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Measuring perceived ceiling height in a visual comparison task

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ABSTRACT

When judging interior space, a dark ceiling is judged to be lower than a light ceiling. The method of metric judgments (e.g., on a centimetre scale) that has typically been used in such tasks may reflect a genuine perceptual effect or it may reflect a cognitively mediated impression. We employed a height-matching method in which perceived ceiling height had to be matched with an adjustable pillar, thus obtaining psychometric functions that allowed for an estimation of the point of subjective equality (PSE) and the difference limen (DL). The height-matching method developed in this paper allows for a direct visual match and does not require metric judgment. It has the added advantage of providing superior precision. Experiment 1 used ceiling heights between 2.90 m and 3.00 m. The PSE proved sensitive to slight changes in perceived ceiling height. The DL was about 3% of the physical ceiling height. Experiment 2 found similar results for lower (2.30 m to 2.50 m) and higher (3.30 m to 3.50 m) ceilings. In Experiment 3, we additionally varied ceiling lightness (light grey vs. dark grey). The height matches showed that the light ceiling appeared significantly higher than the darker ceiling. We therefore attribute the influence of ceiling lightness on perceived ceiling height to a direct perceptual rather than a cognitive effect.

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The perception of interior space and the clearance between head and ceiling is relevant for our daily lives—for example, when passing through a low doorframe or when choosing an appropriate paint to make the living room's ceiling appear a little higher. However, there is surprisingly little research on the perception of ceiling height. Previous studies mostly focused on perceived overall spatial extent of interior space—for example, perceived volume and perceived spaciousness. Spaciousness can be described as the room impression in terms of narrow or wide (cf. Franz, 2006; Franz, von der Heyde, & Bülthoff, 2005; Franz & Wiener, 2005; Stamps, 2007, 2010, 2011; Stamps & Krishnan, 2006), whereas the perceived volume refers to the room's overall perceived extent (cf. Holmberg, Almgren, Söderpalm, & Küller, 1967; Holmberg, Küller, & Tidblom, 1966; Sadalla & Oxley, 1984). In contrast to the perceived spatial extent of single room dimensions (width, depth, or ceiling height), perceived spaciousness and perceived volume are holistic measures that refer to the observer's impression of the interior space as a whole. So far, only a few studies have focused on the perception of the perceived spatial extent of interior space, but it seems that the distinction among the various dependent measures is crucial because when applied to the same interior space, they

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appear to be merely loosely related (Imamoglu, 1973; von Castell, Oberfeld, & Hecht, 2014).

Perceived spatial extent of interior space

Generally speaking, humans are well capable of estimating single spatial dimensions of interior spaces. Regarding *perceived depth*, previous studies, which were mainly run in virtual reality (VR) environments, found an approximately linear increase of perceived depth with increasing physical distance within a range of 3 m to 18 m physical distance. This is true for judgments in units of the metric system (e.g., centimetres; Kunz, Wouters, Smith, Thompson, & Creem-Regehr, 2009; von Castell et al., 2014). It also applies to action-based tasks such as blindfolded walking or throwing a small bag, such that a previously presented distance is subjectively matched (e.g., Geuss, Stefanucci, Creem-Regehr, & Thompson, 2012; Grechkin, Nguyen, Plumert, Cremer, & Kearney, 2010; Kunz et al., 2009). For example, Grechkin et al. (2010), who asked their subjects to walk various distances between 6 m and 18 m, reported that a linear model with the required distance as predictor and the intercept set to zero almost perfectly predicted the actual walked distance, $R^2 = .97$.

With regard to *perceived width*, for VR simulations of interior spaces with square surface areas (16–100 m^2), von Castell et al. (2014) reported an approximately linear increase of verbal width estimates with increasing physical width (4–10 m). For action-based estimates of exocentric distances between 3 m and 5 m in the frontoparallel plane, this was also reported by Geuss et al. (2012). Oberfeld and Hecht (2011) varied physical height and width independently from each other and found that verbal width estimates increased linearly with physical width (4.4–4.6 m) and that perceived width decreased with increasing physical height (2.9–3.1 m) whereas perceived height was unaffected by physical width.

For *verbal judgments of ceiling height* as dependent measure, von Castell et al. (2014) reported an increase of perceived ceiling height with increasing physical surface area. Physical ceiling height was set constant at 3.3 m. Oberfeld and Hecht (2011) as well as Oberfeld, Hecht, and Gamer (2010) reported an approximately linear increase of perceived ceiling height with increasing physical ceiling height (2.9–3.1 m). In the context of a more direct interplay between the spatial layout and the observer's body height in the sense of behavioural affordances (e.g., the passage through a space with a low ceiling), previous studies (e.g., Stefanucci & Geuss, 2010; van der Meer, 1997) reported a high accuracy of action-based as well as verbal decisions. For example, Stefanucci and Geuss (2010) found the subjective criterion of whether to duck or to passage upright through a low frame to be close to the subjects' physical body height, for both a verbal task and an action task.

Taken together, there is a general agreement about an approximately linear increase of the perceived extent of a given spatial dimension with an increase in physical extent. However, three problems remain to be resolved. First, it has not yet been resolved whether in those cases where judgments are biased, the bias is limited to verbal judgments. Only for perceived depth as dependent variable is there a reasonable amount of studies using tasks that do not solely rely on the verbal estimation of distances in artificial units (e.g., centimetres) as opposed to body-scaled units. Using different tasks to measure the perceived extent of spatial dimensions seems to be crucial, as previous studies have reported underestimation of spatial extent in VR to depend on the type of task. For example, Kunz et al. (2009) compared verbal and action-based (blindfolded walking) depth estimates of both high- and low-quality renderings of classrooms and found the simulation quality to influence the verbal depth estimates more strongly than the action-based estimates. Verbal depth estimates showed a more pronounced underestimation of depth for low simulation quality, whereas action-based depth estimates were virtually unaffected by the simulation quality. Moreover, for larger distances within a range of 100–262 m, verbal distance estimates for objects displayed via stereoscopic naturalistic pictures were approximately linearly related to physical distance, while action-based distance estimates (walking on a treadmill) were a compressive function of physical distance (Bergmann et al., 2011).

A second unresolved problem is the limited transferability of ratings from one spatial dimension to another. For example, Geuss et al. (2012), who compared action-based distance estimates in the frontoparallel plane and in depth in a real-life setting as well as in a VR setting, reported that underestimation of perceived distances in VR is plane dependent. Underestimation affected the perception of distances in depth but not in the frontoparallel plane. Compatible with this finding, in an experiment involving a VR room, von Castell et al. (2014) reported smaller verbal underestimation of height and width than of depth.

Third, we know that judgments of physical extent are influenced by extraneous factors such as the orientation of the spatial dimension relative to the observer, the spatial extent of the other spatial dimensions, expectations, or the lightness of the respective surfaces. The mechanisms behind these factors are mostly unexplored.

Aims of the present study

We sought to establish a psychophysical procedure that measures the sensitivity of the human visual system for slight changes in the physical extent of a room's spatial dimensions, without relying on estimates on a metre or centimetre scale. In three experiments, we tested a height-matching task, in which subjects are asked to compare the ceiling height of interior spaces with the height of a pillar in a 2I, 2AFC (two-interval, two-alternative forced-choice) paradigm. Matches on a perceptual dimension within a sensory modality are a standard method in psychophysics. For example, in the visual domain, heterochromatic brightness matches between lights of different wavelength can be used to measure the spectral sensitivity of the eye (Comerford & Kaiser, 1975).

Experiments 1 and 2 evaluated whether our psychophysical approach can be used to measure the relation between physical and perceived ceiling height. The height-matching paradigm provides information about the perceived ceiling height in terms of the point of subjective equality (PSE) of ceiling height and pillar height. It also provides a measure of the subjects' accuracy in discriminating slightly different physical heights in terms of the difference limen (DL). We are not aware of previous studies measuring DLs for ceiling height or other dimensions of interior rooms.

In Experiment 3, we used the height-matching task to measure effects of ceiling lightness on perceived ceiling height (Oberfeld & Hecht, 2011; Oberfeld et al., 2010). The aim of this experiment was to answer the question of whether the greater perceived height of light than of dark ceilings found in our previous studies can be traced back to perceptual rather than cognitive mechanisms. Oberfeld and Hecht (2011) and Oberfeld et al. (2010) had asked subjects to estimate the ceiling height in centimetres by adjusting a vertical slider within a range of 2.00–4.00 m. This direct method of asking for perceived height might give rise to expectation effects. Subjects might rate lighter ceilings to be higher because they implicitly or explicitly assume that lighter ceilings should look higher than darker ceilings. Such expectations might, for example, be fostered by guidelines in textbooks for architects and other practitioners (e.g., Drexel, 2007; Gießler, 1990; Neufert & Kister, 2009) or on web pages with a focus on interior design topics (e.g., Altmeyer, 2012; Huth, n.d.; Schneider-Grauvogel & Kaiser, n.d.). We assume such guidelines to reach a broad public, as interior design and interior decoration issues have become extremely popular during the last decade, as witnessed by TV shows on home improvement and redecoration.

The height-matching task circumvents potential expectation effects. Subjects simply provide an ordinal visual comparison of the perceived ceiling height and the perceived pillar height on each trial. A potential effect of ceiling lightness on the height matches obtained from this type of psychophysical data should represent a direct perceptual effect rather than a cognitive bias or expectation effect. In addition, the height-matching method avoids asking the subjects for height estimates in any unit of measurement and should therefore be more comparable to data concerning perceived width and depth that were collected with action-based tasks.

What do we know from previous psychophysical studies?

Difference limens (DLs) or just noticeable differences for spatial dimensions such as depth, width, and height of interior or exterior spaces have not been determined so far. The DL for visual line length was reported to be about 3% (cf. Swanston & Wade, 2001). Regan and Hamstra (1992) tested three observers for their sensitivity to slight changes in width or height of small rectangles (1.0° visual angle) and reported Weber fractions of 2.9–3.6% for width discrimination and of 2.3–3.7% for height discrimination. However, using rectangles and ellipses in a similar task, Morgan (2005) reported higher Weber fractions for width and height (5–10%).

Stevens (1957) was interested in the relation between the physical stimulus intensity and the sensation magnitude and, thus, analysed ratio judgments between sensation levels instead of DLs. Stevens suggested a power function relation between physical stimulus intensity S and sensation magnitude, $P = c \cdot S^n$, where c is a scale constant, and n is an exponent that depends on sensory dimension. The exponent of this relation was reported to be 1.00–1.10 for "visual length" (length of a line presented in the frontoparallel plane; Stevens, 1957, 1975, p. 15; Teghtsoonian, 1965) and 0.67 for "visual distance" (egocentric distance to small objects; Stevens, 1957).

All these results were obtained for small objects, and it is unclear whether they can be transferred to the perception of considerably larger interior spaces being observed from inside. If so, Weber's law (1846) implies that sensitivity for detecting, for example, a 10-cm change in the spatial extent of a room dimension (e.g., width) decreases with increasing spatial extent. However, this decrease in the detectability should be small within the range of common interior spaces. Based on a Weber fraction of 3%, for example, the minimum detectable change in height should be 7.5 cm for a room with a height of 2.5 m, and 10.5 cm for a 3.5-m room height. The power function exponents obtained by Stevens (1957, 1975, p. 15) and Teghtsoonian (1965) suggest that the perceived width/height of an interior space should be linearly related to physical width/height. Only perceived depth should be a compressed function of physical depth.

EXPERIMENT 1: FIRST EVALUATION OF THE HEIGHT-MATCHING TASK

Experiment 1 was conducted to investigate whether the height-matching task can be used to measure the effect of small changes in physical ceiling height on the perceived height of the room, and to select the optimal parameters for the task.

Method

Subjects

Nine students (five women and four men), aged from 19 to 26 years ($M = 21.56$, $SD = 2.51$) participated voluntarily in Experiment 1. Subjects received partial course credit or payment for their participation. In accordance with the Declaration of Helsinki, all subjects gave their written informed consent and were debriefed after the experiment.

All subjects had normal or corrected-to-normal visual acuity, as tested before the experiment with the aid of a Landolt ring optotype chart. They also had normal stereoscopic acuity, tested with a digital version of the Titmus test (Bennett & Rabbetts, 1998) with stereoscopic disparities of 800, 400, 200, 140, 100, 80, 60, 50, and 40 seconds of arc. In the latter test, the criterion for participation in the experiment was that at least six of the nine trials were answered correctly.

Stimuli and apparatus

We measured the perceived ceiling height of interior spaces by means of a 2I, 2AFC paradigm. As depicted in Figure 1, each trial consisted of two sequentially presented visual stimuli, an interior space, and a pillar. In a VR setting, the stimuli were presented stereoscopically on a large rear-projection screen. The simulated room had a constant surface area (4.50 m width, 6.00 m depth) and a varying ceiling height (2.90, 3.00 m; see Figure 2). All surfaces of the virtual rooms were overlaid with a fine-grained texture. The colorimetric values were measured with a spectroradiometer (specbos 1201) and are reported in terms of the CIE 1931 *xyY* system. The ceiling was coloured light grey ($Y = 15.30$ cd m^{-2}, $x = .338$, $y = .360$), the rear wall and the side walls were coloured medium grey ($Y = 13.02$ cd m^{-2}, $x = .353$, $y = .357$, and $Y = 9.48$ cd m^{-2}, $x = .347$, $y = .353$, respectively), and the floor was coloured dark grey ($Y = 2.88$ cd m^{-2}, $x = .371$, $y = .366$). During the presentation of the pillar, only the floor of the virtual room was visible, while walls and ceiling were removed. The pillar (an

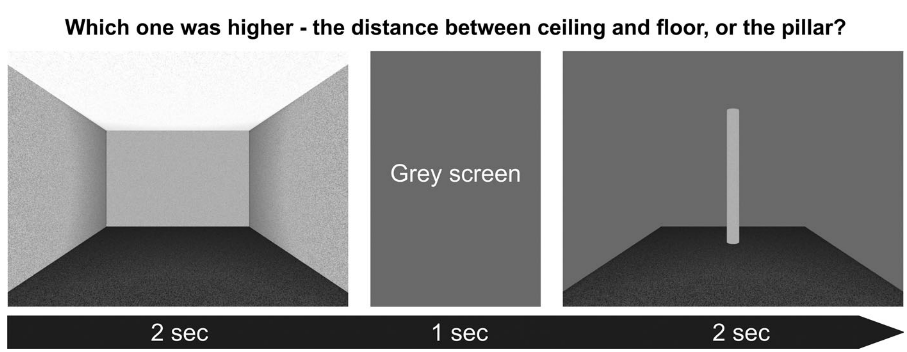

Figure 1 Experiment 1. Two-dimensional screenshots of one stimulus set.

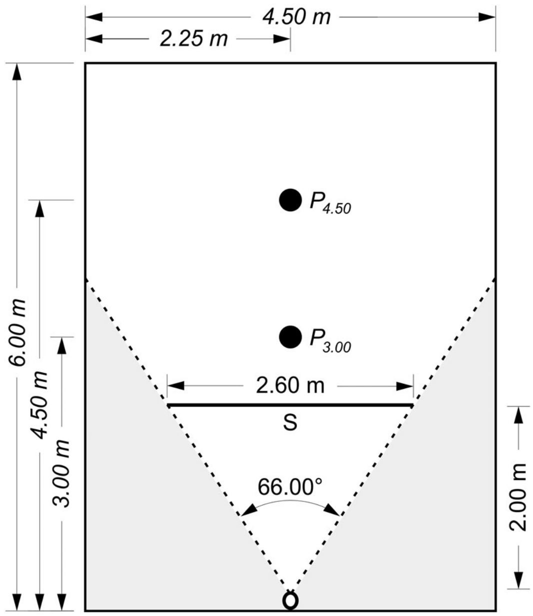

Figure 2 Experiment 1. The observer's (O) position relative to the projection screen (S) and the virtual room (rectangular frame), respectively. $P_{3.00}$ and $P_{4.50}$ denote the virtual positions of the pillar (at 3.00 and 4.50 m distance from the invisible front wall). The grey shaded area of the virtual room was not visible to observers.

upright cylinder with a width of 30 cm) was presented centred horizontally on the ground surface at a simulated distance of 3.00 m or 4.50 m to the virtual room's front wall. The pillar's physical height was varied in eight steps (2.70, 2.80, 2.86, 2.92, 2.98, 3.04, 3.10, 3.20 m).

The stimuli were generated with Vizard 3 (WorldViz, 2010) on a Core i5 computer with an NVIDIA QuadroFX5500 graphics board and were presented on a 2.60 × 1.95-m (horizontal × vertical) rear-projection screen (aspect ratio 4:3) with a 3D-projector (projectiondesign F10 AS3D). It had a resolution of 1400 × 1050 pixels (horizontal × vertical), a colour depth of 32 bits, and a refresh rate of 120 Hz. Subjects wore LCD shutter glasses (XPAND X102). The shutter glasses' switching time was synchronized with the projector's frame rate via an infrared connection. Thus, each eye received 60 frames per second. The individual inter-pupillary distance of each subject was measured with the aid of a calliper ruler before the experiment and taken into account when computing the binocular disparity of the images presented to the left and right eye. During the experiment, observers sat on a height-adjustable chair with their eye position centred at a distance of 2.00 m from the projection screen by means of a chin rest. We did not use head-tracking. The physical field of view was 66° horizontally × 52° vertically.

The observer's virtual position was 20 cm in front of the virtual room's invisible front wall, horizontally centred between the left and the right side wall. The virtual eye-height was set constant at 1.70 m in order to ensure that the same amount of ceiling surface was visible to all observers. The virtual viewing direction was horizontally and vertically perpendicular to the virtual room's rear wall. Subjects were instructed that their virtual position was like leaning with their back against the horizontal centre of the virtual room's front wall. In the software used for the visual simulations, the physical viewing distance and the dimensions of the screen were taken into account when computing the dimensions of the virtual rooms, such that the virtual field of view was identical to the physical field of view.

On each trial, each of the two stimuli was presented for 2 s, with an inter-stimulus interval of 1 s during which the display was uniformly grey. The presentation order (room–pillar or pillar–room) was varied.

The experiment was conducted in a darkened rectangular room with 105 m^2 surface area and 2.90 m ceiling height. Subjects were tested individually.

Design and procedure

Four within-subjects factors were varied in Experiment 1. All factorial combinations of ceiling height, pillar height, pillar position, and presentation order were presented to each observer.

The $2 \times 8 \times 2 \times 2 = 64$ factor level combinations were presented 10 times each, resulting in 640 trials, organized in 20 blocks of 32 trials. Each block contained all factor level combinations of ceiling height, pillar height, and pillar position. The presentation order (room–pillar or pillar–room) was varied between blocks, in order to facilitate the task. We varied the presentation order because order-effects are frequently observed in two-interval tasks (cf. Hellström, 1985; Ulrich & Vorberg, 2009). Within each block, the order of trials was randomized. The experiment consisted of two sessions of 10 blocks each. In each session, blocks with the two presentation orders alternated. The presentation order in the first block of the first session was balanced between subjects. Each session lasted approximately 60 minutes. The minimum and maximum time interval between the two sessions was 1 hour and 1 week, respectively.

Figure 1 provides a schematic outline of one trial. After the presentation of the second stimulus, subjects were asked to decide whether the pillar or the ceiling height had been higher. The question "Which one was higher—the distance between ceiling and floor, or the pillar?" (German: "Was war höher—der Abstand zwischen Boden und Decke oder die Säule?") was displayed at the centre of the screen. The placement (left-hand side vs. right-hand side) of the two response alternatives (pillar, room) corresponded to the presentation order of the two stimuli (pillar first or room first). The response alternative representing the first of the two stimuli was always presented on the left-hand side. The subject responded verbally, and the decision was entered by the experimenter using the computer keyboard. No time limit was imposed for the response.

Subjects received instructions in written form. Further inquiries were answered by the experimenter.

Data analysis

The PSE and the DL were estimated from the psychometric function (PMF) relating the proportion of "pillar higher" responses to the pillar height. A cumulative-normal PMF was fitted for each combination of subject, ceiling height, pillar position, and presentation order, using a maximum-likelihood approach. Each PMF was based on eight data points (corresponding to the eight pillar heights), with 10 trials per data point. The PSE was defined as the 50% "pillar higher" point of the PMF, and the DL was defined as half the difference between the 75% and the 25% point. Figure 3 shows an example of a fitted PMF.

Results and discussion

A likelihood ratio test comparing the fit (deviance) of the cumulative-normal model to the saturated model indicated a satisfactory overall goodness-of-fit of the PMFs. For 63 of the 72 fitted PMFs (87.5%), the *p*-value of the likelihood ratio test was higher than .10, indicating that the saturated model did not provide a better fit than the cumulative-normal model.

As depicted in Figure 4, the mean PSEs corresponded well to the physical ceiling heights across the entire range of ceiling height variation, indicating that the subjects did indeed compare the ceiling (the standard) to the pillar (the comparison).

The left panel of Figure 5 provides a closer look at the mean PSEs of Experiment 1 as a function of physical ceiling height, presentation order, and pillar position. We conducted a repeated measures analysis of variance (rmANOVA) with ceiling height, pillar position, and presentation order as within-subjects factors. The main effect of ceiling height was significant, $F(1, 8) = 106.175$, $p < .001$, $\eta_p^2 = .930$. As expected, the mean PSE for a 3.00-m physical ceiling height was higher than that for a 2.90-m physical ceiling height. However, the mean perceived increase (4.23 cm) was less than half the size of the physical increase.

Did the mean PSEs match the points of objective equality (i.e., the physical ceiling heights)? For the 2.90-m physical ceiling height, we found an almost perfect match between perceived (2.91 m) and physical ceiling height, whereas, for the 3.00-m physical ceiling height, perceived ceiling height (2.95 m) was slightly lower than physical ceiling height. The main effect of presentation order was also significant, $F(1, 8) = 17.190$, $p = .003$, $\eta_p^2 = .682$. The mean PSE was higher when the pillar was presented first. Thus, the subjects were more likely to choose the stimulus in the second interval than in the first interval to be the higher one. In other words, there was a bias towards choosing the second interval. This bias represents a time-order error ("Zeitfehler"; Fechner, 1860; Hellström, 1985). There was a marginally significant Ceiling Height × Pillar Position interaction, $F(1, 8) = 3.572$, $p = .095$, $\eta_p^2 = .309$. The positive effect of physical ceiling height on the PSE was slightly stronger when the pillar was closer to the observer. All other effects were not significant (all $p > .10$). In sum, we found the PSE to be a sensitive measure for the perception of slight changes in physical ceiling height.

The average DLs are displayed in the right panel of Figure 5. The DLs were analysed with the same type of rmANOVA as that used for the PSEs. There were no significant main or interaction effects (all $p > .10$). This indicates that the DL was largely unaffected by the experimental manipulations. However, the DL was slightly larger when the pillar was presented first. On average, the DL was $M_{DL} = 8.57$ cm, $SD_{DL} = 2.25$ cm for the presentation order room–pillar and $M_{DL} = 10.37$ cm, $SD_{DL} = 3.53$ cm for the presentation order pillar–room. The corresponding mean Weber fractions (DL divided by the respective physical ceiling height) were $M_W = 2.91\%$, $SD_W = 0.77\%$, and $M_W = 3.52\%$, $SD_W = 1.21\%$. This result is compatible with reports that the DL is smaller if the "standard" (i.e., the fixed stimulus) is presented in the first interval and the

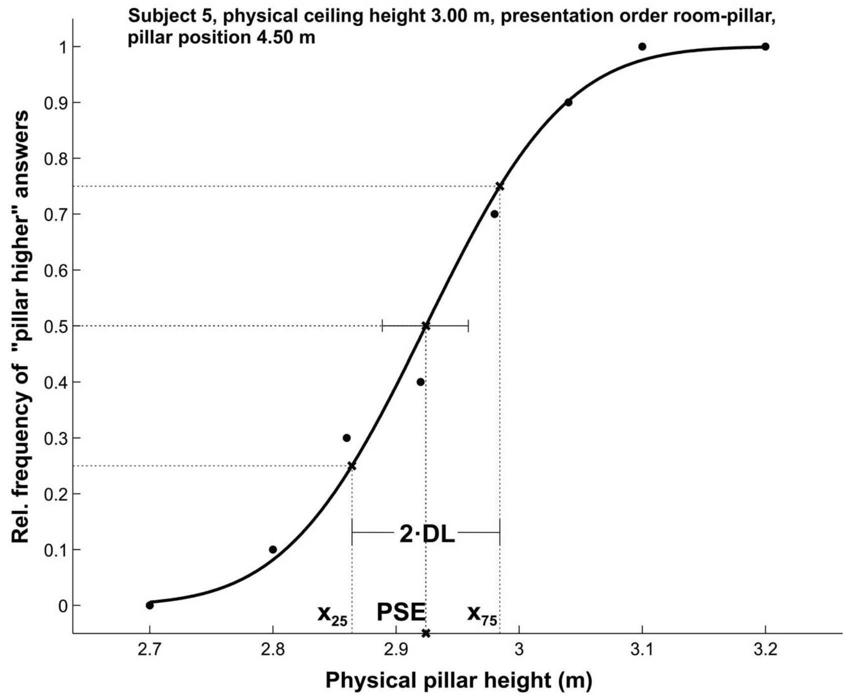

Figure 3 Experiment 1. Exemplar illustration of a psychometric function (black line). PSE = point of subjective equality; DL = difference limen. The black dots represent the eight empirical data points. The values x_{25}, x_{50} (PSE), and x_{75} are indicated by dashed lines. Error bars show the 95% confidence interval (CI) of the PSE. The DL is defined as half the distance between x_{25} and x_{75}.

"comparison" (varied stimulus; which was the pillar in our experiment) in the second interval (Ulrich & Vorberg, 2009; Yeshurun, Carrasco, & Maloney, 2008).

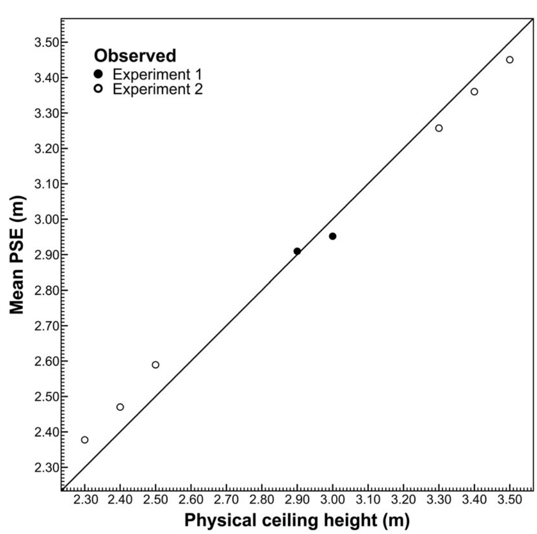

Figure 4 Mean point of subjective equality (PSE) values from Experiments 1 and 2 as a function of physical ceiling height.

EXPERIMENT 2: LARGER VARIATION OF CEILING HEIGHT

As Experiment 1 covered only a narrow range of common ceiling heights, Experiment 2 was conducted to explore whether the findings of Experiment 1 can be generalized to a wider range of ceiling heights (2.30 m to 3.50 m). Moreover, the larger variation of the ceiling height allowed us to examine whether the relation between physical and perceived ceiling height is linear.

Method

Subjects

11 students (six women and five men), aged from 18 to 34 years ($M = 23.27$, $SD = 5.22$), took part in Experiment 2. Subjects received partial course credit or payment for their participation. According to the Declaration of Helsinki, all subjects gave their written informed consent. They were not informed about the hypothesis of the experiment until after data collection. Visual and stereoscopic acuity were tested in the same way as in Experiment 1. None of the subjects had participated in Experiment 1.

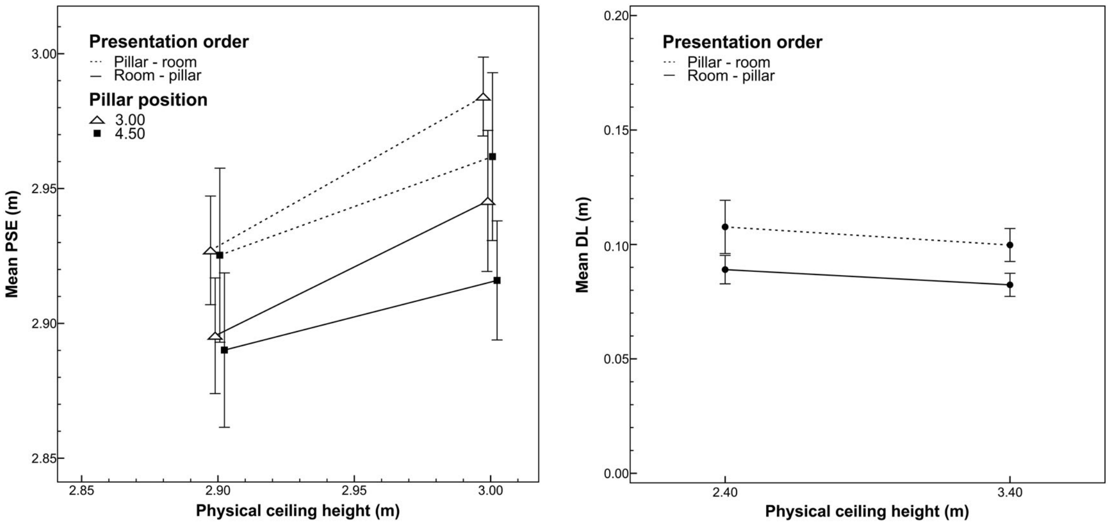

Figure 5 Experiment 1. Mean point of subjective equality (PSE) values as a function of physical ceiling height, presentation order, and pillar position (left panel), and mean difference limen (DL) values as a function of physical ceiling height and presentation order (right panel). Error bars show ±1 standard error of the mean of the 9 subjects in each condition.

Stimuli and apparatus

We applied the same apparatus and basic configuration of the trials as in Experiment 1. Two ceiling height categories were introduced (average ceiling height 2.40 vs. 3.40 m). At both ceiling height categories, ceiling height was additionally varied in three steps (ceiling height alteration; 2.30, 2.40, 2.50 m for the 2.40-m category and 3.30, 3.40, 3.50 m for the 3.40-m category). Pillar height was varied in nine steps; the pillars' mean height was adjusted to the respective ceiling height category (2.15, 2.25, 2.30, 2.35, 2.40, 2.45, 2.50, 2.55, 2.65 m for the 2.40-m category; and 3.15, 3.25, 3.30, 3.35, 3.40, 3.45, 3.50, 3.55, 3.65 m for the 3.40-m category). The pillar was presented at a virtual distance of 4.35, 4.50, or 4.65 m from the virtual room's front wall.

Design and procedure

Five within-subjects factors were varied in Experiment 2. All factor level combinations of ceiling height category, ceiling height alteration, pillar height, pillar position, and presentation order were presented to each observer.

The $2 \times 3 \times 9 \times 3 \times 2 = 324$ factor level combinations were presented five times each, resulting in 1620 trials. Trials were assigned to 10 blocks of 162 trials that included all factor level combinations of ceiling height category, ceiling height alteration, pillar height, and pillar position. Presentation order (room–pillar or pillar–room) was varied between blocks. Within each block, trials were presented in random order. The experiment consisted of five sessions of two blocks each, one with presentation order room-pillar, and the other with pillar-room. The presentation order of each session's first block was balanced between subjects. In the beginning of Session 1, subjects completed two training blocks of 40 trials (drawn at random from the 162 trials) whose presentation order was likewise varied. Note that the training blocks were added because in the course of Experiment 1, we noticed that the subjects needed some trials to become acquainted with the task. Data from the training blocks were not included in the analyses. Each session lasted approximately 60 min. The interval between two successive sessions was minimally 1 hour and maximally 1 week. Apart from that, the basic procedure was identical to that in Experiment 1.

Data analysis

We fitted PMFs using the same approach as that in Experiment 1. A separate PMF was fitted for each combination of subject, ceiling height category, ceiling height alteration, pillar position, and presentation order. Each PMF was based on nine data points (corresponding to the nine pillar heights), with five trials per data point. For three subjects, we were not able to fit the PMFs in at least one factor level combination because their choices varied too little or too unsystematically. We excluded these three subjects from the further analyses.

Results and discussion

A likelihood ratio test was conducted for the PMFs of the eight remaining subjects and revealed a good model fit: For 260 of the 288 fitted PMFs (90.3%), the deviance did not differ significantly from that for the saturated model (all $p > .10$).

Figure 6 shows the mean PSEs. As we were interested in the question of whether the results of Experiment 1 can be generalized across a wider range of physical ceilings heights, we used a multiple linear regression to predict the PSEs from physical ceiling height. Due to the repeated measures structure of the data, a subject-specific, random-effects model approach was used (SAS PROC MIXED; cf. Burton, Gurrin, & Sly, 1998; Liang & Zeger, 1986).[1] Because we expected influences of presentation order and pillar position on the relation of ceiling height and the PSEs, the interaction terms Physical Ceiling Height × Presentation Order and Physical Ceiling Height × Pillar Position were added as further predictors in the regression term. All three predictors were entered simultaneously in the analysis. The intercept was set to zero (regression through the origin). The predictors presentation order and pillar position were effect-coded such that the population slope parameter of physical ceiling height could be estimated. We found a significant positive relation between the mean PSE values and physical ceiling height, $b = 1.0023$, 95% CI = [0.9495, 1.0551]. Both interaction terms also reached significance. For the presentation order pillar–room as well as for more distant pillar positions, the PSEs increased more steeply with increasing physical ceiling height, $F(1, 7) = 9.70$, $p = .017$, and $F(2, 6) = 69.59$, $p < .001$, respectively. The regression model showed a high goodness-of-fit, $R^2 = .92$. Taken together, we found an almost perfect match between the ceiling height matches and the physical ceiling height across the entire range of the ceiling height variation.

We analysed the DLs (see Figure 7) by means of an rmANOVA (univariate approach) with ceiling height category, ceiling height alteration, pillar position, and presentation order as within-subjects factors, using the Huynh and Feldt (1976) correction for the degrees of freedom where applicable. There was a significant effect of the presentation order, $F(1, 7) = 25.687$, $p = .001$, $\eta_p^2 = .786$. The mean DL was smaller for the presentation order room–pillar ($M_{DL} = 10.27$ cm, $SD_{DL} = 5.18$ cm) than for the presentation order pillar–room ($M_{DL} = 12.77$ cm, $SD_{DL} = 8.26$ cm). The corresponding mean Weber fractions were $M_W = 3.65\%$, $SD_W = 1.92\%$, and $M_W = 4.52\%$, $SD_W = 2.86\%$, respectively. This indicates a higher sensitivity in the height comparisons when the room was the first stimulus on a given trial. Note that the direction of the effect is consistent with the non-significant trend from Experiment 1. All other effects were not significant (all $p > .10$).

EXPERIMENT 3: REPLICATION OF THE CEILING LIGHTNESS EFFECT USING THE 2AFC PARADIGM

Experiment 3 was conducted to investigate whether the effect of ceiling lightness on perceived ceiling height (cf. Oberfeld & Hecht, 2011; Oberfeld et al., 2010) can be replicated using the height-matching paradigm. As explained above, asking for perceived height in units like centimetres might give rise to expectation effects. In contrast, in the height-matching task, the subjects provide a visual comparison of the perceived ceiling height and the perceived pillar height, so that an effect of ceiling lightness on the height matches should represent a direct perceptual effect rather than a cognitive bias or expectation effect. Because we assumed the effect of ceiling lightness to be a perceptual effect, we expected the PSEs in the height-matching task to increase with increasing ceiling lightness. To be able to compare the two types of tasks (height-matching vs. verbal estimation), we additionally asked our subjects to estimate the perceived ceiling height in centimetres.

Method

Subjects

24 students (15 women and nine men), aged from 20 to 46 years ($M = 24.92$, $SD = 5.36$), took part in

[1]Random-effects models assume regression parameters (i.e., the slope) to vary from subject to subject and model the correlation structure by treating the subjects as a random sample from a population of all such subjects. The variance–covariance matrix was specified as being of type "unstructured" (UN). The degrees of freedom were computed according to the approach by Kenward and Roger (1997).

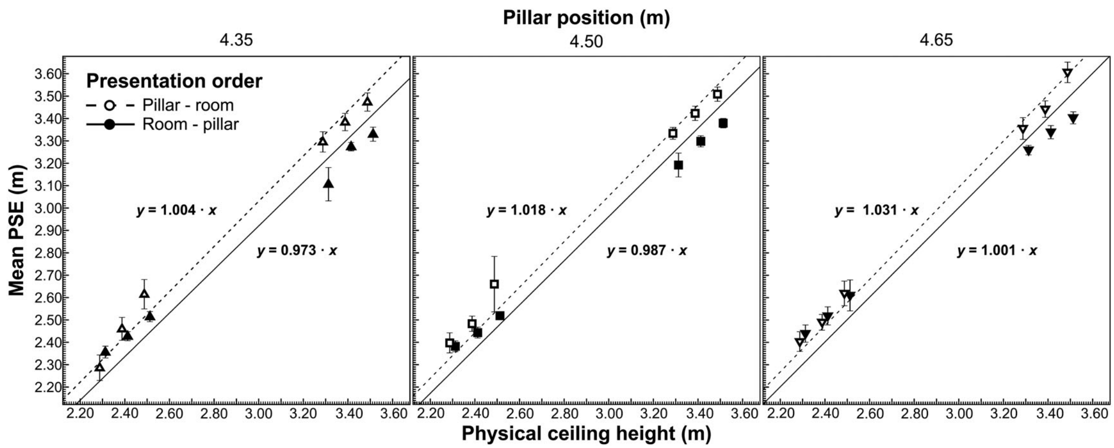

Figure 6 Experiment 2. Mean point of subjective equality (PSE) values as a function of physical ceiling height, presentation order, and pillar position. Error bars show ±1 standard error of the mean of the 8 subjects in each condition.

Experiment 3. Subjects received partial course credit or payment for their participation. Visual acuity was tested using the Freiburg Visual Acuity Test (FrACT; Bach, 1996). Visual acuity of all subjects was 1.00 (Snellen fraction 6/6) or better. Stereoscopic acuity was tested as before. All subjects provided written informed consent and were briefed and debriefed as before. All subjects were familiar with the metric system. None of the subjects had participated in Experiments 1 or 2.

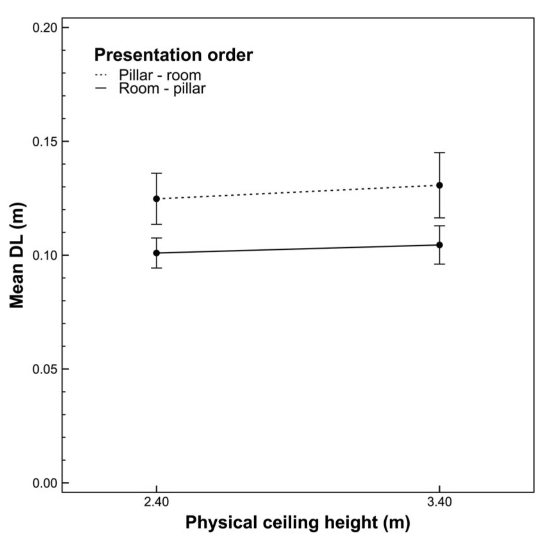

Figure 7 Experiment 2. Mean difference limen (DL) values as a function of physical ceiling height category and presentation order. Error bars show ±1 standard error of the mean of the 8 subjects in each condition.

Stimuli and apparatus

We used the same apparatus and basic trial configuration as in Experiments 1 and 2. Ceiling height was varied in three steps (2.90, 3.00, 3.10 m); pillar height was varied in seven steps. The pillar's mean height was adjusted to the respective ceiling height. Pillar heights were 2.65, 2.75, 2.85, 2.90, 2.95, 3.05, 3.15 m for 2.90-m ceiling height, 2.75, 2.85, 2.95, 3.00, 3.05, 3.15, 3.25 m for 3.00-m ceiling height, and 2.85, 2.95, 3.05, 3.10, 3.15, 3.25, 3.35 m for 3.10-m ceiling height. Pillar positions were the same as those in Experiment 1 (distance of 3.00 m or 4.50 m from the virtual observer). Because we had found lower DL-values in Experiments 1 and 2 when the room was presented first, the presentation order was room–pillar in all trials. A variation of ceiling lightness (light grey vs. dark grey) was introduced as an additional factor. The colorimetric values were $Y = 17.51$ cd m^{-2}, $x = .337$, $y = .359$, and $Y = 1.05$ cd m^{-2}, $x = .337$, $y = .352$, for the light-grey and the dark-grey ceiling, respectively.

In addition to the height-matching task, and using the same stimuli, the subjects also provided estimates in centimetres for the three ceiling heights (2.90, 3.00, 3.10 m) in both ceiling lightness conditions as well as for the three mean pillar heights (2.90, 3.00, 3.10 m), presented at both egocentric distances. For these verbal estimates, on each trial only one room or one pillar was presented without time limit. After the subject had verbally answered the question of ceiling height or pillar height displayed at the bottom centre of the screen, the experimenter entered the value and advanced to the next trial.

Design and procedure

Four within-subjects factors were varied in a fully crossed repeated measures design. All 84 factor level combinations of ceiling height (3), pillar height (7), pillar position (2), and ceiling lightness (2) were presented to each observer. As noted above, we additionally varied the type of the task (height matching, verbal estimation in centimetres).

In the height-matching task, each factor level combination was presented 10 times, resulting in 840 trials. Trials were assigned to 10 blocks of 84 trials that included all factor level combinations. Within each block, trials were presented in random order. Three blocks were presented in Session 1, four blocks in Session 2, and three blocks in Session 3. Subjects completed a training block with 42 trials (drawn at random from the 84 trials) prior to the first block in Session 1. The data from the training block were not included in the data analyses.

For the verbal rating of ceiling height and pillar height, all factor level combinations of ceiling height (3) and ceiling lightness (2) as well as of pillar height (3) and pillar position (2) were presented 10 times each. The resulting 120 trials were presented in random order in one block. This block was presented either before the height-matching training (for one half of the subjects) or after the last height-matching block (for the other half).

The experiment consisted of three sessions. The interval between two successive sessions was minimally 1 hour and maximally 1 week. Each session lasted between 60 and 80 min. In total, Experiment 3 lasted approximately 3.5–4 hours.

Data analysis

Two subjects failed to comply with the experimental protocol and, thus, were removed from all further analyses.

Analogous to the height-matching task in Experiments 1 and 2, the PSE and the DL were estimated from the PMF. A PMF was fitted for each combination of subject, ceiling height, ceiling lightness, and pillar position. Each PMF was based on seven data points (corresponding to the seven pillar heights), with 10 trials per data point.

The data of the verbal estimation task were analysed on the basis of the subjects' mean estimates for each factor level combination. For both dependent measures, perceived ceiling height and perceived pillar height, each experimental condition was presented 10 times to each subject. Means were corrected for outliers using the Tukey criterion. Estimates more than 1.5 times the interquartile range lower than the first or higher than the third quartile were classified as outliers. This affected only 14 of the 1320 ceiling height estimates (1.06%) and 16 of the 1320 pillar height estimates (1.21%).

Results and discussion

In the following sections, we first report the results of the *height-matching task*, then the results of the *verbal estimation task*, and finally a *comparison of the tasks*.

Height-matching task

A likelihood ratio test was conducted for the PMFs of the 22 subjects. Again, we found a good overall goodness of fit of the PMFs: For 213 of the 264 functions (80.7%) the deviance was not significantly larger than that for the saturated model (all $p > .10$).

Figure 8 shows the mean PSE as a function of physical ceiling height, ceiling lightness, and pillar position. We conducted an rmANOVA with ceiling height, ceiling lightness, and pillar position as within-subjects factors, using an univariate approach with Huynh and Feldt (1976) *df*-correction. The mean PSE increased with physical ceiling height, $F(2, 42) = 166.234$, $p < .001$, $\tilde{\varepsilon} = 1.00$, $\eta_p^2 = .888$. As expected, the mean PSE also increased slightly with increasing ceiling lightness, but the effect of ceiling lightness did not reach significance, $F(1, 21) = 2.273$, $p = .147$, $\eta_p^2 = .098$. Instead, there was a significant Ceiling Lightness × Pillar Position interaction, $F(1, 21) = 12.152$, $p = .002$, $\eta_p^2 = .367$. When the pillar was in the far position, then the mean PSE was on average +1.93 cm higher if the room was presented with the light than with the dark ceiling. If, however, the pillar was in the near position, then the PSE was slightly lower (−0.55 cm) with the light than with the dark ceiling. Post hoc, we calculated two *t*-tests for paired samples with the ceiling lightness as the independent variable and the mean PSE (averaged across the three levels of ceiling height) as the dependent variable, separately for each pillar position. For the far pillar position, we found a significant effect of ceiling lightness, $t(21) = 3.692$, $p = .001$. For the pillar in the near position, the effect of ceiling lightness on perceived ceiling height was not significant, $t(21) = 0.886$, $p = .386$. As a measure of effect size, we calculated Cohen's d_z (1988) for the subjects' mean difference in the PSE values for the light-grey

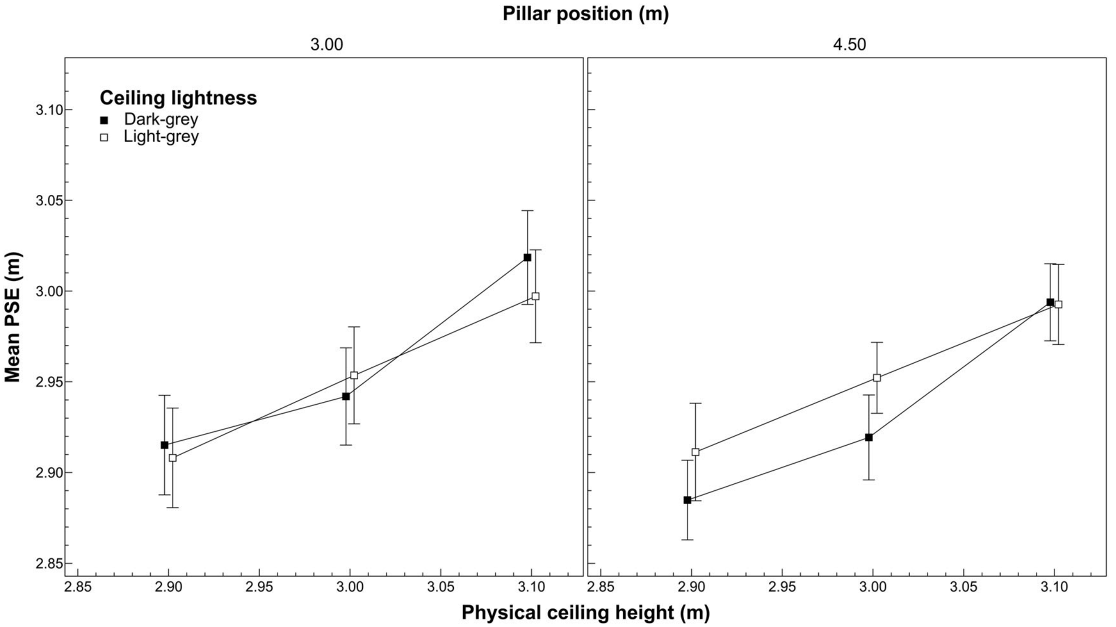

Figure 8 Experiment 3. Mean point of subjective equality (PSE) values as a function of physical ceiling height, ceiling lightness, and pillar position. Error bars show ±1 standard error of the mean of the 22 subjects in each condition.

and the dark-grey ceiling, separately for the far and the near pillar position. Cohen's d_z was 0.79 for the far pillar position and 0.19 for the near position, indicating a medium to strong positive effect of ceiling lightness on the PSE when the pillar was in the far position and essentially a null effect when the pillar was in the near position. We suppose the experimental set-up was responsible for the absence of an effect of ceiling lightness on perceived ceiling height when the pillar was positioned close to the observer. In this near position, the upper edge of the virtual pillar was very close to the upper edge

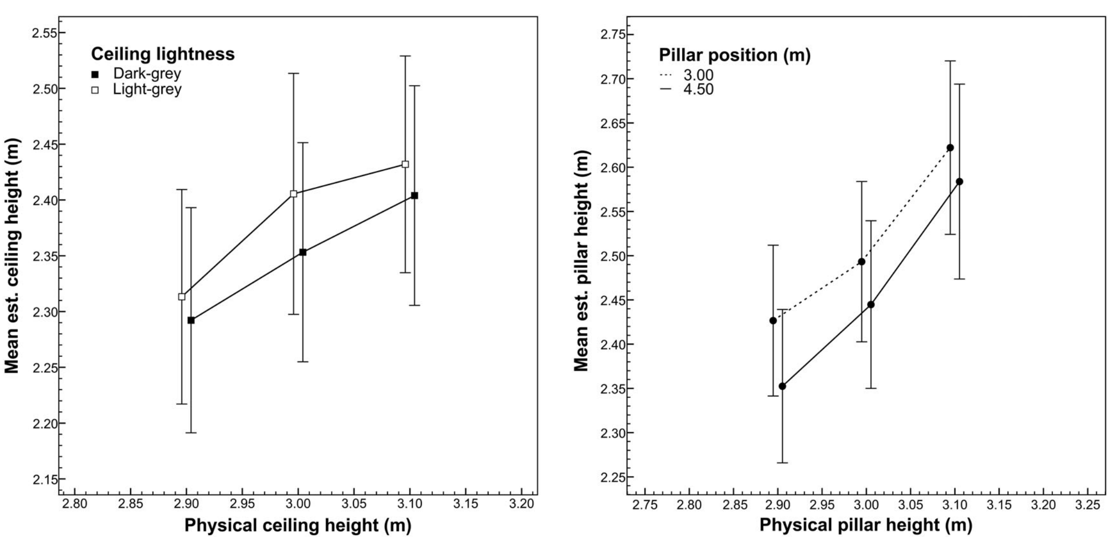

Figure 9 Experiment 3. Mean verbal ceiling height estimates as a function of physical ceiling height and ceiling lightness (left panel), and mean verbal pillar height estimates as a function of physical pillar height and pillar position (right panel). Error bars show ±1 standard error of the mean of the 22 subjects in each condition.

of the projection screen. As a result, there was only a very small part of the virtual room's ceiling ahead of the virtual pillar's upper edge. Thus, when comparing the ceiling height to the pillar height, when the pillar was in the near position, the ceiling lightness might have been somewhat irrelevant for the comparison.

The Ceiling Lightness × Ceiling Height interaction was also significant, $F(2, 42) = 4.456$, $p = .020$, $\tilde{\varepsilon} = .936$, $\eta_p^2 = .175$. As can be seen in Figure 8, the effect of ceiling lightness on the mean PSE was stronger for the two smaller ceiling heights (2.90 m and 3.00 m) than for the 3.10-m ceiling height. All other effects were not significant (all $p > .10$).

Taken together, the significant effect of ceiling lightness observed in the height-matching task, albeit only for the far pillar position, is compatible with our hypothesis: The previously reported positive effect of ceiling lightness on perceived ceiling height (Oberfeld & Hecht, 2011; Oberfeld et al., 2010) represents a direct visual effect rather than a cognitive effect.

The DL remained largely unaffected by the experimental parameters. An rmANOVA (univariate approach) with the same factorial design as that for the PSE showed no significant main or interaction effects (all $p > .10$). The mean DL was $M_{DL} = 9.37$ cm, $SD_{DL} = 4.23$ cm. The mean Weber fraction was $M_W = 3.13\%$, $SD_W = 1.42\%$.

Verbal estimation task

As shown in the left panel of Figure 9, the mean verbal estimates of the ceiling height increased with increasing ceiling lightness and physical ceiling height. Furthermore, the mean verbal estimates showed a considerable underestimation of ceiling height. We conducted an rmANOVA (univariate approach) with the verbal estimates as the dependent variable, and ceiling height and ceiling lightness as within-subject factors. The main effect of ceiling lightness was significant, $F(1, 21) = 5.615$, $p = .027$, $\eta_p^2 = .211$. On average, the light-grey ceiling was rated to be 3.38 cm higher than the dark-grey ceiling. Cohen's d_z (Cohen, 1988) for this difference was 0.51, indicating a medium-sized effect of ceiling lightness on perceived ceiling height. Note that this result is consistent both with the results of the height-matching task when the pillar was in the far position (see above) and with results from verbal estimation tasks in previous studies from our lab (cf. Oberfeld & Hecht, 2011; Oberfeld et al., 2010). The main effect of ceiling height was also significant, $F(2, 42) = 36.125$, $p < .001$, $\tilde{\varepsilon} = .959$, $\eta_p^2 = .632$. The Ceiling Lightness × Ceiling Height interaction was not significant ($p > .10$). Taken together, we found the perceived ceiling height to be higher for the light-grey ceiling than for the dark-grey ceiling as well as to increase with physical ceiling height.

The mean pillar height estimates are depicted in the right panel of Figure 9. Perceived pillar height increased with increasing physical pillar height. Consistent with the mean ceiling height estimates, we found a considerable underestimation of the pillar height. We calculated an rmANOVA (univariate approach) with pillar height and pillar position as the within-subjects factors. The main effect of physical pillar height was significant, $F(2, 42) = 39.290$, $p < .001$, $\tilde{\varepsilon} = .833$, $\eta_p^2 = .652$. All other effects were not significant (all $p > .10$).

Comparison of the tasks

Was the effect of ceiling lightness on perceived ceiling height influenced by the type of task (height matching vs. verbal estimation) or task order (verbal estimation in first block vs. verbal estimation in last block)? To answer this question, we calculated an rmANOVA (univariate approach) with type of task, ceiling lightness, and ceiling height as within-subjects factors, task order as between-subjects factor, and perceived ceiling height as the dependent variable. For the height-matching task, only the PSE values for trials that presented the pillar in the far position were taken into account in this analysis.

Consistent with the separate analyses of the height-matching and the verbal estimation task, we found a significant main effect of ceiling lightness, $F(1, 20) = 9.172$, $p = .007$, $\eta_p^2 = .314$. The Type of Task × Ceiling Lightness interaction did not reach significance, $F(1, 20) = 1.396$, $p = .251$, $\eta_p^2 = .065$. This indicates that the effect of ceiling lightness on perceived ceiling height was largely unaffected by the type of task.

Task order did not significantly influence perceived ceiling height, $F(1, 20) = 0.093$, $p = .763$, $\eta_p^2 = .005$. All interactions that involved task order were also not significant (all $p > .10$). Thus, both the verbal ceiling height estimates and the ceiling height matches can be regarded as largely independent of task order.

Likewise, in line with the separate analyses, the main effect of ceiling height was significant, $F(2, 40) = 91.937$, $p < .001$, $\tilde{\varepsilon} = 1.000$, $\eta_p^2 = .821$. In addition, there was a significant main effect of task, $F(1, 20) = 31.789$, $p < .001$, $\eta_p^2 = .614$. The mean ceiling height estimates obtained from the verbal estimation task were smaller than those in the height-matching task. Note that this is not a meaningful effect, but can simply be attributed to a fundamental difference between the two methodological approaches. In the height-matching task, the PSE values quantify the effects of variations in ceiling lightness or other parameters on the perceived ceiling height, based on a direct comparison with perceived pillar height. It is rather unimportant how the height of the pillar and the ceiling are judged on an absolute scale (e.g., in centimetres). In contrast, in the verbal estimation task, the height estimates reflect both effects of the experimental parameters and effects like a general under- or overestimation of the ceiling height on the centimetre scale. All remaining effects in the rmANOVA were not significant (all $p > .10$).

Taken together, we found the effect of ceiling lightness on perceived ceiling height to be robust across type of task and task order.

GENERAL DISCUSSION

We conducted three experiments, in which we explored the influence of physical ceiling height and ceiling lightness on the perceived ceiling height of virtual interior spaces in a visual comparison task. We decided on this type of measurement mainly for two reasons: First, the direct perceptual matching of the two visual stimuli avoids asking subjects for estimates in artificial units (e.g., in centimetres). The latter might give rise to expectation effects or other cognitive biases. Second, the height-matching task provides information about the subjects' ability to detect slight changes in the physical ceiling height, which had not been collected before. In Experiments 1 and 2, the visual comparison task proved to be an appropriate method for measuring perceived ceiling height. Also, our data for the first time provide difference limens for ceiling height. The height-matching task developed in this paper can be recommended as an alternative method for measuring the perceived spatial extent of interior spaces without the need to refer to units such as metres or centimetres. It should be noted that the task can also be used with adaptive procedures instead of the method of constant stimuli that we have employed in this study. For example, the PSE can be estimated by a simple up–down procedure (Levitt, 1971). Simultaneous estimates of the PSE and the DL can be obtained by combining two transformed up–down adaptive rules (Jesteadt, 1980) tracking different points on the psychometric function (for an example see Oberfeld, 2007).

In Experiment 3, we replicated the effect of ceiling lightness on perceived ceiling height (Oberfeld & Hecht, 2011; Oberfeld et al., 2010) both with the height-matching task and with a verbal estimation task.

Psychophysical measures of ceiling height compare well to existing measures of spatial extent

Judging ceiling height might reflect a more complex process than judging the length of a line or the size of an object. Nonetheless, since psychophysical data exist only for the latter, we relate our findings to such measures. The mean matched ceiling heights (PSEs) complied very well with the physical ceiling heights across the range of ceiling height manipulations. With the intercept set to zero, we found a positive linear relation between the ceiling height matches and physical ceiling height. The slope was very close to 1.00, indicating an almost perfect match between the perceived spatial extent and the physical spatial extent. Stevens (1957, 1975, p. 15) and Teghtsoonian (1965) reported an exponent of 1.00–1.10 for the perceived spatial extent of lines in the frontoparallel plane. Thus, the close to perfect match between the perceived spatial extent and the physical spatial extent is maintained in the more complex situation where the observer is inside the volume that has to be judged.

In terms of the sensitivity, the DLs remained fairly small (8.57 cm–12.77 cm) across the range of experimental manipulations. The Weber fractions were in a range of 2.91–4.52%. These Weber fractions are about the same size or even smaller than those reported for visual line length (cf. Swanston & Wade, 2001) or for the width and the height of small rectangles or ellipses (cf. Morgan, 2005; Regan & Hamstra, 1992).

We conclude that the perception of ceiling height is at par with results obtained with size/length perception of small objects observed from the outside. In this context, it would be interesting to investigate whether this surprisingly high accordance between interior space perception and object perception can be expanded to the perception of other spatial dimensions such as width and depth, or to more complex measures such as area or volume. For example, Morgan (2005) as well as Nachmias (2008) presented small rectangles and ellipses and reported larger Weber fractions for changes in area than for changes in height or width, and Teghtsoonian (1965) found the perceived area of simple 2D geometric forms to be a compressive rather than a linear function of physical area.

Comparison of the results from Experiment 3 with previous studies involving magnitude estimation

In the height-matching as well as in the verbal estimation task, we basically replicated the positive effect of ceiling lightness on perceived ceiling height that was reported in two previous studies from our lab (Oberfeld & Hecht, 2011; Oberfeld et al., 2010). Both methods produced similar effects, notwithstanding the deviating case of the near pillar position in the height-matching task (see the discussion section of Experiment 3).

In Experiment 3, we observed a systematic underestimation of ceiling height in the verbal estimates. In our previous studies, this underestimation was not present (Oberfeld & Hecht, 2011; Oberfeld et al., 2010). Because we used a similar experimental setup and basic configuration of the experiment, we attribute the now observed underestimation to differences in the operationalization of the verbal measure. Even though in all three studies subjects were asked to rate the perceived ceiling height in centimetres, in the two previous studies, subjects indicated perceived ceiling height by adjusting a slider on a vertical centimetre scale. The scale's range was restricted to values between 2 m and 4 m. We assume that this restriction might have provided a frame of reference for the subjects' estimates. As ceiling height ranged between 2.90 m and 3.10 m in both previous studies, using the scale's mean value as a standard would produce estimates very close to the virtual room's physical extent. Following this consideration, the general underestimation of ceiling height in the verbal estimation task, which we found in the present study, can be explained through a lack of reference.

In sum, the results of both the verbal estimation task and the height-matching task confirm the results of the two previous studies on ceiling lightness effects (Oberfeld & Hecht, 2011; Oberfeld et al., 2010): Interior spaces with lighter ceilings are perceived to be higher than interior spaces with darker ceilings. Because the height-matching task consisted of an ordinal visual comparison of ceiling height and pillar height, we assume the height matches to be largely independent of cognitive influences. Thus, we consider the observed effect of ceiling lightness on perceived ceiling height as a direct perceptual effect. However, in the height-matching task, the effect was only detected with the pillar in the rear position, and the virtual environments we presented were somewhat artificial. For these reasons, additional studies using higher fidelity simulations of interior spaces are highly desirable.

CONCLUSIONS

There are three major conclusions from the present study. First, the difference limens for ceiling height provided by our height-matching task show that the human visual system is quite sensitive to small shifts in the physical ceiling height of interior spaces. It is able to detect changes of about 3%. Second, changes in ceiling lightness cause changes in perceived ceiling height on an early, presumably pre-cognitive level of visual perception. In other words, lighter ceilings are not just thought to be higher than darker ceilings, they really look it. Third, the height-matching task developed in this paper can be used to obtain highly precise estimates of the perceived spatial extent of interior spaces without the need to refer to units such as metres or centimetres.

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