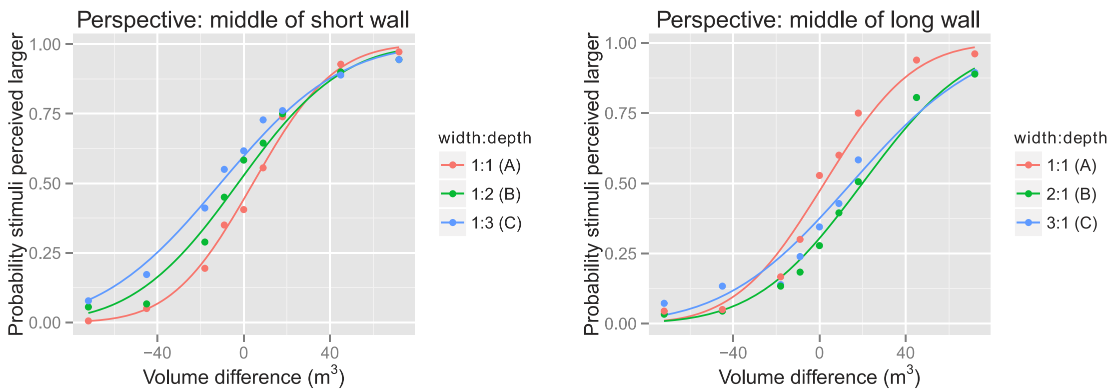

Figure 2. The psychometric curves obtained in the two different viewing conditions: middle of the rectangular room's short wall (left) and middle of the long wall (right). The *x*-axis shows the volume difference between the experiment stimulus and the constant stimulus. Nine volume differences were used (see Method). The *y*-axis corresponds to the probability that the stimuli were perceived as larger than the constant stimulus based on the responses from all participants in that perspective. The colors represent the width:depth ratios of the rooms (see Figure 1). We observed some interval bias (left), which was taken into account via the intercept term in the model used for analysis. Room size judgments are viewer dependent, as demonstrated by an elongation bias that acts in the opposite direction depending on the viewing perspective of the rooms.

psychometric curve and looks at the "shifting" of the curve in the different experimental conditions (viewing perspectives and room elongations). The predictor used in the baseline model was the volume difference between the experiment and the constant stimuli. Interactions with the volume difference predictor corresponded to a change in the steepness of the curve. All other terms in the model corresponded to a left–right shift of the curve parallel to the *x*-axis. Models were fit using Laplace approximation with the lme4 package in R (Bates et al., 2014), and random intercepts[1] and slopes were grouped by subject. To investigate the effect of each experimental factor (viewing perspective and room elongation) on the participant's response, we analyzed the models using an analysis of deviance with likelihood ratio tests. The model with all terms and their interactions is subsequently referred to as the *model of conditions* (see Modeling viewpoint-dependent biases).

Results

Room size judgments are viewer dependent

We investigated the effect of room elongation (room ratios A, B, and C; see Figure 1) and viewing perspective (middle of the short wall vs. middle of the long wall) on the participants' volumetric judgments. Our results indicated a significant effect of elongation, $\chi^2(2) = 25.82$, $p < 0.001$, and viewing perspective, $\chi^2(1) = 11.91$, $p < 0.001$, on the probability the experiment stimuli were perceived as larger than the constant stimulus. Importantly, the interaction between viewing perspective and room elongation was significant, $\chi^2(2) = 119.04$, $p < 0.001$, suggesting that comparative judgments of room size were dependent on the observer's viewing perspective (Figure 2). To understand this interaction, we analyzed both perspectives separately.

There were significant effects of room elongation in both perspectives: middle of the short wall, $\chi^2(2) = 63.92$, $p < 0.001$; middle of the long wall, $\chi^2(2) = 81.14$, $p < 0.001$. When rooms were viewed from the middle of the short wall, the coefficients were positive (room B = 0.25, $p < 0.001$; room C = 0.44, $p < 0.001$; B and C are the coefficients corresponding to the room elongations in Figure 1). These positive coefficients corresponded to a leftward shift of the response curve and were therefore directly related to participants' accuracy in the task and their resulting point of subjective equality (PSE). The decrease in PSE meant that participants perceived the rooms as larger as they became more elongated when viewing them from the middle of the short wall (Figure 2). However, the effect occurred in the opposite direction when participants viewed the rooms from the middle of the long wall: The coefficients were negative (room B = –0.48, $p < 0.001$; room C = –0.28, $p < 0.001$), and participants perceived more elongated rooms as smaller when viewed from the middle of the long wall. Those results demonstrate a viewpoint-dependent bias in volumetric judgments of computer-generated rooms.

Decrease in precision with rectangular rooms

To examine participants' response precision, we checked whether the slope of the function varied with perspective and room elongation. The slope of the function is affected by terms that interact with the volume difference predictor. There was a significant interaction between volume difference and room elongation, $\chi^2(2) = 57.81$, $p < 0.001$, meaning that the slope changed in different elongation conditions (rooms A, B, or C). From the perspective of the short wall, the slopes for rooms A, B, and C were 0.013, 0.011, and 0.0091, respectively (dy/dx at PSE; see Figure 2, left). From the perspective of the long wall, the slopes for rooms A, B, and C were 0.012, 0.010, and 0.0086, respectively (Figure 2, right). This means that participants' response probabilities (the *y*-axis in Figure 2) changed more gradually for more elongated stimuli than for less elongated stimuli. For instance, at a volume difference providing a 0.5 response probability when the volume of rooms of types A, B, and C viewed from the middle of the short wall is increased by 1 m^3 (Figure 2, left), the increase in response probability is 0.013 for the room ratio 1:1, 0.011 for the room ratio 1:2, and 0.0091 for the room ratio 1:3. The slopes were shallower for the more elongated stimuli than for the less elongated stimuli, indicating that participants were less precise and less sensitive to volume differences. In other words, the more the rooms deviate from the square shape, the larger the difference in volume participants need in order to detect which room is the largest or smallest. The resulting random effects for the intercept and slope had *SD*s of 0.36 and 0.011, respectively, with a 0.25 correlation.

Discussion

Experiment 1 investigated the effect of room elongation and viewing perspective on comparative volume judgements of rooms displayed on a computer screen. Results showed a substantial effect of room elongation (rectangularity) on volume perception of rooms: Rectangular rooms were perceived less precisely in terms of the slope of the function and showed a shift in PSE compared with square rooms. If participants' volume judgments were independent of the observer's viewpoint, we would have expected rectangular rooms to be perceived as larger than square rooms of equal volume in all perspectives. In contrast to this hypothesis, we measured a significant interaction between the elongation of the rooms and the observer's viewing perspective. Compared with square rooms, rectangular rooms of equal volume were perceived as smaller when viewed from the middle of the long wall and larger when viewed from the middle of the short wall. Hence, biases in judgments of elongated rectangular spaces are egocentric (viewpoint dependent) and not allocentric (viewpoint independent). In a second experiment, we investigated whether our results hold in a more ecological environment in the presence of stereoscopic depth cues via an active exploration of the rooms by means of head movements and real-time head tracking.

Experiment 2

In Experiment 2, we investigated whether the significant interaction between room elongation and viewing perspective measured in Experiment 1 would hold when rooms are displayed in an HMD. Experiment 2 presents a few advantages over Experiment 1. In Experiment 1, minor head movements might have occurred because the participant's head was not fixed by a chin rest. This could have created cue conflicts between the displayed image and the perceived image and may have added noise to our data. To avoid this type of influence in Experiment 2, we used real-time head tracking and stereoscopic depth cues so that the virtual room was updated strictly according to the viewer's head position and orientation. Hence, we had better control over the visual information available to the observer. Another advantage from Experiment 2 is the fact that rooms were virtually surrounding the observer, and participants could directly explore the space by means of head movements. Hence, the visualization conditions of the rooms were closer to a real-life scenario in Experiment 2. This also means that additional cues, including proprioceptive information obtained via head rotation, were available to the participants. Multisensory research suggests that information gathered about one stimulus (e.g., object shape), via the combination of several sensory modalities, can lead to a more robust estimate of the stimulus property in question (for details see Ernst & Bülthoff, 2004). Similar mechanisms might occur in volume perception of rooms when vestibular cues and signals from neck muscles (obtained via head rotation) are combined with more precise visual information about the space (e.g., stereoscopic cues). The combination of these additional sources of information could generate a more accurate perception of room size. Hence, the bias measured in Experiment 1 could vanish when measured in Experiment 2.

Participants

A total of 36 participants took part in Experiment 2. Four participants reported symptoms of tiredness or discomfort and did not complete the task. This is a relatively normal dropout rate for virtual reality experiments lasting 1 hr or longer with an HMD with a lot of rotational movement (Ruddle, Volkova, & Bülthoff, 2013). Thus, only 32 participants (20 males, 12 females; mean age = 25.5 years, $SD = 5.98$) were included in the analysis. As in Experiment 1, participants were divided into two groups in order to decrease the duration of the experiment. Group 1 (15 participants) saw the rooms from the perspective of the middle of the short wall, and group 2 (17 participants) saw the rooms from the perspective of the middle of the long wall. All participants gave written informed consent prior to the experiment and were paid for their participation. Participants and the obtained data were treated strictly in accordance with the Declaration of Helsinki.

Technical setup

The HMD was an nVisor SX60 (NVIS, Inc., Reston, VA) weighing 1 kg, with a 44° horizontal and 35° vertical field of view based on manufacturer specifications. We used this field of view for rendering the scene. There was a 1280×1024 resolution per eye (5:4) on an F-LCOS display with a 100:1 contrast ratio. In contrast to the laptop, the HMD provided stereo cues and motion parallax to the user with real-time tracking of the head position and orientation via Vicon MX13 cameras (Vicon, Oxford, UK) using Vicon Tracker software at 120 Hz. The central position between the two HMD lenses was calibrated to a known position in the room, with the HMD perpendicular to a mark on the ground. The virtual object was then positioned and oriented to this known position. We used a test environment—a rectangular room aligned with the physical room—to check the calibration of the space. The experimenter wore the HMD and raised or lowered it to check the alignment of a real and virtual Vicon-tracked object. The experimenter verified that the real and virtual objects were colocalized at the beginning of each experimental session. We based our calibration on a level pitch and average interpupillary distance for all individuals (Thompson, 2002). The virtual cameras were therefore displaced by 6.5 cm. The latency of the setup was measured using the method from Di Luca (2010). The method measured the delay between physical movement of the HMD and the virtual update on the display as 41 ms ($SD = 24$ ms). Note that optical distortions will still be present in our display and that HMDs cannot entirely replicate real-world perception (for details, see Kellner et al., 2012; Kuhl, Thompson, & Creem-Regehr, 2008).

Method and stimuli

Stimuli identical to those used in Experiment 1 were used in Experiment 2. Pilot testers suggested that participants would need more time than in the laptop condition to get an overall impression of room size and rotate their head from one side of the room to another. Thus, each room was displayed for 10 s instead of 5 s. With this additional looking time, using the method of constant stimulus would extend the duration of the experiment to 3 hr 30 min. Pilot participants showed signs of tiredness in this situation (e.g., random responses). In order to reduce the duration of the experiment, we decided to present the stimuli using a one-up, one-down adaptive staircase method (i.e., fewer trials; Levitt, 1971). With this method the experiment lasted approximately 1 hr 15 min, including breaks and instruction. The mean number of trials was 99.81 (compared with 270 in Experiment 1). Participants were given 2-min breaks every 20 trials. The overall procedure was the same as in Experiment 1 (see the video in the supplementary materials).

Analysis

The adaptive staircase method enabled us to detect the PSE from the head-mounted experiment (convergence point = mean of the last three reversals from each of two staircases). The PSE results were analyzed using likelihood-ratio tests. We used linear mixed-effect models with random intercepts grouped by subject in all analyses.

Results

Is the perceptual bias observed in the HMD?

The key question here is whether we will observe a significant interaction between room elongation and viewing perspective on the PSE values in the HMD when more cues (proprioceptive and stereoscopic) are available to the participants. There was a significant interaction between viewing perspective and room elongation on participants' PSE values, $\chi^2(2) = 8.53$, $p = 0.014$. The main effects (marginal to the interaction) were not significant ($p > 0.05$). To understand the interaction, we analyzed room elongation separately. There was a significant difference between the two perspectives for the most rectangular rooms (3:1 and 1:3 ratios; room C in Figure 1), $t(20.58) = -2.12$, $p = 0.046$. This means that the same rectangular room (room C) is perceived as larger when viewed from the middle of the short wall and smaller when viewed from the middle of the long wall (i.e., room ratio 3:1 is different from room ratio 1:3). The difference between the middle ratios 2:1 and 1:2 was smaller and not significant ($p > 0.05$). This result is in line with the idea that the more rectangular rooms produce a more pronounced bias.

Effect of egocentric ratio on room size perception in both experiments

The room stimuli can also be thought of as one viewing perspective and five egocentric width:depth ratios (i.e., the five ratios depicted in Figure 1).

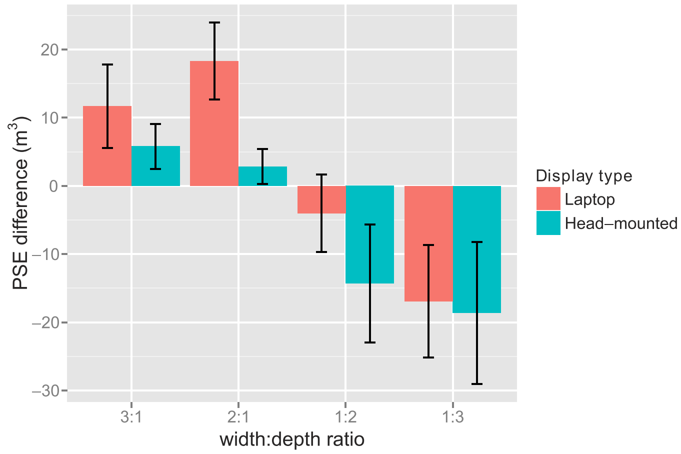

Figure 3. PSE differences for both display types. The PSE values shown in this figure represent the differences from participants' baseline responses in the 1:1 ratio. For instance, a PSE difference of 0 means that participants were responding the same as with a square room. Error bars represent ±1 *SE*. Ratios of 3:1 and 2:1 are from the perspective of the middle of the long wall, and ratios of 1:2 and 1:3 are from the perspective of the middle of the short wall. The 3:1 to 1:3 decrease in PSE difference observed in the rooms' ratios illustrates the significant effect of egocentric ratio found on the results of Experiments 1 and 2.

Considering the data in this way, it is possible to look for a linear effect of ratio on the PSE for each experiment. A linear mixed-effect model with random intercepts grouped by subject showed a significant effect of ratio on the PSE values in Experiment 1, $\chi^2(1) = 17.80$, $p < 0.001$, and Experiment 2, $\chi^2(1) = 10.34$, $p = 0.0013$. This result, observed in both experiments, showed that participants' responses were systematically biased by the egocentric ratio (i.e., the room's ratio relative to the observer's viewpoint). This means we observed a significant decrease in PSE values as the room's aspect ratio increased in depth and decreased in width from the observer's viewpoint. This effect can be visualized in Figure 3. For more details regarding individual variation in responses, see section S1 in the supplementary materials.

PSE comparisons between Experiments 1 and 2

To assess differences in PSE results between Experiment 1 (laptop) and Experiment 2 (HMD), we used linear mixed-effect models on the PSE values, with the factors viewing perspective, room elongation, and display type (laptop vs. head mounted) as fixed effects. Overall, if the results were a consequence of the experiment setup, we would expect different results between Experiment 1 with the laptop display and Experiment 2 with the HMD. There was a significant effect of perspective on participants' PSE, $\chi^2(1) = 10.43$, $p = 0.0012$, and an interaction between perspective and elongation, $\chi^2(2) = 19.16$, $p < 0.001$. There was no significant effect of display type or interaction with display type ($p > 0.05$). Results from both experiments can be seen in Figure 3.

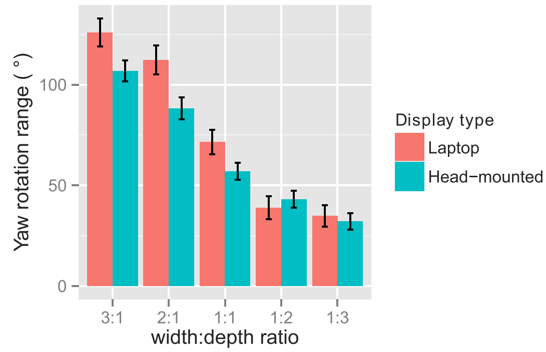

Figure 4. Yaw rotation range. The figure indicates the yaw rotation range used by participants in the two display types for the different width:depth ratios. The figure shows that participants adjusted their left–right observation of the rooms to the width of the room. As the rooms get wider (3:1 ratio), the rotation range increases. Error bars represent ±1 *SE*.

Are participants looking around the room differently across experiments?

It is important to make sure that the different methods used for observing the space (joypad vs. head rotation) led to the same amount of room visualization between the two experimental setups. To investigate this point, we compared the range of yaw rotation obtained via head rotation (HMD experiment) and control pad motion (laptop) as the rooms were getting wider or narrower from the observer's point of view (see Figure 1). If participants were limited in time to look around the space or focused their observation on a single aspect of the room, we would have expected to see a fairly similar range of orientation for all room ratios. This is not what we observed. There was a significant effect of egocentric ratio on the yaw range, $\chi^2(1) = 185.94$, $p < 0.001$, meaning that participants increased their left–right rotated head motion (or control pad motion) to apprehend the space when rooms were wider from the viewer's perspective (Figure 4). Hence, participants made use of the observation time we gave them to observe the space. There was no effect of display type on yaw rotation range, $\chi^2(1) = 2.96$, $p = 0.085$, or interaction between ratio and display type, $\chi^2(1) = 1.43$, $p = 0.23$. In summary, it seems that participants observed the rooms using a relatively similar rotation range across experiments.

Discussion

The goal of Experiment 2 was to investigate whether the effect of room elongation and viewpoint on room size perception would hold when more cues (including stereoscopic and proprioceptive cues) were provided to the participants. Results of Experiment 2 showed a significant interaction between viewing perspective and room elongation, meaning that rectangular rooms of equal volume were perceived differently (smaller or larger than square equivalent) depending on the observer's viewpoint. This result is backed up by the presence of a systematic bias of egocentric ratio (i.e., the room's ratio relative to the observer's viewpoint) on the participants' PSE values. These findings show that as the rooms get narrower and deeper from the observer's viewpoint (Figure 1), participants perceived the room as larger (PSE bias decreases; see Figure 3). Hence, the viewer-centered elongation bias measured in room size perception seems to hold within the presence of cues (proprioceptive and stereoscopic) that were not available by presenting the rooms on a computer screen (Experiment 1).

Interestingly, participants' yaw rotation range and PSE results were rather similar across the two experiments. Although minor head movements and other cue conflicts due to the lack of head tracking in Experiment 1 could have increased variance in the data, thus reducing the chance of detecting a difference between the two experiments, the variance was not large enough to hide the significant effect of egocentric ratio present in both studies. Hence, the effect of egocentric ratio measured on room size perception seems to be rather robust and not bound to the methodological characteristics of each experiment.

In the last section of this article we provide general mathematical descriptions of our data by creating a power law model that predicts volume perception from the physical properties of the room (egocentric depth and width). The advantage of modeling our data in this way is twofold. First, the power law model relates our work to previous research on figures and objects by using the same underlying formula (Ekman & Junge, 1961; Gärling, 1970; Krider et al., 2001; Teghtsoonian, 1965). Second, it enables us to generalize our predictions to any arbitrary room size, including other "in-between" ratios not present in the stimuli. This provides an important foundation for future work and offers concrete information for architectural applications with regard to predicted room size perception.

Modeling viewpoint-dependent biases

Power law functions are known to provide a good fit to size judgments associated with figures and space in general (Ekman & Junge, 1961; Teghtsoonian, 1965). They are particularly well suited for describing elongation biases by applying unequal weight to the separate dimensions of the figure or space, as shown in Equation 1 (Gärling, 1970; Krider et al., 2001):

$$R_{it} = D_{it} W_{it}^{\alpha} \quad (1)$$

In Equation 1, R_{it} is the perceived area of the stimulus for participant i and trial t, D_{it} and W_{it} are the dimensions of the stimulus that varied across trials, and α is a weighting parameter that controls the contribution of D and W to the product. Participants' size estimations were a scale of perceived area—for example, $S_{it} = b\ R_{it}$, where S represented the participants' area estimates and b was a scale constant estimated from participants' responses. Given that such power law models were able to predict elongation biases in figures (for a review, see Krider et al., 2001), the model may be a good predictor of elongation biases in indoor spaces. Applied to rooms, D_{it} and W_{it} represent the egocentric depth and width of the stimuli, respectively.

Power law model description for Experiment 1

For Experiment 1, we used a generalized linear mixed-effect regression model to predict the probability of participants responding that the experiment stimulus was larger (Agresti, 2007). Let y_{it} represent the observation from participant i in trial t ($0 =$ *smaller than the constant stimulus,* $1 =$ *larger than the constant stimulus*), and let u_i be the participant's intercept term modeled as a random variable from the normal $N(0, \sigma)$ distribution. The expected value of the participant's response is $\mu_{it} = E(Y_{it}/u_i)$ and is modeled in the following equation:

$$\Phi^{-1}(\mu_{it}) = u_i + \beta_0 + \beta_1 H_{it} R_{it} \quad (2)$$

where Φ^{-1} is the probit link function; β_0 and β_1 represent the fixed-effect intercept and coefficient, respectively; R_{it} is given in Equation 1; and H_{it} is the height. Height does not affect the predictions (it is constant for all i and t) but is included because judgments were volume based. The presence of a random intercept term u_i means that the effect $\beta_0 + \beta_1 H_{it} R_{it}$ is applied within subjects. The exponent α in Equation 1 was a free parameter and was estimated iteratively by maximizing the log likelihood, resulting in $\alpha = 0.81$. The fact that alpha was less than 1 means that participants' responses could be explained by attributing more weight to the depth of the rooms relative to the width. To visualize the participants' responses predicted from the egocentric depth and width of the rooms (Equation 2), see the model fit plotted in Figures 5 and 6 (right).

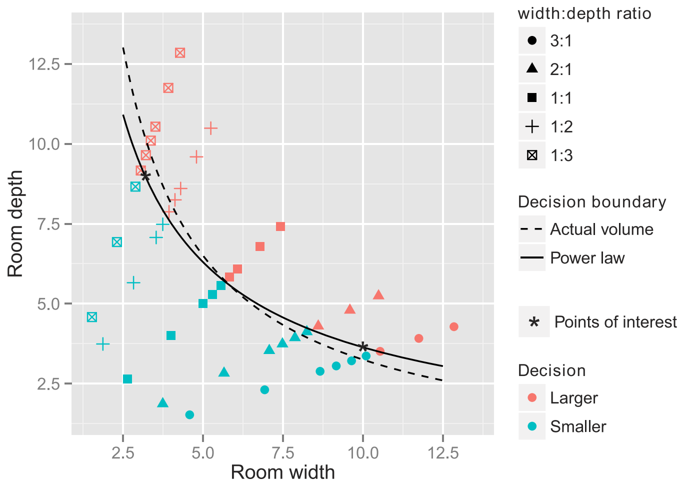

Figure 5. The decision boundary for Experiment 1: 50% contour line of the power law surface fit. All the experiment stimuli from Experiment 1 are plotted based on their width (*x*-axis) and depth (*y*-axis). The plotted symbols correspond to the different width:depth ratios of the room. When the majority of participants' responses compared with the constant stimulus were *larger*, the stimuli are plotted in red; otherwise they are plotted in blue. The dashed line is the contour line at 0.5 probability—namely, the decision boundary (i.e., change from red to blue) that one would expect if participants based their decision on the actual volume difference of the room ($\alpha = 1$). The solid line shows the decision boundary from the power law model fit—that is, the 0.5 contour line of the surface in Figure 6 (right). The power law was a significant improvement compared with the model based on actual volume difference (solid line vs. dashed line, $p < 0.001$). The effect of increasing or decreasing α is to rotate the decision boundary clockwise or counterclockwise, respectively. Hence, the fact that $\alpha < 1$ caused the power law decision boundary to rotate counterclockwise compared with the actual volume difference. The points of interest indicated on this graph are examples of predictions from the model that could be used for optimizing space in architecture.

Evaluating the power law model fit of Experiment 1

We evaluated the goodness of fit for our model by using an F1 score and a likelihood ratio test of the model deviance. The F1 score describes how well the model classifies participants' responses as larger or smaller than the constant stimulus, whereas the likelihood ratio test compares the improvement or reduction in goodness of fit when adding or removing model terms (McCullagh & Nelder, 1989; Wichmann & Hill, 2001). We also tested our model's ability to predict the data from Experiment 2 using Akaike information criterion and evidence ratios (Akaike, 1998; Wagenmakers & Farrell, 2004).

F1 score: The F1 score considers both the precision and recall of the model to compute the score. An F1 score of 1 indicates that the model classifies participants' responses perfectly, whereas an F1 score of 0 indicates that the model is not able to predict participants' responses. The model precision—true positive predictions/(true positive predictions + false positive predictions)—was 0.91. The recall—true positive/(true positive + false negative)—was 0.84. The F1 score—the harmonic mean of the model precision and recall—was 0.87. Hence, the power law model was a good fit to our data.

Likelihood ratio test: We compared the power law model with unequal weight on room dimensions ($\alpha = 0.81$) with one with equal weight on room dimensions ($\alpha = 1$). We refer to the latter as the *baseline model* because it is equivalent to predicting participants' response probabilities from the actual volume of the space. The classification boundary of this baseline model is shown as a dashed line in Figure 5. Note that both models fit the data well in the 1:1 ratio due to the intercept term β_0. The effect of the intercept term is to move the decision boundary diagonally and account for any interval bias. However, the baseline model fails to make correct predictions for the more elongated stimuli. The direct comparison of baseline and power law models shows that the power law model ($\alpha = 0.81$) is a significant improvement compared with the baseline, tested via a likelihood ratio test (the first term was the perceived volume $H_{it}D_{it}W_{it}^{\alpha}$ with $\alpha = 1$, and the second term was the perceived volume with $\alpha = 0.81$), $\chi^2(1) = 87.63$, $p < 0.001$.

Evaluating power law model fit of Experiment 1 by predicting Experiment 2 results

To predict the results of Experiment 2, we derived predicted PSE values from the power law fit for all five egocentric ratios. Those values are indicated on the surface plot in Figure 6 (right). Let y_{ij} represent the observed PSE values for Experiment 2 for participant i and egocentric ratio j. Let Q_j denote the predicted PSE values obtained from the power law fit to Experiment 1. The linear mixed-effect model predicting Experiment 2 results is therefore

$$E(Y_{ij}/u_i) = u_i + \beta_0 + \beta_1 Q_j \quad (3)$$

If $\alpha = 1$ (Equation 1), indicating no bias toward a particular dimension, the power law model would predict no change in PSE bias across ratios (the value Q would be the same for all ratios, j, and Equation 3 would reduce to an intercept-only model). This is the baseline model for our predictions of Experiment 2 results. We can then test the improvement of using the power law model fit ($\alpha = 0.81$, giving different predictions for Q depending on room elongation j) to predict Experiment 2 observations by using a likelihood ratio test. The predictions from the power law fit were a significant improvement compared with the baseline model, $\chi^2(1) = 10.19$, $p = 0.0014$. As expected, the

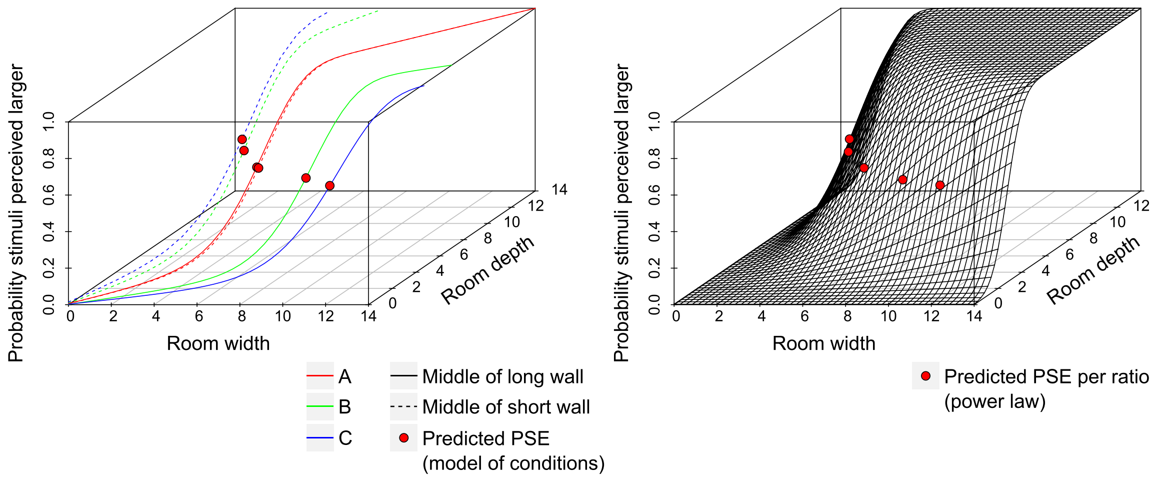

Figure 6. Visual comparisons of model predictions for Experiment 1. Left: The model of conditions used in the Results section of Experiment 1. Specifically, the probability that stimuli were perceived larger was modeled from volume difference, viewing perspective (middle of short wall vs. middle of long wall), and room elongation (A, B, or C from Figure 1). Right: The power law model applied to the present data on volume perception from Experiment 1. This graph is a direct result of Equation 2, shown without the random intercept term for visualization purposes. The 50% contour line of the surface plot is shown in Figure 5. One advantage of this power law model (right) over the model of conditions (left) is that the power law model makes predictions for any arbitrary room size and ratio. The red circles on the surface represent the derived PSEs for the five ratios used in the study, which were used to predict the results of Experiment 2.

results show that the power law fit from Experiment 1 was able to predict the results from Experiment 2 better than the baseline model.

We also tested whether the power law fit from Experiment 1 would provide better predictions for the data of Experiment 2 compared with simply using the fits from each condition—namely, the model of conditions. This model was used to analyze the effect of elongation and viewpoint on the perceptual judgments of Experiment 1 and has a parameter for each condition and their interactions (see Experiment 1 Analysis). We used the Akaike information criterion with evidence ratios to compare predictions for Experiment 2 based on the power law model and the model of conditions (Akaike, 1998; Wagenmakers & Farrell, 2004). Predictions for each model were expressed via Equation 3. Q_j was derived from the predicted PSE values of model fits to Experiment 1 from either the power law (see red circles in Figure 6, right) or the model of conditions (see red circles in Figure 6, left). Results showed that the power law was a better predictor of Experiment 2 results compared with the model of conditions, with an evidence ratio of 2.47 in favor of the power law. In summary, the power law model fit of Experiment 1 seems to be a good predictor of Experiment 2, as verified by the likelihood ratio test and the evidence ratio.

Linear bias based on egocentric ratio

An alternative to using a power law model as a general description of our results is to predict data of Experiment 1 from the actual volume difference between the rooms via a linear function of egocentric ratio to account for the bias:

$$\Phi^{-1}(\mu_{it}) = u_i + \beta_0 + \beta_1 V_{it} + \beta_1 C_{it} \quad (4)$$

where V_{it} is the actual volume difference between the rooms and C_{it} is the coded egocentric ratio 3:1, 2:1, 1:1, 1:2, 1:3, coded as 0, 1, 2, 3, 4. The term V_{it} predicts accurate responses, and C_{it} captures the perceptual bias.

Modeling our data via this linear bias (Equation 4) also provided a good fit to our data. Compared with the power law (see Evaluating the power law model fit of Experiment 1), there was a minor improvement in precision (precision = 0.92), the same recall (recall = 0.84), and subsequently a minor improvement in the F1 score (F1 = 0.88—a 0.01 difference compared with the power law model). However, this alternative model (Equation 4) produced more extreme predictions than the power law model (Equation 2) as rooms become more elongated. The diverging properties of the power law model and the linear bias are illustrated in supplementary materials S2. For instance, a room of 1-m width by 11-m depth would be predicted as larger than the constant stimulus when it is in fact 60 m^3 smaller (the predicted probability that participants would respond *larger* is greater than 0.5). As a direct comparison, the same room (1 m × 11 m) would be predicted as smaller than the constant stimulus by the power law model. Overall, the power law model seems to provide more conservative predictions than the alternative linear model for ratios with a larger deviation from a square shape. These more conservative properties could be one reason to prefer the power law (Supplementary Figure S2). In future work it would be interesting to collect data for higher room ratios (rectangular rooms increasing in elongation) in order to better distinguish the quality of the fit for the power law and the linear bias.

Model discussion

We have shown that a general description of our data can be provided using a power law model or by using a linear bias based on egocentric ratio. One advantage of modeling room size perception data via a power law is that it can relate our work more directly to previous research on volume or area perception of objects and figures. Power law functions have been used multiple times in the literature to describe elongation biases by applying unequal weight to the separate dimensions of a figure or space (Gärling, 1970; Krider et al., 2001). In our study, the power law model showed that participants' results could be explained by placing less weight on the egocentric width of the space. It is interesting to note that the model fit gave a similar alpha value to studies on figures (which obtained alpha values of 0.6 to 0.8 depending on conditions in Krider et al., 2001). This raises the question of whether similar mechanisms underlie the perceptual biases of figures or objects and indoor spaces. Research on area judgments of figures and objects suggests that an observer's attention can be directly manipulated toward one specific dimension of the stimulus. For instance, drawing a set of horizontal lines around two figures can highlight the figures' horizontal side and encourage their use in area comparisons (Krider et al., 2001). It would be interesting to test whether experimentally triggering the observer's attention on a different dimension of the room (e.g., highlighting the width of the space with a color) could affect the perceptual bias measured in our study. In that case, we would expect the value of the exponent alpha measured in our study to increase as the width becomes more salient. A correlational investigation could look at the changes in alpha due to manipulations in all sets of physical and virtual stimuli: figures, objects, and rooms.

Another interesting benefit from modeling our data, whether we use the power law model or the linear bias of egocentric ratio, is its potential application for architecture. Our model fit could be used as a guideline for predicting perception of room size in interior architectural design (Häuplik-Meusburger, 2011). For example, consider the left point of interest marked with an asterisk in Figure 5: a room of 3.21-m egocentric width by 9-m egocentric depth. The power law model fit predicts that participants would perceive the room as equal in volume compared with the constant stimulus when in fact it is 6.33 m^3 smaller than the constant stimulus. For the right point of interest in Figure 5, we would expect participants to perceive the room as being equal in volume to the constant stimulus even though it 16.8 m^3 larger (10-m egocentric width by 3.66-m egocentric depth). These types of predictions could be valuable for optimizing physical space—for example, in extraterrestrial (space stations) and naval (submarines) habitats. One interesting question for future work is whether the value of alpha would remain the same when testing rooms in real physical space and whether participants' bias toward the depth of the rooms would change if the height of the room was directly manipulated. In our current model, it is not clear whether the width and height dimensions of the rooms are combined with equal weight. This aspect could not be explored because the height of the rooms remained constant across trials. It would be worth varying the height dimensions of the rooms to investigate the relative contribution of this dimension to volumetric judgments of rooms (i.e., whether a secondary bias could be induced by the height of the space).

General discussion

The goal of this research was to investigate whether elongation biases observed in figures and objects can be found in enclosed spaces. In both studies, we found that room elongation relative to the viewpoint biased participants' volume judgments of computer-generated rooms. The observation of a bias in rectangular stimuli is consistent with previous results on area judgments of elongated figures (Anastasi, 1936; Holmberg & Holmberg, 1969; Smith, 1969). Differential findings regarding the direction of the elongation bias have been previously reported in the literature. Elongated shapes were perceived as larger than more compact ones in Anastasi and colleagues (Anastasi, 1936; Holmberg & Holmberg, 1969) and vice versa in Smith (1969). In our study, we go one step further by identifying one factor that could contribute to changes in the elongation bias direction: the observer's viewpoint on the room. Participants' PSEs were related to egocentric ratio such that judgments associated with identical rectangular rooms (ratios 1:3 and 3:1; see Figure 1) were biased in the opposite direction (smaller vs. larger) when observed from a different viewpoint.

In Experiment 2, some of the findings suggest that participants may have been slightly less biased by the elongation ratio of the room in the 1:2 and 2:1 ratios. It has been shown that the direction and extent of elongation biases on figures or objects could be changed when visual cues are combined with other sensory modalities (e.g., haptic information; Krishna, 2006). The more realistic visualization of the room as well as the presence of additional sensory cues (stereoscopic and proprioceptive cues induced via head rotation) could have contributed to adjusting or correcting part of the elongation bias in room size estimates. This idea is directly in line with research on multisensory integration and could be further pursued by investigating how different sensory information (e.g., auditory, visual, proprioceptive) about room size combines and influences each other (Ernst & Bülthoff, 2004).

There were other variations across the two setups. For instance, the horizontal geometrical fields of view used in the laptop were not directly matched to the one used in the HMD. We also used different psychophysical methods to measure results in each setup, and head tracking was provided only in Experiment 2. In our experimental context, we do not think those variables played a fundamental role in the perceptual bias because we did not detect a significant difference between the results of Experiments 1 and 2. It may be that the difference is small relative to the variance in the data and that more power would be needed to reliably detect it. Further research would be needed to investigate the direct effect of methodological variables on the perceptual bias associated with room size estimates.

Interestingly, modeling participants' response from the egocentric depth and width dimensions of the rooms suggested that subjects applied more weight to the egocentric depth of the space than to the egocentric width ($\alpha < 1$). This result is directly in line with the effect of egocentric ratio found on the PSE values in Experiments 1 and 2. The notion of egocentric ratio involves both width and depth of the space. When the ratio changes in such a way that depth increases but width decreases in relation to the observer, participants are biased toward perceiving the space as larger. In that sense, an increase in depth relates positively with the perceptual bias, whereas an increase in egocentric width relates negatively with the perceptual bias. Hence, the egocentric bias measured in room size perception could potentially be explained by participants relying predominantly on the depth of the space compared with the width. Such interpretation would be in line with previous work on figures and objects suggesting that elongation bias in area judgments is driven by the presence of unequal weight on the dimensions of the stimulus (Krider et al., 2001; Raghubir & Krishna, 1999).

Elongation biases measured in figures and objects have often been explained by the use of anchor and adjustment heuristics (for review, see Krider et al., 2001, pp. 407–408). These heuristics consist of anchoring one's judgment on a reference point and making adjustments to reach one's estimate (Fischer, Carmon, Ariely, & Zauberman, 1999; Kahneman, 1992; Tversky & Kahneman, 1974; Tversky, Sattath, & Slovic, 1988). In complex judgmental situations, such as comparing two figures of similar area, subjects have the tendency to overweight one or two dimensions of a stimulus to simplify their judgments. Similar processes could happen for volume comparisons of rooms: When there is no obvious answer regarding which room is larger than the other, participants might be overusing one salient dimension of the room—in our case the egocentric depth of the space, as suggested by the power law model. This hypothesis would need to be further explored before a firm conclusion can be drawn.

Another explanation for our results may be derived from ecological psychology (Gibson, 1979; Meagher & Marsh, 2015). Contrary to objects, surrounding spaces are those in which we can perform various actions (e.g., working, playing, walking). Thus, we could also expect different mechanisms for the estimation of their volume. Gibson (1979) developed the idea that part of the world is perceived in terms of the functional opportunities offered by the environment (notion of affordance). In line with this idea, participants could judge a rectangular room as larger because it is associated with more action or interaction possibilities depending on their viewing position. For instance, an individual observing the rooms from the middle of the short wall could stand at a greater interpersonal distance from other occupants and/or move about twice the distance in one direction than when observing the rooms from the middle of the long wall. Hence, one could interpret the greater or smaller estimated spaciousness of rectangular rooms through the notion of anticipated behavioral constraint—the way the room can expand or constrain behavioral possibilities (Gibson, 1979; Proshansky, Ittelson, & Rivlin, 1970).

Conclusions

The goal of this study was to investigate the effect of room elongation and viewpoint on the volume perception of computer-generated rooms. In line with previous work on area judgments of figures, participants were biased by the elongation of the space. In addition, the same rectangular rooms were judged to be either larger or smaller than a square room of reference depending on the viewing perspective of the space. This means that participants were biased by egocentric information. Although the relation between biases in volume judgments of rooms and area judgments of figures is not entirely clear, egocentric biases measured in room size could potentially be explained by similar mechanisms: anchoring on one salient dimension of the space. Overall, our research may be regarded as an initial exploration of the mechanism involved in volume perception of rooms. We have defined and modeled conditions in which rooms of equal volume can be perceived as larger or smaller. A common issue in urban planning for living and transportation is how to gain the sensation of spaciousness within a limited physical space. In this regard, our study could be used as a guideline for predicting perception of room size in interior architectural design. This is an interesting avenue for linking fundamental research to social applications.

Keywords: room size perception, spatial perception, volume perception, viewpoint, perceptual biases

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Footnote

[1] Changing the intercept of the generalized model's linear core corresponds to a left–right shift in the resulting sigmoid curve.

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